Vertical Type Reciprocating Compressor for LNG Boil Off Gas (BOG) Injection

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As the shipbuilding industry is enforcing environmental regulations, low-speed dual-fuel engines, such as ME-GI, are attracting rising attention. Such an engine requires a gas-injection compressor (GIC) to supply LNG boil off gas (BOG), and the demand for GICs is expected to grow. Hence, KOBE Steel has developed a vertical type LNG BOG reciprocating compressor suitable for GIC for ME-GI engines. In developing the compressor, we have utilized proven technologies, such as low temperature suction, high pressure discharge, and a high-performance oil-separation system. A vertical type suited to the installation space on a ship has been adopted, and ease of maintenance has been ensured. This paper describes its development.

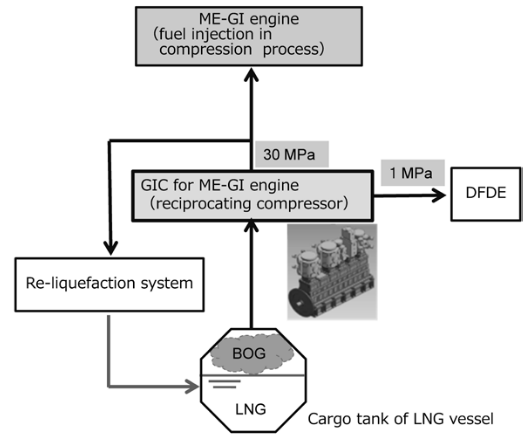


Fig. 1 Gas supply unit of ME-GI engine for LNG carrier

Introduction

The environmental regulations set by the International Maritime Organization (IMO) were strengthened. As a result, new low-speed, dual-fuel engines fueled by heavy oil and natural gas for direct propulsion are attracting attention in the shipping industry; they have begun to be adopted on LNG carriers. In the case of a low-speed, dual-fuel, electronically controlled, gas-injection diesel engine (hereinafter referred to as an "ME-GI engine"[1)]), fuel must be supplied into its combustion chamber at a pressure as high as approximately 30 MPa; hence, a gas-injection compressor (hereinafter referred to as a "GIC") is required to pressurize the gas.

There also is a prospect that more than 150 LNG carriers will be newly constructed between 2017 and 2021,[2)] and the demand for compressors for LNG carriers is expected to grow correspondingly. Hence, Kobe Steel has been promoting the development of compressors for ships to expand the applications in the compressor business. This paper describes the product development of GICs for ME-GI engines.

1. Gas supply system for LNG carrier equipped with ME-GI engine

Fig. 1 shows a gas supply system for an LNG carrier equipped with an ME-GI engine. The amount of boil-off gas (hereinafter referred to as "BOG") generated from an LNG tank varies depending on the capacity and thermal insulation performance of the tank and usually falls in the range of approximately 3.0 to 5.0 t/h. The generated BOG is pressurized up to 30 MPa and supplied to the ME-GI engine for propelling the LNG carrier, with a portion of the gas being pressurized up to about 1 MPa to be supplied to a dual-fuel diesel engine (DFDE)[3)] to power the on-board auxiliary machinery.

A carrier may be equipped with a re-liquefaction unit for collecting and liquefying surplus BOG and returning it to the tank when the fuel gas consumption of the engine is less than the amount of BOG generated from the LNG tank, or when the carrier is stopped. The efficiency of such a re-liquefaction unit increases as the pressure of the supplied gas increases. When a re-liquefaction unit is installed with an ME-GI engine, BOG at a pressure of approximately 30 MPa is supplied to the re-liquefaction unit. This increases the efficiency of re-liquefaction, improves the fuel efficiency and demonstrates excellent economy.

A compressor unit for supplying BOG to an ME-GI engine must be reasonably compact, since it is installed in a limited space onboard. The unit also is required to be capable of directly suctioning BOG at about -160°C and raising it from atmospheric pressure to 30 MPa. Thus, various other technologies are also required: e.g., a technology to extract gas from an intermediate portion and a technology to efficiently respond to the amount generated and to the amount of BOG supplied, the amounts changing depending on the engine load. The re-liquefaction unit requires an oil-separation unit for supplying gas with the oil appropriately removed.

The following describes the features of a reciprocating compressor, which Kobe Steel developed for ME-GI engines.

2. Compressors for ME-GI engines

2.1 Compressor specifications (vertical compressor)

Kobe Steel has delivered a number of high-pressure LNG BOG compressors to LNG-receiving terminals. They adopt vertical GICs while exploiting the technologies for producing high-pressure gas from the low-temperature BOG.

Each GIC consists of a 5-stage compressor for pressurization up to 30 MPa and includes an intermediate portion at the second stage to extract the gas for a DFDE. The compressor unit comprises a BOG compressor, a main electric motor, a gas cooler, an interconnect piping between the stages, an oil suppling device, and a drum for preventing pulsation, all mounted on a common skid. The dimensions of the unit for a process volume of 5 t/h is 7 m x 10 m x 6.5 m. **Table 1** compares the size (including the maintenance space) of vertical and horizontal compressor units with equivalent function and performance.

In general, a vertical compressor tends to be subjected to an unbalanced force caused by the reciprocation of pistons, a force greater than that experienced by a horizontal compressor. In a vertical machine with a crankshaft with 6 throws, the unbalanced force can be cancelled out by a 120° angular phase shift between each pair of throws, i.e., (i) #1 & #6 throws, (ii) #2 & #5 throws, and (iii) #3 & #4 throws. This concept has been adapted for the 5-stage compressor for ME-GI engines, in which a balancing throw without a cylinder is provided to maintain the balance of the compressor and minimize the unbalanced force exerted on the foundation on the ship.

Another advantage of vertical compressors exists in their rider rings. In the case of a reciprocating compressor with piston rings, rider rings are provided to prevent each piston from contacting the corresponding cylinder liner during the reciprocating motion of the piston.

Unlike the case of horizontal machines, rider rings in a vertical compressor need not support the weight of the pistons and wear significantly less.

Table 1 Unit size of vertical- and horizontal-type compressors (including maintenance space)

Compressor type	Vertical type	Horizontal type
Width (m)	7	10
Length (m)	10	10
Height (m)	6.5	5
Foot print [W×L] (m^2)	70	100

For this reason, the replacement frequency of rider rings can be greatly reduced compared with that for a horizontal machine. There is also no damage, such as seizure, due to the contact between a piston and cylinder liner, which improves not only the economic efficiency but also the reliability.

2.2 Gas volume control

The suction gas temperature of a compressor can be cryogenic (approximately -160°C) when the BOG generated in an LNG tank is directly suctioned, or the temperature can rise to near room temperature when the gas is re-liquefied utilizing the cold energy of the suction gas. When a compressor that has been shut down for a long period of time is restarted, room temperature gas is suctioned immediately after the restart, and the temperature lowers with the passage of time.

Such a significant change in the suction gas temperature changes the amount of gas processed by each cylinder of the corresponding stage and also affects the pressure balance. These are phenomena characteristic of low-temperature compressors. In addition, as described above, the balance between the amount of BOG generated from the LNG tank and the amount of gas being consumed by the engine changes constantly, and the operation conditions of the compressor change at the same time. Stable operation in such an environment calls for various measures including control methods and appropriate design margins. In this regard, Kobe Steel fully exploits its technology backed up by its abundant operational experiences with low-temperature compressors for LNG-receiving terminals. In addition, the GIC is provided with a volume adjustment device including a suction-valve unloader and a clearance pocket, while each stage is provided with a spillback line, so as to cope with any rapid fluctuations of the engine load.

2.3 Oil separation unit

Fig. 2 depicts a flow diagram of a GIC system for an ME-GI engine. The BOG generated from an LNG tank is pressurized to 30 MPa by the compressors and supplied to the engine. Each compressor includes plastic sliding parts, such as piston rings, rider rings, and piston-seal packings. In order to ensure their durability and reliability, lubrication oil is supplied inside the cylinder of the high-pressure stage. This has enabled long-term continuous operation.

Meanwhile, the oil contamination in the gas supplied to an ME-GI engine must be minimized. To

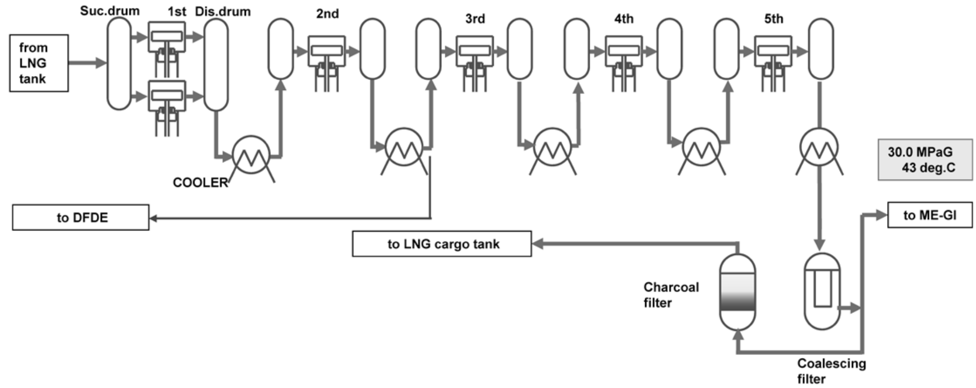


Fig. 2 ME-GI GIC flow diagram

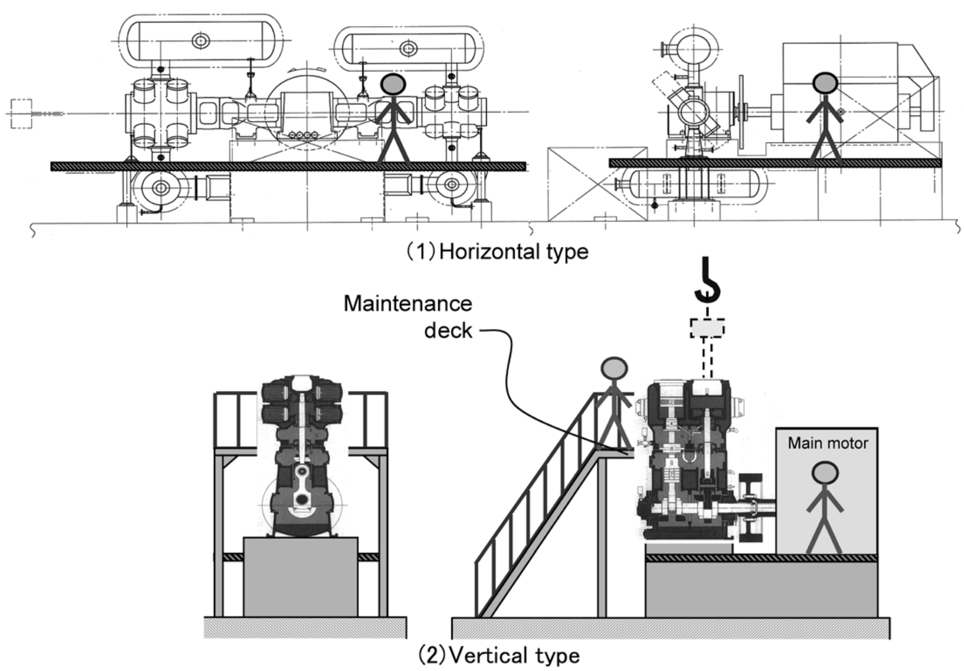


Fig. 3 Horizontal- and vertical-type reciprocating compressor units

this end, a high-performance filter for oil separation is installed in the downstream of the compressor exit to remove the lubricant oil contained in the gas.

Furthermore, in the case where a re-liquefaction unit is installed, the gas supplied at a high pressure rapidly expands, liquefying the oil dissolved in the gas. The oil content must also be removed. Hence, this system has an additional activated carbon filter in the downstream of the above-described high performance filter to further strengthen the oil removal performance.

Kobe Steel has introduced an advanced oil-separation unit as described above and has delivered a number of oil-flooded screw compressors, each involving a large amount of oil flooded during the compression process, for applications such as LNG-receiving terminals and helium liquefaction apparatuses, applications requiring processing without oil contamination. All these oil-flooded screw compressors are operating without any problems.

The compressors for ME-GI engines also exploit these technologies to suppress the influence of oil on the engine and re-liquefaction unit. Maximum consideration was given so as not to deteriorate the durability or the reliability of the sliding parts of the compressors.

2.4 Maintainability (maintenance requiring 24 hours or less)

Fig. 3 shows the reciprocating compressors of the horizontal type and vertical type. A horizontal-type compressor comprises a crank case and cylinder that are fixed to the foundation and is less likely to cause vibration. However, it has a drawback: a large installation area must be secured, including a space for pulling out the pistons in the horizontal direction during maintenance.

A vertical-type compressor, on the other hand,

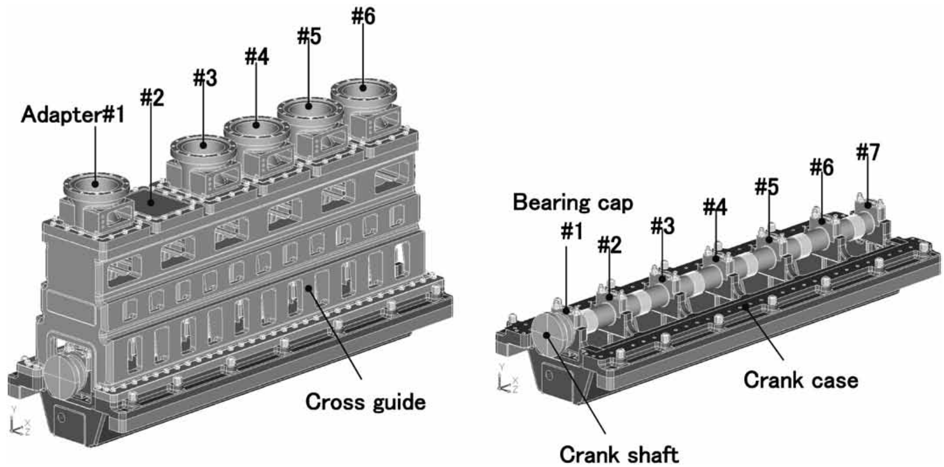


Fig. 4 3D-CAD model for FE analysis

only requires installation space for the crank case, and the installation area can be small. In addition, each piston is pulled out in the vertical direction during maintenance, so it therefore has the advantage of effectively utilizing the limited space on board and allowing, for example, the installation of other apparatuses adjacent to the compressor unit.

Maintenance work on compressors is presumed to be conducted while the ship is in dock. For any maintenance that should be performed on board, a structure that allows the replacement of a cylinder and piston as a set was adopted so as to recover the compressor during a short period of time in the berth. In other words, the structure allows a cylinder to be separated from the cross guide with a piston inserted in it. Short-term maintenance could not be realized with the conventional method, which requires the separate tasks of removing cylinder valves, the main expendable parts of a reciprocating compressor, from the cylinders, removing replacement parts such as piston rings, rider rings, piston-seal packings after pulling out the pistons, and so on. The newly developed compressor system has a structure that allows collective replacement, by means of which the maintenance work period for all the cylinders is expected to be shortened to approximately 24 hours.

2.5 Verification using prototype machine

In this development, a three-dimensional analysis model combining the principal components of a compressor, including the crank case, was prepared to ensure strength reliability; and a stress analysis by the finite element method (FEM) was carried out under the analysis conditions based on operating states, including the actual gas pressure during operation and the inertia force (i.e., load generated by the reciprocating motion of pistons, etc.) The amount of deformation and strength were confirmed for each principal component.[3)] **Fig. 4** shows the 3-D CAD model used for the analysis.

In addition, a load test using a prototype machine was conducted to quantify the stress generated in each principal component and to verify whether sufficient rigidity was secured. The natural frequency of the compressor was also confirmed by the analysis. It was measured using the prototype machine (a compressor having the size of the actual machine), and the vibration phenomena with changing RPM were confirmed to make sure that the natural frequencies of the compressor and the RPM component do not coincide (or resonate).

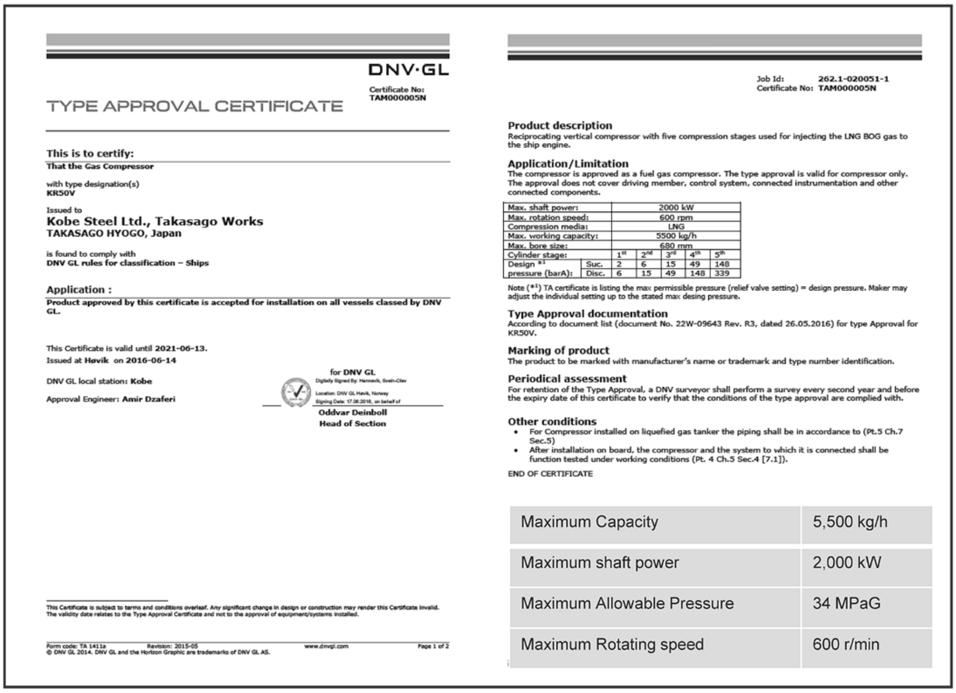
2.6 Class authentication

Vessel equipment can be mounted on ships only after authentication by ship classification societies. A compressor cannot be installed on a ship unless it is approved by the classification organization and has passed the inspections required for class certification.

To develop a compressor to be installed on a ship, a type approval was obtained from a classification agency, DNV-GL, in June 2016. **Fig. 5** shows the certificate.

3. Other applications related to LNG carriers

An X-DF[4)] engine is another type of low-speed dual-fuel engine of a new direct propulsion system adapted for LNG carriers. From the aspect of compressor specifications, the pressure of the BOG to be supplied to this engine is about 2 MPa: the main feature of the engine is a pressure lower than that for ME-GI engines, while its other characteristics, such as processing volume, are almost the same. It should be noted,



DNV·GL

Certificate No:
TAM000005N

TYPE APPROVAL CERTIFICATE

This is to certify:
That the Gas Compressor

with type designation(s)
KR50V

Issued to
Kobe Steel Ltd., Takasago Works
TAKASAGO HYOGO, Japan

is found to comply with
DNV GL rules for classification – Ships

Application :
Product approved by this certificate is accepted for installation on all vessels classed by DNV GL.

This Certificate is valid until **2021-06-13.**
Issued at **Høvik** on **2016-06-14**

DNV GL local station: **Kobe**

Approval Engineer: **Amir Dzaferi**

for **DNV GL**
Digitally Signed By: Hannevik, Svein-Olav
Location: DNV GL Høvik, Norway
Signing Date: 17.06.2016, on behalf of
Oddvar Deinboll
Head of Section

This Certificate is subject to terms and conditions overleaf. Any significant change in design or construction may render this Certificate invalid. The validity date relates to the Type Approval Certificate and not to the approval of equipment/systems installed.

Form code: TA 1411a Revision: 2015-05 www.dnvgl.com Page 1 of 2
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Job Id: **262.1-020051-1**
Certificate No: **TAM000005N**

Product description
Reciprocating vertical compressor with five compression stages used for injecting the LNG BOG gas to the ship engine.

Application/Limitation
The compressor is approved as a fuel gas compressor. The type approval is valid for compressor only. The approval does not cover driving member, control system, connected instrumentation and other connected components.

Max. shaft power:		2000 kW				
Max. rotation speed:		600 rpm				
Compression media:		LNG				
Max. working capacity:		5500 kg/h				
Max. bore size:		680 mm				
Cylinder stage:		1st	2nd	3rd	4th	5th
Design *1 pressure (barA):	Suc.	2	6	15	49	148
	Disc.	6	15	49	148	339

Note (*1) TA certificate is listing the max permissible pressure (relief valve setting) = design pressure. Maker may adjust the individual setting up to the stated max desing pressure.

Type Approval documentation
According to document list (document No. 22W-09643 Rev. R3, dated 26.05.2016) for type Approval for KR50V.

Marking of product
The product to be marked with manufacturer's name or trademark and type number identification.

Periodical assessment
For retention of the Type Approval, a DNV surveyor shall perform a survey every second year and before the expiry date of this certificate to verify that the conditions of the type approval are complied with.

Other conditions
- For Compressor installed on liquefied gas tanker the piping shall be in accordance to (Pt.5 Ch.7 Sec.5)
- After installation on board, the compressor and the system to which it is connected shall be function tested under working conditions (Pt. 4 Ch.5 Sec.4 [7.1]).

END OF CERTIFICATE

Maximum Capacity	5,500 kg/h
Maximum shaft power	2,000 kW
Maximum Allowable Pressure	34 MPaG
Maximum Rotating speed	600 r/min

Fig. 5 Type approval certificate from DNV-GL

however, that the pressure of 2 MPa is not high enough to re-liquefy BOG, and there also is a need for a compressor to perform re-liquefaction in addition to GICs. Many of the requirements for these compressors are held in common with the compressor for the ME-GI engine, mentioned above. **Fig. 6** is the overview of the fuel supply system for an X-DF engine. In this case, a system combining a Kobe Steel's screw compressor for GIC and a reciprocating compressor for re-liquefaction was adopted, and the company received the order for the first machine in 2016.

As in the case of the gas supply system for an ME-GI engine, this gas supply system for an X-DF engine is also required to have a compressor control system that ensures a stable fuel supply and optimum re-liquefaction for the amount of BOG generated and for a load that varies with the load of the engine. The system, which couples the screw compressor and reciprocating compressor to control the flow rate, could only be developed with Kobe Steel's unique technology and know-how that work on both types of compressors.

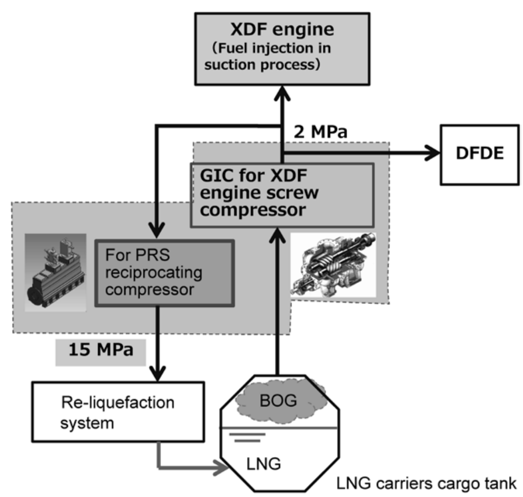

Fig. 6 Gas supply system for X-DF engine of LNG carrier

Conclusions

Under increasingly stringent environmental regulations, LNG carriers are inclined to employ new propulsion engines using natural gas as their fuel. Kobe Steel has developed a vertical reciprocating compressor used for the fuel supply system of these new propulsion engines. In developing this compressor, the company's proprietary technologies, involving low temperature, high-pressure oil separation, are used to realize improved maintainability. In addition, the company has received an order for the compressor for a re-liquefaction unit attached to the fuel supply system and are building a control system combined with the screw compressor for GIC.

Kobe Steel will strive to further refine these compressor units, continue development so as to respond flexibly to the need for compressors required for the various gas supply systems of ships, and contribute to the field of LNG carriers.

References

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