Change of exploitation parameters of a vessel after the switch to the usage of LNG as the main fuel

L V Ivanov, A Y Baranov, V A Tsvetkov, A V Vasilenok and A M Andreev
ITMO University, 9, Lomonosova st., Saint Petersburg, 191002, Russia

E-mail: lvivanov@itmo.ru

Abstract. The study presents the analysis of the changes in the fuel autonomy and the effective range performed by the vessels which underwent modernization in order to use LNG as the main fuel. In this article various variants of modernization were considered. It is suggested that the project core geometry of the self-propelled tankers and tugboats should not be altered. The change in the parameters of the fuel autonomy after placing the cryogenic fuel tanks of different constructions was estimated. The various operating modes of cargo tanks of different constructions were observed. Besides that, there are two possible operating modes, particularly the drainage mode and the drain-free mode. It is proved that the tugboats’ fuel autonomy is reduced 2 times. The usage of the boil-off-gas in the self-propelled LNG carrier’s engine compensates for the decrease in the fuel autonomy. Thus, it depends on the distance between the final consumer of LNG and the loading satellite terminal of the cryogenic product whether to opt for using self-propelled or tug and barge transport.

1. Introduction
Liquefied natural gas (LNG) is an environmentally friendly, energy efficient and fairly cheap type of fuel. In the regions with developing production of LNG, liquefied gas may become a viable alternative to the traditional fuels such as diesel fuel (DF) and coal. As a general rule, the water transport is used to deliver LNG in industrial amounts. It is reasonable to modernize vessels that deliver LNG so that they can consume LNG as the main type of fuel. It may reduce the shipping cost by means of the reduction of the shipping leg.

Construction of new gas carrying vessels requires big sums of money. The construction project of a gas carrier vessel includes engineering of the vessel hull. The usage of the existing engineering projects adapted to the navigation conditions of a particular water basin can significantly reduce the cost of the development of the gas carrier project. The modernization of existing LNG carriers makes it possible to build the LNG carriers’ fleet in the shortest possible time.

Traditionally, in the arrangement of the delivery of oil products a large volume of shipping is performed by means of tug and barge transportation [1], therefore, they are considered in the article on the equal basis with self-propelled vessels.

The analysis is carried out basing on the example of the Russian Federation where the manufacturing facilities are located in the northern parts of Siberia. The specific location of the LNG sources of terminals Sabetta and Utrenniy in the gulf of Ob requires the usage of river-sea vessels for shipping.

2. Technical solutions for modernization
The most widespread types of vessels were selected to undergo the modernization. Those ships will be
employed in LNG shipping. They are tugboats with the power of 600-900 ehp and the self-propelled low-tonnage oil tankers with the total displacement tonnage of 3,680 and 3,216 tons. While modernizing the vessels, it is proposed to modernize the propulsion system of the vessel to use LNG as fuel. It is suggested that the propulsion unit should be changed in order to function as the gas-diesel in the dual-fuel mode. It is also advised that the cryogenic fuel tank should be installed as the replacement for the traditional marine diesel oil (MDO) or Heavy Fuel Oil (HFO) tanks. The modernization is expected to be carried out without changing the geometry of the hull. This kind of modernization is considered in SWOT analysis in the Yangtze shipping case study [2]. The authors characterize the increase in the volume of a fuel tank as a weakness. But since the Chinese LNG bunkering infrastructure is better developed than the infrastructure of Siberian Russian rivers, the fuel autonomy loss is not big of a problem. During the exploitation of the dual-fuel power plant, it is necessary to install the tank for the pilot diesel fuel. The placement of the diesel tanks is supposed to be on the upper deck.

When the self-propelled tankers undergo modernization, the cargo tank is required to be changed in order to be able to store LNG. The basic product oil tanks can be replaced with the independent LNG tanks. Various LNG tank systems are known. They differ in volume utilization, weight, type of thermal insulation and its thickness. Moreover, LNG tanks can be exploited in various modes. The boil-off gas is removed from the tanker in the drainage mode. In the drain-free mode LNG vapour is stored inside the tank. That causes the increase in the internal pressure which is also known as the pressure build-up.

Membrane tanks which are used for sea shipping are not suitable for this modernization project, since this kind of cargo containment systems is the integral and inseparable part of the vessel’s hull.

The most important criterion for choosing the cargo containment system for the modernization is the compactness. The highest parameters of useful utilization of space are characteristic of prismatic tanks type A (LNT A-BOX) and type B (IHI SPB) [3-4]. Those tanks are not designed to store LNG at high internal pressure. Cylindrical type C tanks can be used at high pressure, but they poorly integrate into the existing geometry and, therefore, they have the lowest level of compactness of placing in the vessel’s hull.

![Figure 1. Volume utilization coefficient for fuel tank types A, B and C.](image)

Type B tanks have lower specific weight than that of type A tanks, since there is no secondary barrier in the construction of type B tanks that allows the latter to be fitted into the original deadweight of the oil tanker. For tug and barge transportation it is rational to use type C tanks which are installed on barge-platforms [1,5]. By varying the initial filling level of the tank such tanks can be used in drain-free mode without exceeding the maximum allowable internal pressure and loss of LNG [6]. It is possible to calculate the volume of cryogenic LNG fuel tanks after modernization.
Table 1. The volume of the fuel tanks after the modernization

| Vessel type         | Fuel tanks volume before the modernization, m³ | Tanks volume with type C fuel tanks installed, m³ | Tanks volume with type A/B fuel tanks installed, m³ |
|---------------------|-----------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| Tanker P-77         | 99                                            | 41.6                                             | 58.7                                             |
| Tanker 621          | 103.6                                         | 43.5                                             | 61.5                                             |
| Tugboat 1741A       | 65.3                                          | 38.8                                             | 27.4                                             |
| Tugboat 758B        | 80.8                                          | 48                                               | 33.9                                             |
| Tugboat 07521       | 158                                           | 93.7                                             | 66.3                                             |

In the case of modernizing the self-propelled tankers, the volume of the transported LNG after the modernization can be determined by the relation of the volume of displacement and the total bulk volume of the tanks. For each type of cargo containment systems, it is necessary to take into consideration the parameters of the vessel on which the tanks are installed. For A type tanks this relation is:

\[
a = \frac{LBD}{W} = \frac{195.3 \times 30.9}{45000} = 1.17
\]

where \(L\) - length overall, m; \(B\) - beam, m; \(D\) is draught, m; \(W\) - total volume of cargo containment system, m³.

For B type tanks the relation can be calculated in the similar way. In this calculation the overall dimensions of the tanker “Polar Spirit” were used:

\[
a = \frac{238.94 \times 49.88}{88100} = 0.95.
\]

The total volume of cryogenic cargo tanks after the modernization of Lenaneft P-77 is going to be:

for type A:

\[
W_A = \frac{108.6 \times 14.8 \times 2.5}{1.17} \approx 3400 \text{ m}^3;
\]

for type B:

\[
W_B = \frac{108.6 \times 14.8 \times 2.5}{0.95} \approx 4200 \text{ m}^3.
\]

The quantity of appeared boil-off gas depends on the boil-off rate. BOR shows the amount of evaporating LNG per day. For tanks IHI SPB and LNT A-BOX the BOR index is 0.15 %/day. Therefore, the volume of BOG is equal to:

for type A:

\[
BOG_A = W_A \cdot BOR_A = 3400 \cdot 0.0015 = 5.14 \text{ m}^3/\text{day};
\]

for type B:

\[
BOG_B = W_A \cdot BOR_A = 4200 \cdot 0.0015 = 6.31 \text{ m}^3/\text{day}.
\]

Type C tanks installed on barges can be efficiently used in the drain-free mode.

3. The analysis of changes in the degree of fuel autonomy and effective range of LNG shipping

Ship fuel autonomy according to capacity of cryogenic fuel tank after the modernization can be calculated by the formula:

\[
A = \frac{V}{Q \cdot BOG}
\]

where \(Q\) is consumption of fuel LNG, m³/day.

The consumption of fuel LNG for Lenaneft P-77 will be:

\[
Q = \frac{M \cdot n \cdot q \cdot 24}{10^3 \cdot \rho_{\text{LNG}}} = \frac{660 \cdot 2 \cdot 156.24}{10^3 \cdot 430} = 11.49 \text{ m}^3/\text{day},
\]
where $M$ - main engine power, kW; $n$ - quantity of main engines; $q$ - fuel consumption, g/kWh*h; $\rho_{\text{LNG}}$ - density of LNG, kg/m$^3$.

Evaporated boil-off gas is reasonable to supply to the vessel’s engine. However, this mode of exploitation can be applied only to self-propelled vessels, since there is no technical possibility to transport boil-off gas from barge to tugboat [7]. In this case of LNG shipping, the endurance of tugboats according to the fuel capacity is:

**Table 2. Fuel autonomy of tugboats after the modernization**

| The project of the vessel | Original autonomy, day | Autonomy after the modernization, day |
|---------------------------|------------------------|-------------------------------------|
|                           |                        | Tank types A/B | Tank type C |
| Tugboat 1741A             | 9                      | 6           | 4.2        |
| Tugboat 758B              | 15                     | 6.9         | 4.9        |
| Tugboat 07521             | 20                     | 10.4        | 7.4        |

After the transition to the gas engine fuel, the level of fuel autonomy of tugboats is significantly decreased. This is caused by the lower specific density of LNG. Besides that, part of the usable space of the hull can be taken by the thermal insulation of the fuel tanks.

**Table 3. Fuel autonomy of self-propelled vessels after the modernization**

| The project of the vessel | Original autonomy, day | Autonomy after the modernization, day |
|---------------------------|------------------------|-------------------------------------|
|                           |                        | Tank type A | Tank type B |
| Tanker P-77               | 15                     | 9.2        | 11.3        |
| Tanker 621                | 15                     | 11.9       | 16.3        |

In the design of cryogenic tank it is possible to vary BOR level. This leads to the change in the amounts of boil-off gas generation. Volume of BOG supplied to the main dual-fuel engine as fuel helps to make an increase in the fuel autonomy of the gas carrying vessel.

Effective range of LNG shipping is estimated by means of considering conditions under which the full fuel autonomy potential is used. The total shipping comprises the condition of the distance that the loaded vessel has covered in order to reach the consumers. The distance is equal to the distance covered by the loaded vessel to the initial point. This distance is the effective delivery range:

$$ R_L = R_{UL} = R, $$

where $R_L$ - distance covered by a loaded vessel, km; $R_{UL}$ - distance covered by a vessel without load, km; $R$ - effective delivery range.

The effective delivery range can be found according to the following equation:

$$ R = A \cdot x \cdot S_L \cdot 24 = A \cdot (1 - x) \cdot 24 \cdot S_{UL} $$

where $x$ - percentage of swimming in the loaded state; $S_L$ - speed of a loaded vessel, km/h; $S_{UL}$ - speed of an unloaded vessel, km/h.

In this case the effective delivery range can be calculated for the modernization variants under study.

The speed of a tug is considered in the fully loaded condition with a barge’s total capacity of 3000-5000 t. The unloaded vessel’s speed is decreased, since the empty barges should be towed to the point of departure. The effective delivery range of self-propelled tankers is significantly bigger than that of the tugboats. All that allows the self-propelled tankers to deliver LNG to the most remote consumers.
### Table 4. The effective delivery ranges

| The project of the vessel | The speed of a loaded vessel, km/h | The speed of a vessel without load, km/h | The effective delivery range, km |
|--------------------------|-----------------------------------|----------------------------------------|----------------------------------|
| Tanker P-77              | 19                                | 35                                     | 3350                             |
| Tanker 621               | 18.5                              | 35                                     | 4740                             |
| Tugboat 1741A            | 12                                | 16.5                                   | 1002                             |
| Tugboat 758B             | 10                                | 16.5                                   | 1028                             |
| Tugboat 07521            | 11                                | 16.5                                   | 1655                             |

### 4. Conclusion

After the modernization that allows vessels to use LNG as the main fuel and does not require changes in the vessel’s geometry, the fuel autonomy has noticeably decreased. This decrease in the autonomy can be compensated by the usage of boil-off gas from the cargo containment system in the main dual-fuel engine. The system of this kind can be used only in self-propelled LNG carriers. By changing the parameters of the thermal insulation, the fuel autonomy can be varied. The effective LNG delivery range performed by self-propelled LNG carriers is 2.5-3 times wider than the one performed by tug and barge LNG transportation. Thus, it is efficient to deliver LNG to the remote consumers by means of self-propelled vessels. The parameters of thermal insulation should be chosen according to the distance to the most remote consumers.

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