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Typology of Gas Carriers

C. Gonzalez-Gutierrez[1,*], C. Perez-Labajos [1,3]

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ABSTRACT

This work aims to describe the typology of the Gas carrier fleet, differentiating between the two main subgroups which are forming this maritime transport segment, those who transport liquified natural gas (LNG carrier) and those who transport liquified petroleum gases (LPG carriers), highlighting and explaining the main technical characteristics that are defining these types of ships.
The LPG and LNG carriers have similarities and differences among them, making necessary a differentiation between both sub-fleets. In the same way, within the LPG and LNG fleets, is possible to find notorious differences regarding sizes, cargo systems and propulsion systems. These differences are underlying the need of separate between LNG and LPG ships when the Gas carrier fleet is under analysis

1. Introduction.

The global merchant fleet in January 2017 accounted 93,161 ships in service (United Nations, 2018), the gas carrier fleet in the same period consisted of 1,926 ships in service, being 1,484 LPG carriers and 442 LNG carriers (IHS Markit, 2017), showing an increment in the gas carriers deadweight from the year 2016 to 2017 of 9.7% (United Nations, 2018). Gas carriers is a subgroup within the Tanker fleet. Gas carriers are specialized tankers, which are divided into two large groups: gas carriers that transport liquefied petroleum gases, known as LPG carriers, and ships that transport liquefied natural gas, known as LNG carriers. Gas carriers transport cargo either under pressure, under moderate pressure and low temperature, or at very low temperatures (cryogenic) (McGeorge, 1995).

The first ship that was designed for the bulk transportation of liquefied gases dates from the year 1931 for the transportation of Liquefied Petroleum Gas, and the ship name was "Agnita". On other hand, the first ship that transported liquified natural gas was a ship named "Methane Pioneer" entered into service on 1959 (Gray, 2004). LNG and LPG ships were concepts that began to be used in the first half of the 20th century. However, the transport of liquefied gases in bulk was not a very important market until the end of the 20th century compared to other segments of maritime transport such as the transport of solid bulks and crude oil. In the scientific community, the interest on LPG or LNG carriers has not appeared until 1977, when the first articles appeared, when the first incidents and accidents began to occur within the gas carriers. In the 1960s and 1970s, the first incidents involving gas tankers were recorded. A ship of the LPG type, called "Mundogas Oslo" was the first accident recorded in 1966, while the first major accident recorded by an LNG ship was the one that occurred on the ship "LNG Libra" in 1979 (Cabioch, F. et al., 2009), then the scientific community started to pay more attention to the safety of these ships.

Liquefied natural gas (LNG) is currently one of the preferred options as an energy source by many industries because this fuel produces negligible NO_x and SO_x emissions, in addition to a reduction in CO_2 emissions of around 20% in comparison with other fuels more commonly used by the industries with high carbon contents (Calderón et al., 2016). These characteristics make natural gas an important alternative in the global energy mix since it provides flexibility when balancing the electrical networks that are connected or that depend on renewable energies, as well as being a cleaner alternative to fuels

[1]University of Cantabria. Germán Gamazo nº 1, 39004 Santander, Cantabria (SPAIN). Coastal and Ocean Planning and Management I+D Group

[2]Professor of Marine Economics of the Department of Navigation and Naval Construction Science and Techniques. Tel. (+034) 942201362. E-mail Address: clabajos@unican.es.

[*]Corresponding author: C. Gonzalez-Gutierrez. Tel. (+034) 620595749. E-mail Address: carlos.gonzalezgu@alumnos.unican.es

derived from the oil for the transport sector. The consequence of these benefits of using LNG as an energy source would imply the increment of the LNG fleet in the coming years.

The other group within the maritime transport of gas carriers are ships that transport liquefied petroleum gases. LPG is a set of products resulting from the natural gas and crude extraction processes, and therefore it is logical to assume that the available supply of LPG will depend on the levels of crude oil and natural gas production (Adland et al., 2008). Having said that, the LPG is an option that is being also considered in order to ensure that energy demand is met and it is also an alternative as a fuel for transportation since it is less polluting than other fossil fuels that are used globally (Baranzini et al., 1996; Johnson, 2003).

This work is structured in three more sections: 2. LPG carriers overview, 3. LNG Carriers overview and 4. Concluding remarks.

2. LPG Carriers overview.

This section aims to provide a brief description of the LPG maritime transport, highlighting the main characteristics of the LPG as product and its trading, following it with a description of the LPG gas carriers.

2.1. LPG maritime transport, brief overview.

In the beginning, when the LPG started to appear because of the extraction of crude oil, the use and consequently the transport of LPG was not an option considered given its complexity when transporting it, this fact made the LPG originating in the oil extraction and refining processes to be discarded, burning it in industrial flares.

Modern LPG production goes back to the early 1900s with the *Rockgas Production Co*., selling LPG in bottles or cylinders for residential use. This type of container used a combination of propane and butane like that of today, although today, the gas in such containers is much cleaner and more refined than at the beginning of the 20th century.

With technical advances in materials, container systems and the acquisition of more knowledge about the usefulness of these gases, the demand for LPG increased and the need for the massive movement of these gases arose.

The first ship specially designed for the transport of LPG was the British-made Agnita, delivered in 1931. However, the first ship to transport LPG in bulk was the Natalie O Warren, which began operating in 1947 on a regular route from Houston to New York.

Regarding the composition of LPG and its commercial utility, the most important and therefore most widely used liquefied petroleum gases are ethylene, butane, and propane, which are known as alkene compounds (unsaturated hydrocarbons with a double carbon bond in their molecule).

LPG is liquefied for transport on ships and then transformed back into a gaseous state for use as a heating fuel, motor fuel, or as a raw material in the petrochemical or chemical industries. The volume in the liquid state of LPG is reduced from 2,300 to 13,500 times the volume in the gas state.

LPG transportation is characterized by continuous commercial transactions due to the arbitrage economy that dominates this sector. On the demand side, there are three types of charterers: 1) end users who normally sign long-term contracts with LPG producers to secure a fixed amount of volume for their own consumption. 2) Energy companies with upstream facilities that produce LPG, being able to sell LPG in long-term contracts to fixed buyers or commercialize them in spot markets according to market conditions. 3) intermediaries (traders), who have no assets and simply benefit from moving cargo between different geographic locations. Apart from the first type of charterer, the other two types of charterers can choose the destination according to the market situation, this characteristic implies that the LPG fleet needs to have high degree in flexibility.

The maritime LPG market has not attracted much interest from the scientific community, which is why it has not been the subject of much academic attention as shown by the works of Adland, et al., (2008) and Engelen et al., (2011), despite being a market on the rise due to its importance as a fuel, raw material and energy alternative.

Table 1: Main trades of the LPG market.

Type of gas	Evaporation point (°C)	Specific Density	Main trade
LPG			
Propane	-42.3	0.58	Raw material & heating
Ethane	-88.6	0.55	Raw material & heating
Butane	-0.5	0.60	Raw material & heating
Petrochemical			
Ammonia	-33.4	0.68	Fertilizers
Olefins			
Ethylene	-103.9	0.57	Raw material in chemical processes
Propylene	-47	0.61	Raw material
Butadiene	-5	0.65	Raw material
VCM	-13.8	0.97	Raw material

Source: Stopford, (2009).

As a fuel, LPG is gaining importance in the transport sector given the lower amount of harmful emissions to the atmosphere compared to other fuels used (Raslavičius et al., 2014). When LPG is used as a raw material for the manufacture of chemicals, the price is important because imbalances of supply and demand in the petrochemical industry cause price differences between regions and, of course, LPG is competing with other materials raw materials such as gasoline (Stopford, 2009). Northeast Asia (Japan, China, and South Korea) is the world's largest LPG importing region, followed by Western Europe and the United States.

Traditionally, the Middle East has been the main export area for LPG, however recent developments in the petroleum product markets in North America have shown how changeable market dynamics can be in this sector. After the discovery of shale gas, the US has become an increasingly important LPG exporting region, increasing LPG exports from 9 million tons per year in 2013 to almost 24 million tons in 2016, being Asia and Europe are the main recipients of these shipments (The World LPG Association, 2017).

2.2. *Description of the LPG fleet.*

LPG ships are tankers ships specially designed to transport liquefied petroleum gases in bulk. LPG ships can carry different gases such as ammonia, propylene, and vinyl chloride. The different types of products that these ships can transport influence the construction of the ships, and above all, the cargo systems installed. Virtually all LPG ships can carry the most significant products such as propane, butane, ammonia, propylene, ethylene, and vinyl compounds.

Considering the temperature and pressure required to transport the various liquefied petroleum products, LPG vessels can be divided into three categories: pressurized, semi-refrigerated and fully refrigerated (Babicz, 2015). Small LPG vessels (less than 6,000 m^3 of cargo capacity) are often pressurized. The semi-cooled or semi-pressurized design is used for cargo capacity of around 10,000 m^3, and the fully refrigerated technique is intended for cargo spaces between 10,000 m^3 and 100,000 m^3.

Fully refrigerated LPG vessels typically have prismatic-type cargo tanks and typically carry LPG cargoes and some petrochemical cargoes. The cargo on ships is transported at atmospheric pressure and in fully refrigerated conditions. The ships are equipped with a liquefaction plant (sub-cooling plant) that can maintain the temperature of the cargo within the required limits.

Semi-refrigerated LPG vessels are commonly known as semi-pressurized vessels and are generally built with horizontal or bilobed cylindrical tanks capable of withstanding pressures of up to 10 bar. The ships are equipped with a liquefaction plant capable of maintaining the temperature and pressure of the cargo. Ships generally carry loads of LPG and petrochemicals gases and are generally used in spot markets.

There is a subgroup within these semi-refrigerated LPG ships, and they are the LPG ships that transport ethylene, transporting this product at -104 °C. These vessels are among the most sophisticated in the fleet in terms of construction and are designed to carry loads with multiple compositions at the same time and have separate liquefaction plants to avoid cross-contamination of the different cargo tanks.

Fully pressurized LPG vessels operate in coastal businesses. They have horizontal cylindrical tanks that are capable of withstanding internal pressures of 20 bar and can carry loads such as propane at ambient temperature. Due to the construction requirements of cargo containment systems, these vessels are restricted in size and are the smallest in the LPG fleet.

Since the density of the cargo carried by these vessels varies from 0.5 to 0.9 kg/l, they have low drafts and higher freeboards.

Most LPG vessels are built with double hulls as this is a safety requirement and, for those vessels that do not have this characteristic, there should be a minimum distance between the cargo tanks and the hull specified by the Classification Societies in their structural building design guides. The structural arrangement forward and aft is like that of other tankers, the cargo section is framed transversely or longitudinally, depending mainly on the size of the tanks, and the inner area of the hull has special structural considerations as it must support the cargo tanks. All LPG vessels have free spaces around the cargo tanks that are monitored for gas leaks and in many vessels these spaces are also inert. Gas cargoes in liquid state are transported under positive pressure at all times so that no air can enter the tanks and create a flammable mixture (Germanischer Lloyd, 2012).

Ballast water cannot be transported in cargo tanks, so double-hull, double-bottom, bilge tank spaces are used to control the ship's ballast condition (Eyres et al., 2012).

Regarding cargo tanks, there are two main families, integral tanks, and independent tanks. Integral tanks are generally used in LPG ships where the cargo must be transported near to atmospheric pressure conditions, for example, butane. This is because, with this type of cargo tank, it does not require special considerations to mitigate the expansion or contraction of the tank structure. Freestanding cargo tanks are self-supporting structures and are not a structural part of the ship's hull. This type of cargo tank is subdivided into types A, B and C (Senjanović et al., 2006).

Type 'A' tanks are built primarily with flat surfaces. The maximum allowed design pressure of these tanks in the vapor space for this is 0.7 bar; this means that loads must be transported in fully cooled conditions and near to atmospheric pressure (typically below 0.25 bar, gauge pressure).

The material used for Type 'A' tanks is not resistant to crack propagation. Therefore, to ensure safety, in the unlikely event of a gas leak, a secondary containment system is required. This secondary containment system is known as a secondary barrier and is a feature of all tankers with Type 'A' tanks capable of carrying cargo below -10 °C (CCNR/OCIMF, 2010).

For fully refrigerated LPG vessels (which will not carry cargo below -55 °C), the secondary barrier must be a full barrier capable of containing the entire volume of the tank at a defined heel angle and can be part of the tanker's hull, this being the most used design. In this case, the ship's hull must be made of special steel capable of withstanding low temperatures. The alternative is to build a separate secondary barrier around each cargo tank. The IGC Code stipulates that a secondary barrier must be able to contain leaks from the tank for a period of 15 days (International Maritime Organization, 1986).

On these vessels, the space between the cargo tank (sometimes referred to as the primary barrier) and the secondary barrier is known as the retention space. When flammable cargoes are transported, these spaces must be filled with inert gas to avoid creating a flammable atmosphere in the event of a primary barrier leak.

Type 'B' tanks can be constructed of flat surfaces, or they can be of the spherical type. This type of containment system is subjected to a more severe material stress analysis than the A tanks, with special emphasis on the study of material fatigue and the propagation of cracks due to the low temperatures at which the cargo is found inside the tanks. This type of cargo tank is rarely found in LPG vessels (Senjanović et al., 2006; Hiroshi et al., 2013), being more representative in LNG vessels, so it will be detailed in the section about LNG carriers.

Type 'C' tanks are typically spherical or cylindrical pressure tanks having design pressures greater than 4 bar gauge. The cylindrical containers can be mounted vertically or horizontally. This type of containment system is always used in semi-pressurized and fully pressurized gas carriers. In the case of semi-pressurized tanks, they can also be used for fully refrigerated transport, due to the steel used is appropriate for low-temperature containments. Type 'C' tanks are designed and constructed in accordance with conventional pressure vessel codes. The structural stresses of the building material are kept low. Consequently, a secondary barrier is not required for Type 'C' tanks and the holding space can be filled with inert gas or dry air and for fully pressurized tankers normal air can be allowed (Senjanović et al., 2006; CCNR/OCIMF, 2010).

In the case of fully pressurized ships, where the cargo is transported at ambient temperature, the tanks can be designed for a maximum working pressure of approximately 18 bar gauge pressure. For semi-pressurized ships, cargo tanks and associated equipment are designed for a working pressure of approximately 5 to 7 bar and a vacuum of 0.3 bar (relative to gauge pressure in both cases).

Typically, cargo tank steels for semi-pressurized ships are capable of withstanding shipping temperatures of -48 °C for LPG gases or -104 °C for ethylene.

Regarding the propulsion systems installed on the LPG carriers when this work is done, only two and four-strokes diesel engines are used as main propulsion engines. However, in years 2013 and 2014, the first request for designing engines capable of using ethane as fuel started (Wartsila, 2016).

3. Description of the LPG fleet.

This section aims to provide a brief description of the LNG maritime transport, highlighting the main characteristics of the LNG as product and its trading, following it with a description of the LNG gas carriers.

3.1. LNG maritime transport, brief overview.

The history of the LNG market goes back to 1959, when the world's first LNG vessel, the Methane Pioneer, transported the first cargo of LNG from the United States to the United Kingdom. From this successful milestone, different countries began to commit and implement commercial LNG projects on a large scale. In 1964, the UK began importing LNG from Algeria. In 1969, the United States exported LNG from Alaska to Japan for the first time. At that time, the LNG business began to take off globally with different importing countries and regions such as Japan, Europe, South Korea, China, among others (Paltsev, 2015).

The transportation of natural gas on a massive scale is carried out through gas pipelines or through specialized vessels, as is the case with the transportation of LPG. Although transportation through gas pipelines has declined in recent years, it still has 2/3 of the natural gas transportation market (Paltsev, 2015).. This is because importing countries are increasingly distant from production fields, making the transport of natural gas in its liquid state through ships more efficient, from an economic point of view, as the transport distance increases.

Natural gas is a fossil energy source that formed deep in the Earth's surface. Natural gas contains many different compounds. The largest component of natural gas is methane, a compound with one carbon atom and four hydrogen atoms (CH_4). Natural gas also contains smaller amounts of natural gas liquids (like propane and butane) and non-hydrocarbon gases, like carbon dioxide and water vapor. Natural gas is used mainly as fuel.

Liquefied natural gas (LNG) is a clear, colorless, non-toxic liquid that forms when natural gas is cooled down to -162ºC. The cooling process reduces the volume of the gas 600 times, making it easier and safer to store and transport. In its liquid state, LNG is not flammable.

The LNG supply chain can be summarized in the place of extraction, where natural gas is obtained, which is sent through a network of pipes to a liquefaction plant (usually close to the place of extraction), where it is cooled to its condensation, becoming LNG. This liquified natural gas is exported by LNG vessels to the importing countries. When the LNG reaches its destination, it is converted back to gas in regasification plants. It is then transported to homes, businesses, and industries where it is burned to generate heat or electricity.

The biggest demand of LNG in 2016 is found in Asia, where 73% of the total LNG volume were demanded by Asian countries (GIIGNL, 2017). The biggest exporters of LNG are Qatar and the Pacific Basin countries, summing up the 75% of the total LNG exported in 2016 (GIIGNL, 2017). One particularity of the LNG trade is that most of the LNG contracts are under long term time charter agreement (more than 15 years duration), being the 72% of the cases in 2016, while the short term or spot market for LNG in 2016 was the 28% of the commercial agreements in place for within the LNG fleet (GIIGNL, 2017).

3.2. Description of the LNG fleet.

Within this class of LNG carriers, there are two types of ships whose operation is totally different. On the one hand, conventional LNG tankers, which transport the LNG from a liquefaction plant to a regasification plant. And, on the other hand, ships called FSRU (Floating Storage Regasification Units), which, although they are designed to sail, they perform a different function at an operational level, and this is that the FSRU perform the functions of a regasification plant, receiving the LNG from other conventional LNG vessels, heating up the LNG received and converting it into natural gas, and then sending it ashore through a pipeline distribution network.

LNG ships are highly technologically advanced ships, and they are designed considering safety as an essential factor and the use of special materials and designs to safely handle LNG transported at very low temperatures (-162 °C). They are robustly designed and built, and most risks are minimized by strictly adhering to the requirements of the International Maritime Organization (IMO) and other organizations (classification societies) during the design process.

The strict structural control (stress and fatigue of the construction material) during the design of these ships is critical. Terminal's draft and depth restrictions lead to increased length and beam of large LNG vessels. Consequently, the stress levels in the ship's structure are higher (Zalar, et al., 2006).

LNG vessels can be divided according to their cargo tanks into independent (self-sustained) or membrane tanks, the membrane type being the most used, being installed in 73% of the fleet while independent ones are in 27% (IGU, 2017).

Cargo tanks in LNG carriers are exposed to material stresses because the cargo is transported in cryogenic conditions and, due to repeated loading and unloading with the consequent change in temperature when the ships arrive to a regassification terminal or to a liquefaction terminal. In addition, cargo tanks continuously operate under dynamic pressure loads due to movements of the fluids inside, known as sloshing, caused by hydraulic pressure and waves produced in the fluid inside the tanks. To prevent damage to the membranes caused by the combination of sloshing movements and increased internal pressure, the membranes are corrugated, and corrugations are formed through a stamping process.

The membrane tanks on LNG vessels are spherical (also known as the Moss type) or prismatic. Ships with the Moss type have several spheres (from 3 to 5) in the ship's hull, and because the hull shape is almost rectangular, leaves a large amount of unused space for cargo. For efficient utilization of the internal volume of the ship's hull, membrane-type LNG vessels with prismatic tanks are the most attractive option today (Zhang, 2015). However, unlike the spherical tank geometry, the rectangular tank does not have the same tensile strength. The sloshing problem is an essential factor and becomes an important concern for the design of membrane type tanks, one of the most dangerous situations is when sloshing occurs simultaneously in all tanks, which endangers the stability for ships, being one of the most dangerous factors when the movement of the liquid enters the resonance phase (Zhang, 2015).

Traditionally, the propulsion system in the LNG fleet has been dominated by steam plants, since the 1960s. However, the change in commercial patterns from traditional long-term contracts to a short-term contract or in the spot market, would require a greater level of flexibility in the shipping routes and, consequently, it would require more optimized designs, to increase the energy efficiency to reduce the fuel consumption, being this one of the biggest contributors to operational costs.

Although steam plants offered some advantages, such as low maintenance costs and a simpler design (especially in the management the Boil-Off Gas from the tanks), they also have other disadvantages, especially the low thermal efficiency and the higher freight transport costs resulting from higher fuel consumption, being necessary the use of alternative propulsion systems. This is also supported by the development of more efficient cargo tanks, which provide lower BOG flows than the types of cargo tanks previously installed on LNG ships with steam plants, naturally generating insufficient BOG to develop the energy required for propulsion, making it necessary to supplement it with forced BOG or liquid fuels, this fact led to the appearance of a new alternative for the propulsion of the ship, such as the appearance of diesel propulsion – electrical (Ekanem et al., 2015; Fernández et al., 2017). This need for more thermally efficient propulsion systems on LNG vessels led to the order in 2001 of the first LNG vessel with a diesel-electric propulsion system, becoming the replacement for the traditional propulsion of steam plants.

The diesel-electric propulsion system also has other advantages compared to traditional steam plants, such as reducing the space required for the power plant, gaining space for cargo transport; It is also easier and faster to stop and start the propulsion plant, and in addition, this diesel-electric propulsion system increases the degrees of redundancy with four (five or up to six) main engines and two propellers in most of the LNG vessels with diesel-electric propulsion system.

Dual four-stroke engines are very flexible in terms of fuel possibilities, they can use residual fuel, distillate fuel, and BOG. There is an extensive literature on the operation and performance of dual four-stroke engines and this diesel-electric propulsion system, as can be seen in the research works by Mustafi, et al. (2013), Bora et al., (2014), Lounici et al., (2014), Yang et al., (2015), Cameretti et al., (2016) and Mousavi et al., (2016) among others. There is another variety of diesel-electric propulsion on LNG ships, and this is by means of azimuth propellers. Specifically, there is a series of LNG vessels designated for a specific project known as the "Yamal" project, whose propulsion system is through three azimuth propellers, directed by electric motors, which are powered by 6 dual 4-stroke engines (Gierusz, 2015).

In between this implementation of the diesel-electric system as an alternative to steam plants, another different proliferation system for LNG ships appeared. This propulsion system consists of two-stroke diesel engines, with a liquefaction plant installed on board to handle the BOG, converting it back to LNG, avoiding the loss of cargo during the navigation (Chang et al., 2008; Ekanem et al., 2015).

The latest developments in propulsion systems on LNG ships are given by the appearance of dual two-stroke engines, with high- and low-pressure gas injection. These ships, in addition to the propulsion system by means of these engines, have installed 4 auxiliary four-stroke engines also with gas injection. In addition, the ships are equipped with subcooling plants or liquefaction plants for (in addition to gas combustion units) to manage the evaporated LNG from cargo tanks (Fernández et al., 2017). This alternative for propulsion systems seems that it may become the dominant alternative in the near future.

4. Concluding remarks

Gas carriers are a unique segment within the maritime transport, very complex and with different subgroups within the same fleet. For technical analysis focused on assessing the fuel consumption or the atmospheric emissions, LNG and LPG carriers should be analyzed separately due to the differences seen between them, especially in terms of dimensions, power installed for propulsion (as shown in Table 2 and Table 3) and propulsion systems employed.

This fact may influence on the outcome of global studies, such as the 3rd IMO GHG Study from 2014, where LNG and LPG carriers are studied together, giving average results which may be biased because the notorious differences between LNG and LPG carriers. This may have a big impact for example, in emissions studies, when is applied the methodology bottom up (International Maritime Organization, 2014), for averages values taken for service speed, auxiliary power and propulsion power.

Table 2: Average values of main engines power, auxiliary engine powers and Service speed.

Gas Carriers	Average Main Engine Power (kW)	Average Auxiliar Energy installed (kW)	Average of Service Speed (kn)
LNG	30,495	18,838	19.0
LPG	5,643	1,844	14.1

Source: Authors.

Table 3: Average values of deadweight, gross tonnage, length, and cargo capacity.

Gas carrier	Deadweight (tons)	Gross tonnage (tons)	Length (m)	Cargo capacity (m^3)
LNG	83,057	105,279	284	150,260
LPG	16,638	14,529	130	22,117

Source: Authors.

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