Comparison of Spherical and Membrane Large LNG Carriers in Terms of Cargo Handling

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ABSTRACT
This study presents a comprehensive comparative analysis of spherical and membrane large LNG carriers with respect to cargo handling. The spherical Moss and the Mark III membrane types have the capacity of 185,000 m³ and 204,000 m³, respectively. The study includes analyses on boil-off gas generation rate, cargo tank warm-up and cooldown, cargo offloading, residual cargo handling, and comparative safety analysis. The boil-off gas generation rate is estimated as a function of insulation thickness. For a carrier without a steam turbine propulsion system, irrespective of the types, the boil-off gas should be liquefied in a reliquefaction unit. The heat ingress into the piping and its elements are found to have a significant influence on the gas temperature entering the unit. Tank warm-up and cooldown study shows the flexibility mainly governed by the thermal stress and consequently the plausible tank temperature variation limits. The two types of LNG carriers show little variation in cargo offloading rate, but considerable difference in the amount of residual cargo. This residual cargo should be treated in a proper way. The comparative safety analysis of the two LNG carriers shows the relative advantages and disadvantages over each other.

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1 INTRODUCTION

The LNG carriers are designed, constructed and equipped to carry cryogenic liquefied natural gas (LNG) stored at a minimum temperature of -163 °C and atmospheric pressure with density of 500 kg/m³. The spherical and membrane types are accepted worldwide as cryogenic cargo containment systems.

The spherical independent tank (by Kvaerner-Moss Technology) consists of insulated single wall spherical tank, supported by a vertically built skirt. The skirt is connected with the tank around the periphery of the equator. The cargo tank material is aluminum alloy. Each cargo tank is seated in a separate cargo hold with the tank skirt mounted directly on the foundation deck. The leak protection system prevents hull structural members from direct contact with cryogenic liquid cargo in accordance with the Classification Society's requirements. The Mark III (by Gaztransport & Technigaz) reduces insulation thickness and weight significantly.

The insulation of tanks, irrespective of its type, is designed and constructed to accommodate the boil-off rate as specified, for example, 0.15%/day. The LNG cargo tank has a filling limit. Especially for the membrane type, voyages sea with cargo tank filling ratio between 10% of the tank lengthwise and 80% height wise are prohibited without rigorous safety studies due to sloshing.

A number of technologies to design the cargo hold and handling systems have entered into practice for LNG carriers. Evaluation for ensuring the structural integrity and the precise design of the cargo system is the most important concern. Numerous economical reasons lead to a significant increase in tank capacity and innovations in cargo handling systems such as BOG reliquefaction systems and propulsion systems such as dual fuel electric driven or diesel driven engines, etc. The most critical concern of the LNG transportation societies is how to meet and manage the new environmental and economical challenges.

LNG carriers should be adequately and safely designed for storing and handling their cryogenic cargo. This study presents a comparative analysis of a spherical and membrane-typed cryogenic cargo hold and cargo handling system. Evaluation of a cargo handling system is one of the most important elements in this study.
2 VISIBILITY OF LNG CARRIER

Cargo containment systems have influence not only on the transport capacity but also on the visibility. This section compared a spherical and a membrane type LNG carrier. Figure 1 shows the each ship’s visibility at ballast condition. The shaded areas represent the blind zone.

![Figure 1: Extent of blind zone and invisible length at ballast condition (M = 1.05L)](image)

As shown in Figure 1, the spherical typed-LNG carrier has a lower visibility than the membrane type. Both types have almost the same principal ship dimensions except cargo capacity.

3 CARGO OPERATION

3.1 Emergency discharge of cargo

The spherical LNGC is capable of pressure discharging of cargo in emergencies when all cargo pumps in a cargo tank fail. Pressure discharging transfers LNG in the tank containing the failed cargo pumps to other tanks in normal condition. The procedure may also perform at berthed condition if permitted by the terminal and the regulatory bodies concerned. In case of the pressure discharge at sea, the operation should perform under still water condition.

The pressure discharge procedure accompanies the tank pressure peaks reaching about 1.9 barg at pressurization. Therefore, the set pressure of the tank pressure relief valve should be adjusted higher under the supervision of the master and the changes recorded in the ship’s log in accordance with the requirement of the rules.

During emergency pressure discharge from the tank, the vapor returns from a combined high-duty heater and vaporizer. The vaporizer capacity is sufficiently covered to maintain cargo tank pressure during emergency pressure discharge of cargo. In order for the operation to be controlled at low pressure, it is highly recommended to monitor the rate of pressure increase in the cargo tank. Ballast adjustment is also performed to keep the ship balanced during emergency discharge.
On the other hand, the Mark III LNGC has an emergency cargo pump for discharging LNG in the case when both cargo pumps fail. Each tank has a column where an electric motor-driven emergency cargo pump is lowered and a column with a nitrogen purge connection is to be used as an emergency cargo pump.

In principle, one emergency cargo pump is installed on the ship to cover all cargo tanks. The emergency cargo pump is handled through the top of cargo tanks without opening the tanks. Lowering of the emergency cargo pump in all tanks is to be demonstrated before the gas trial and the pump will be kept in the lowered position in the last tank for an operation test during the gas trial.

The emergency discharge operation is shown in Figure 2.

The emergency discharge operation is shown in Figure 2.

![Emergency Discharge](image)

**Figure 2.** Emergency discharge operation for spherical (left) and membrane (right) type cargo containment systems

### 3.2 LNG Jettisoning

A containment or insulation system failure in one or more cargo tanks may necessitate the jettisoning of cargo from that particular cargo tank to the sea. This is carried out using a single main cargo pump discharging LNG through a portable jettisoning nozzle fitted on the ship’s manifold.

Since jettisoning of LNG creates hazardous conditions, the following deserve due consideration.

- All circumstances of failure must be carefully evaluated before the decision to jettison cargo is taken.
- All relevant fire fighting equipment must be manned and maintained in a state of readiness during the entire operation.
- All accommodations, other openings and all vent fans must be secured.
- The No-Smoking rule must be rigidly enforced.
- The water curtain on the side of the jettison is to be running to protecting the ship’s structure.

Weather conditions and the heading of the vessel relative to the wind must be considered to ensure that the jettisoned liquid and resultant vapor cloud are carried away from the vessel.

The portable jettisoning nozzle is capable of being mounted on any liquid manifolds, projecting 3 m over the ship’s side and providing an outlet velocity of 40 m/s when supplied by two cargo pumps at rated capacity. The operation procedure is shown in Figure 3.
3.3 Cargo Tank Cool-down

Roughly speaking, analysis of cargo tank cool-down consists of two parts. The first part is to determine for a given spray rate the resultant temperature drops in the gas phase, the internal tower, and the tank shell.

These are obtained by solving the transient energy balance which considers the heat flow into the tank through the insulation and the cooling effect of the LNG spray delivered at \(-163\, ^\circ C\).

The second part is to estimate the thermal stress using a FEM tool, which receives various predefined conditions from the part.

In general, it is assumed that the tank wall is a lumped mass, and that all parts of the tank have the same temperature. The gas phase temperature and heat transfer coefficients play a role of time-dependent boundary conditions. HYSYS.Plant, a dynamic process simulator, was used to calculate the thermal distribution during cool-down. The temperature profile and the heat transfer coefficients were then used as boundary conditions for the FEM model program. For the cool-down calculation of the LNG cargo tank, uniform gas temperature is assumed throughout the tank at any instance of time. In addition, temperature at the tank wall and the internal tower are assumed to be uniform. In the heat transfer calculation, the droplet evaporation on the tank wall is neglected. The main heat transfer mechanism of the tank cool-down between the solid walls and surrounding gas is accounted for by natural convection.

The velocity of the fluid is assumed to observe the turbulent film model. That is, the velocity is zero on the heated body, increases rapidly in a thin boundary layer adjacent to the body and has a vanished gradient far from the body. The temperature gradient between stagnant fluid and solid body is produced by heat transfer. The fluid motion due to natural convection results from buoyancy force arising from changes in density.

Tank cool-down for a spherical and membrane LNG Carrier is performed for the spray rate, and the results for transient profiles of mass flow and temperature are shown in Figures 4 and 5. When the tank gas temperature reaches the natural gas dew point, spray efficiency sharply decreases and then residual LNG appears. The tank wall temperature is higher than that of the tank gas. Some of the residual LNG will evaporate when it contacts the wall. This results in a somewhat lower tank wall temperature than predicted in the calculation.
3.4 Cargo loading and offloading

Generally, cargo loading and offloading times are specified for the design of cargo pumps and pipes. Figures 6 and 7 show pressure drops of related lines and estimated loading and unloading times of typical membrane cargo tanks.

During loading and offloading operations, NPSH available varies since the cargo level inside the tank changes with operation time. Discharge time is divided into several stages; the buildup period for starting pumps, the load stage and the slowdown or stripping stage at the end of discharge. Spherical cargo tank design and evaluation has a similar approach to those of LNG cargo pumps and pipes.

During the operations, the condition of the cargo containment and handling system should be continuously monitored from the IAS and various safety protections should be provided to keep the system in a reliable state at all times to evaluate their design. This study employs a dynamic simulation of all cargo handling processes for a rigorous process monitoring.
4 BOR CALCULATION

The cargo tank is thermally insulated to achieve a boil-off rate not exceeding 0.15 percent by gross cargo volume per day at 32°C seawater temperature and 45°C ambient air temperature.

There is a trade-off between boil-off rates and insulation thickness. Reducing the boil-off rate leads to an increase in insulation cost, and vice versa. Figure 8 presents boil-off rates with insulation thickness. Estimation and prediction of boil-off rates guides design of reliquefaction systems, cargo tank insulation systems and cargo handling systems.
5  LNG reliquefaction system

Linde patents provide the basis for reliquefaction designs commercially available. The Linde process is composed of two nitrogen compressors and a BOG (boil-off gas) compressor as shown in Figure 9. The cold stream from the nitrogen expander is exchanged with BOG to be liquefied. The Tractebel process is much similar to the Linde process except for elimination of the expansion valve.

The reliquefaction system simplifies the Linde process by removing the expansion valve and increasing energy efficiency by optimizing the number of compressors for the nitrogen cycle. The outstanding features are a nitrogen-rich purge, automatic capacity control, pre-cooling system and high reliability.

Process variables requiring precise estimation are BOG flow rates and their temperatures. Heat ingress through piping and fittings is possibly mitigated by insulation of bellows, pipes and valves. Casing the BOG headers reduces the heat loss from the forced convective heat transfer. As shown in Figure 10, preliminary inlet temperature of the reliquefaction system is revealed.
Because the BOG header is exposed to the atmosphere, heat ingress is inevitable. In accordance with the increased suction temperature of the reliquefaction system, the compressor capacities and nitrogen chilling system should be enlarged. Table 1 shows the effects of suction temperature on different BOG specifications.

Table 1. Reliquefaction specification for BOG suction temperature

<table>
<thead>
<tr>
<th>BOG Rate</th>
<th>4,128 kg/hr (0.12%/day)</th>
<th>5,125 kg/hr (0.15%/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOG Suction Temperature</td>
<td>-120</td>
<td>-110</td>
</tr>
<tr>
<td>LD Compressor Power, kW</td>
<td>220</td>
<td>236</td>
</tr>
<tr>
<td>N₂ Mass Flow, kg/hr</td>
<td>81,870</td>
<td>85,740</td>
</tr>
<tr>
<td>N₂ Cycle Power, kW</td>
<td>3,492</td>
<td>3,657</td>
</tr>
</tbody>
</table>

6 CONCLUSION

The comparative analysis of the two LNG carriers in terms of the cargo handling system shows the relative advantages and disadvantages of each. The membrane type LNG carrier has a better visibility than the spherical type whose cargo tank protrudes to hinder the visibility. In emergencies of cargo pump failure, the spherical type is capable of pressure discharge while the membrane type should be equipped with an emergency cargo pump. Before and during jettisoning of LNG into the sea extreme consideration and caution are required.

Cargo handling systems are compared for spherical and membrane large LNG carriers based on the results of dynamic simulation. Dynamic simulation is an excellent tool for evaluating the cargo handling system of large LNG carriers. The solutions are based on optimal design to minimize cargo handling system optimal design. Due to the flexibility of dynamic solutions, it is well adapted for design optimization.
In addition, the membrane LNG carrier is capable of loading more than 8% LNG cargo in identical principal ship dimensions. The boil-off gas rate is presented as a function of insulation thickness with a generally accepted boil-off gas rate of 0.15%/day. Insulation and cargo handling system should be designed based on the specified BOR.

Estimated cool-down time for spherical type tank is 16 hours, satisfying the temperature requirement of the equator sensor at -110°C. During cool-down, the maximum suction volume is observed to be 12,000 m³/hr at 1.5 hour. The membrane cargo tank has a cool-down time of about 10 hours with a cargo tank atmosphere temperature of -140°C. The maximum boil-off rate is predicted to be about 8,500 m³/hr at 1 hour.