Unlike all cargo ships, liquefied natural gas (LNG) carriers have continued to use steam turbine propulsion plant despite more efficient diesel engine being available. This is because the gas that naturally evaporates from the cargo (called boil-off) is used as fuel for the steam turbines, and until recently there was no other use for it. The ability to reliquefy the gas given off by the cargo now makes it possible to increase the amount of LNG delivered to the discharge port, which is more profitable than using it as ship’s bunker.

Reliquefying LNG and returning it to the cargo tanks means that gas never enter the engine room, adding to the general safety margin. Total separation between cargo and engine room means that the propulsion system and type of fuel used can be chosen freely.

1. Introduction

The cargo of liquefied natural gas on a LNG carrier is kept in a liquid state -163°C in the tanks. Due to warming up during transportation, gas naturally evaporates from the cargo and the boil-off gas can be used in the boiler for production of some of the steam required for a steam-turbine propulsion plant. However, additional energy generated by forced evaporation of gas or fuel oil is also needed to obtain the required power for an optimal service speed.

In principle there are two ways of handling the boil-off gas. It can be either be burnt in a boiler, gas turbine or dual-fuel diesel engine to provide power for the propulsion of the vessel, or the boil-off gas can be reliquefied and returned to the cargo tanks.

Reliquefaction plants have been used for many years on liquefied petroleum gas (LPG) carries. Cargoes such as butane and ethylene are kept liquid below their boiling points, and boil-off gases are returned to the cargo tanks by reliquefaction systems that have been offered and supplied by Hamworthy Gas Systems for almost 40 years.

2. Reliquefaction system

Reliquefaction is based on a closed nitrogen cycle extraction heat from the boil-off gas. Several novel features such as separation and removal of incondensable components have resulted in a compact system with low power consumption. A boil-off gas reliquefaction system in combination with slow speed diesel-mechanical of diesel-electric propulsion has both economic and technical advantages.
2.1 LNG cargo cycle

LNG cargo-cycle components are: a low duty compressor, a plate-fin cryogenic exchanger and a separator. Boil-off is evacuated from the LNG tanks by a conventional centrifugal low duty compressor and sent directly to the cold box to be reliquefied. The cold box is cooled by a closed refrigeration loop called the Brayton cycle, employing nitrogen as the working media.

The vapour is compressed and cooled in a plate-fin cryogenic exchanger. This is to ensure condensation of hydrocarbons to LNG. In cases with high content of N2 in the Boil-off gas, there may be fractions of nitrogen that will not be condensed and remains as gas bubbles in the LNG. In such cases phase separation takes place in the liquid separator. From the separator the LNG is dumped back to the storage tanks, and if present, the nitrogen-rich gas phase is discharged to atmosphere or burnt in an oxidiser. In cases with lower N2 content in the Boil-off gas, everything will be condensed and returned to the cargo tanks without any discharge to the atmosphere.

2.2 Refrigeration loop

The cryogenic temperature inside the cold box is produced by a nitrogen compression-expansion cycle. Nitrogen gas is compressed in a three-stage centrifugal compressor. The gas is cooled by water (seawater or indirect) after each stage. After the last cooler, the gas is led to the 'warm' part of the cryogenic heat exchanger where it is pre-cooled and then expanded in the expander. The gas is then introduced into the 'cold' part of the cryogenic heat exchanger where it cools and reliquefies the boil-off gas to LNG.

The nitrogen then continues through the 'warm' part of the cryogenic heat exchanger before it is returned to the suction side of the three-stage compressor. This N2-compressor/expander unit is an integrated gear centrifugal compressor with one expander stage. The unit has a gear with four pinions where each of the four wheels is coupled to a separate pinion. This configuration ensures that expander is linked directly into the gearbox and relieves the electric motor.

The advantages of this solution are that it results in a more compact design with reduced power consumption and therefore lower costs.

2.3 Automatic capacity control

Increasing or decreasing the amount of nitrogen in the loop changes the cooling capacity. The amount is
changed by injecting or withdrawing nitrogen to the receiver. If the cooling capacity is too high, the inlet expander temperature will decrease. The control valve to the receiver at the compressors will open to withdraw the nitrogen from the main loop.

Correspondingly, if the cooling capacity is too low, the inlet expander temperature will increase. The control valve from the receiver to the compressor suction side will open to inject nitrogen into the main loop.

The boil-off gas cycle is also an independent loop. The cargo tank pressure is kept almost constant by varying the mass flow through the compressor. The boil-off compressor is a two-stage centrifugal unit with diffuser guide vanes for controlling capacity.

3. Reliquefaction technology

3.1 Redundancy

Redundancy is required by International Association of Classification Societies (IACS). The requirement is fulfilled if a thermal oxidiser or flare system capable of burning the maximum boil-off rate is installed, or alternatively two 100 per cent reliquefaction plants with one cold box. This latter option would comprise duplication of boil-off gas compressor and N2-compressor/expander units, but only one cold box, one LNG phase separator, and auxiliary systems.

To maintain the current reliability of steam-turbine-driven LNG carriers the reliquefaction system only uses proven high quality components used in plant ashore, and the low-duty compressors in the Moss RS reliquefaction system are the same as used on all LNG carriers today. An availability analysis performed concluded a 99.98 per cent availability of spare parts, which is at the same level as - or better than - ship machinery in general.

3.2 Onshore LNG plant

The Moss RS reliquefaction system offered by Hamworthy Gas System AS is now technically mature and includes proven components. The completion of an onshore LNG plant in Norway demonstrate the feasibility of the reliquefaction technology. The Norwegian plant uses the same type of (Brayton) cooling cycle and control principles as the reliquefaction system for LNG carriers as well as the three-stage N2 compressor with expander and the cold box.

The advantages in terms of operating costs with diesel engine solution with reliquefaction compared to steam turbine depends on the cargo capacity, boil-off rate and propulsion power. These items may make it more or less attractive to use diesel engines, but the advantage will in all cases be large and in favour of diesel engine propulsion and a reliquefaction system.

4. System's Merits

The concept have following merits.

4.1 Economic merits
- increased cargo quantity delivered
- reduced 'heel' (see below) required on ballast voyage
- large saving in total fuel consumption
- improved propulsion redundancy
- allows more profitable freight contract.

'Heel' is the small amount of LNG cargo (about 2 per cent of the ship's capacity) retained on board to keep the tanks and pipelines cold ready for loading the next cargo. It can be circulated through the cargo pumps and lines, and sprayed into the cargo tanks to cool them further before arrival at the loading berth.

4.2 Technical merits
- the nitrogen in the LNG boil-off gas is not
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reliquefied in the Moss RS plant; this lowers the cargo's nitrogen content during the voyage, resulting in better control of tank pressure and a lower requirement for the reliquefaction system.

- the system uses only proven components with extensive references from air-separation and peak-shaving plants (gas storage tanks acting as 'buffers' for varying demand levels) worldwide
- the system is prefabricated on skids for easy installation and hook-up
- there is no - or limited - increase in cargo-handling machinery space
- the system has automatic capacity control with an operating range from 0-100% capacity
- the system can be stopped or operate in a "stand-by mode" during unloading, which eliminates the need for extra generator capacity
- during ballast voyages, the cargo tank temperature can be maintained by spraying reliquified LNG back into the cargo tanks which reduce the initial increase of BOR on laden voyage
- the required 100 per cent redundancy can be arranged in several ways
- no extra crew are needed for its operation and maintenance
- if diesel engine propulsion is chosen, its design, installation and operation will be well known to shipyard and owner.

5. Appendix

LNG glossary

Natural gas is mainly methane (around 90 per cent or more), but may also contain ethane, propane and heavier hydrocarbons, and small quantities of nitrogen, oxygen, carbon dioxide, sulphur compounds, and water. Liquefaction removes the oxygen, carbon dioxide, sulphur compounds and water.

Liquefied natural gas (LNG) is natural gas that has been cooled to -161°C (its boiling point at atmospheric pressure) when it condenses into a colourless, odourless, non-corrosive and non-toxic cryogenic liquid. It is generally handled at slightly above atmospheric pressure by maintaining a low temperature. [In contrast: liquefied petroleum gas (LPG) mainly consists of propane, propylene, butane, and butylene in various mixtures, and can be stored as a liquid by applying pressure alone.]

Cryogenic liquids are liquefied gases that are kept in their liquid state at very low temperatures, and have boiling points below -150°C. LNG is stored as a 'boiling cryogen': a very cold liquid at its boiling point for the storage pressure. Insulation alone does keep maintain a low enough temperature, and LNG is kept in liquid form by auto-refrigeration.

Auto-refrigeration is the process which keeps the LNG at its boiling point, so that any added heat is countered by the energy lost by venting LNG vapor (boil-off). LNG will stay at near constant temperature if kept at constant pressure.

Boil-off is the small amount of LNG evaporating from a tank during storage, cooling the tank and keeping the pressure inside the tank constant and the LNG at its boiling point. Rise in temperature is countered by boil-off being vented from the storage tank. If the vapor is not drawn off, then the pressure and temperature inside the vessel will rise.

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