BOIL-OFF RATE IN LNG STORAGE TANKS AS A FUNCTION OF INITIAL LIQUID TEMPERATURE

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KEYWORDS

LNG, Boil-off-gas, BOG, Holding time, BoilFAST

ABSTRACT

This work presents simulations performed using the online tool BoilFAST, where the boil-off rate in a Liquefied Natural Gas (LNG) tank has been investigated for various starting temperatures, and for different storage tank dimensions. The simulations have been performed to investigate whether BoilFAST can be used for analyzing LNG boil-off and for assessing the fuel tank size and geometry for a maritime vessel. Sloshing in maritime LNG storage tanks is known to cause pressure drops which may compromise the supply pressure to the gas engine. A novel and cost saving means to combat this risk could be to heat the LNG during bunkering to a temperature equal to the equilibrium temperature at which the vapor pressure equals the minimum required pressure of the engine. However, if the LNG is overheated, this may compromise the requirement of 15 days of holding time of the LNG in the tank without exceeding the maximum allowable pressure. Simulations show that when the LNG is heated prior to filling into the storage tank, the fulfillment of the holding time requirement depends on the tank geometry, as well as the filling degree and temperature gradient through the tank walls.

INTRODUCTION

Liquefied Natural Gas (LNG) was introduced as a maritime fuel in 2000, when the ferry Glutra was the first ship to use this fuel (Einang and Haavik 2000). Today, LNG is a well-proven maritime fuel, which compared to other traditional alternatives is a low-carbon fuel. Combustion of LNG gives less emission of CO_2, NO_x, and SO_x than the traditional fuels (DNV GL 2019). Therefore, LNG is often described as a transitional fuel on the path to zero-emission fuels.

Norway has a goal of reducing CO_2 emissions by 55 % by 2030, as announced at the United Nations Climate Change Conference - COP27 (Norwegian Government 2022). To contribute to meeting this goal the maritime sector must also convert to more environmentally friendly fuels, e.g low carbon or zero emission fuels. The most mature fuel alternative to marine diesel oil or marine gas oil today is LNG. However, one of the disadvantages of LNG is the lower volumetric energy density as compared to traditional fuels (Solakivi et al. 2022). Another challenge is that LNG is a cryogenic liquid, and the storage, processing, and fuel supply system is therefore more complex and requires more space than the traditional fuel systems. This may especially be a challenge for small to medium sized vessels, where there is limited available space and where keeping investment, operational, and maintenance costs down is critical.

Another challenge with LNG fuel systems is pressure drop in the LNG storage tank caused by sloshing (Grotle 2018, Nerheim et al. 2021). The reason for such pressure drops is the phase equilibria of the LNG, in combination with the tank design and movements of the tank.

Today, the most common means to reduce the risk of pressure drop is to install an LNG pump, which increases the complexity and costs of the system. Other methods for mitigating pressure drop in LNG tanks have also been proposed, but have not been documented in practice and/or theoretically. In this paper, a theoretical analysis of heating the LNG as an alternative mitigating measure is presented. This method would require less processing equipment onboard the ship and therefore save costs.

The background for this analysis is the operational reliability of an LNG fuel system in small to medium-sized vessels. For these vessels, it is critical to keep the system costs and dimensions down. Hence, reducing the number of components and the complexity of the fuel system is crucial. This may be achieved if sloshing can be avoided by heating the LNG during bunkering, thereby making an LNG pump in the fuel processing system redundant.

In this paper, the consequences of heating the LNG during bunkering is analyzed using the open simulation tool BoilFAST. As a starting point, the simulations are performed on a static tank. The holding time and boil-off rates are compared for three different tank sizes and various loading temperatures of LNG and different ambient temperatures.

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LNG FUEL SYSTEMS

LNG is natural gas in the liquid state. Natural gas is produced from reservoir fluids, and the exact composition may therefore vary around the world. A typical natural gas contains more than approximately 80 vol% of methane, some ethane and propane, and minor quantities of heavier hydrocarbons and other gases (GIIGNL 2019). The phase diagram of the natural gas composition used in this study is shown in Figure 1.

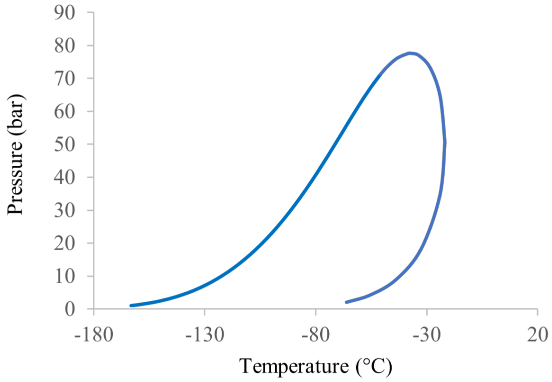

Figure 1: The phase envelope of a typical natural gas.

The density of LNG decreases with increasing temperature. Hence, as the temperature of LNG in a closed storage tank increases over time due to heat ingress from the surroundings, the volume of the LNG in the tank will increase. Therefore, the International Maritime Organization (IMO) has defined a loading limit (LL) for maritime LNG tanks which specifies the maximum allowable filling volume of a given LNG tank (IMO - International Maritime Organization 2015). This limit depends on the temperature of the LNG at the time of loading. The allowable volume of LNG increases with increasing temperature. The objective of this regulation is to prevent LNG to expand and reach the top of the tank and the relief valves when the temperature increases.

Another requirement set by IMO is the holding time, as described in the IGF code (IMO-International Maritime Organization 2021). An LNG storage tank must be designed to keep heat ingress low, so that if the tank is closed the pressure will not increase beyond the setting of the relief valves (10 bar) within 15 days, with no consumption except for supporting the hotel load on board.

In maritime LNG fuel systems, the liquefied gas is evaporated, heated, and then supplied to the engine at a specified temperature and pressure. The supply pressure is maintained by the pressure of the gas cap in the tank. A gas engine requires a supply pressure in the range 3.5 − 5.3 barg (Rolls-Royce 2020). At temperatures around −160 °C the equilibrium pressure of the LNG is around 1 bar, i.e. below the pressure required by the engine. A Pressure Build-up Unit (PBU) is therefore used, which evaporates a small amount of LNG and returns the gas to the gas cap in the tank. However, due to the temperature difference between the gas and liquid phases in the tank, the gas cap will be cooled down and condense if severe sloshing occurs. This causes the pressure to decrease rapidly and may result in supply failure to the engine. One means to avoid this problem is to install an LNG pump downstream of the LNG tank. This secures sufficient supply pressure at all times, but it also adds costs, components, complexity, and potential leakage points.

As illustrated in the phase diagram of Figure 1, the LNG equilibrium pressure increases with temperature. Another means to mitigate pressure drop due to sloshing is therefore to heat the LNG before it enters the storage tank on board. Heating of the LNG during bunkering could be performed onboard the ship or on the quayside. In the latter case, this processing would not add any weight to the ship. In both cases, the heating equipment would not add any complexity to the LNG fuel system during normal operation. Furthermore, the LNG fuel processing system could be simplified, as the LNG pump would become redundant. Hence, saving costs and space on board, and making LNG a more feasible fuel alternative for small- to medium-sized vessels.

If the LNG is heated during bunkering, the vapor pressure of the LNG will be increased and the total tank pressure will be less affected by sloshing. In this way, the tank pressure is maintained in all weather conditions. The question is to which extent this method affects the holding time of the LNG tank. This method has not yet been documented in practice. It is therefore the objective of this work to investigate the holding time for different tank sizes with LNG loading temperatures in the range from −164 °C to −140 °C through simulations.

Previous studies have investigated the boil-off as a function of various tank sizes, geometries and filling degrees (Kalikatzarakis et al. 2022, Lin et al. 2018) but detailed analyses of the effect of loading temperature of the LNG has not been found. This is therefore the main focus of the present paper. The BoilFAST simulation model was found to be a feasible tool for this work, and it was also an objective for this work to assess the applicability of this tool with respect to dimensioning and designing maritime LNG systems. Validation of the simulation model through comparison with real data was not within the current scope but is planned for further work.

METHOD

This study was performed using a typical LNG composition from the North Sea area, as given in Table 1. The simulations were performed using the free online software BoilFAST (V. Jusko et al. 2021). The pressure increase over time was investigated by varying the following parameters:

- Loading temperature (T_L) of the LNG
- Filling degree of the LNG tank
- Ambient temperature (T_A)
- LNG tank size/geometry

Table 1: Natural Gas Composition.

Component	Mol fraction
Methane	0.862085
Ethane	0.09
Propane	0.03
Butane	0.01
Pentane	0.0003
Hexane	0.000015
CO_2	0.0001
N_2	0.0075

The following conditions were assumed in the analyses:

- Horizontal, cylindrical LNG tank
- Static tank, i.e. no sloshing of the fluid in the tank
- Constant ambient temperature during the day
- No solar irradiation

In a maritime vessel, the LNG in the tank will be subject to sloshing. However, the present analysis was simplified and assumed static tanks with no sloshing. Three different tank sizes and geometries were used in the simulations, and the volumes of the LNG storage tanks were chosen based on what would be feasible dimensions for small to medium-sized maritime vessels. An overview of the tank dimensions and material specifications are given in Table 2.

The orientation of all three tanks was horizontal. Dimensions and geometry of the different tank sizes were adopted from data available online. It was not possible to obtain detailed data from manufacturers, so the thickness and the heat conductivity of the various tank shells and insulation were collected from various sources, as indicated in the overview in Table 2.

The time step in the simulations was set to 12 hours. For each time step, the LNG temperature, tank pressure, boil-off rate, and properties of the gas and liquid phases were calculated using BoilFAST.

RESULTS AND DISCUSSION

Using the BoilFAST software, the pressure increase as a function of time was investigated for static, horizontal LNG storage tanks of volume (V_T) of 23, 75, and 150 m^3, respectively. The simulations were performed starting with several different loading temperatures of the LNG, to study how the initial temperature affected the holding time of the tank. Analyses were run with loading temperatures (T_L) of −164, −156, −148, and −140 °C.

In the simulations, the only heat source was assumed to be heat ingress from the surroundings through the tank walls. Heat leak due to pipes and valves was neglected, as well as any gas consumption for supply to the hotel load on board. For the ambient air, three different constant temperatures (T_A) were assumed: 5, 15, and 25 °C. An overview of the conditions of the various simulations is given in Table 3.

With a relief valve setting of 10 bar the loading limit curve for the given LNG composition is shown in Figure 2, together with the density of the LNG as a function of LNG temperature. The loading limit curve was used to define the volume of LNG in the various tanks at the different starting conditions of the simulations.

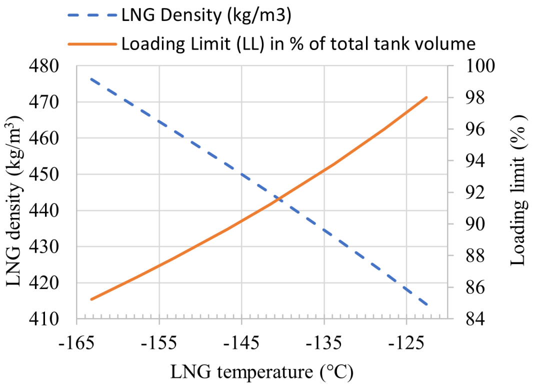

Figure 2: The Loading Limit (LL) for the given LNG composition, assuming a 10 bar relief valve setting.

The heat conduction through the tank insulation is proportional to the temperature difference between the LNG in the tank and the ambient air. Hence, at a given LNG temperature, the heat influx to the tank increases with the outside air temperature (T_A). Similarly, at constant ambient temperature, the heat ingress decreases with increasing loading temperature (T_L) of the LNG.

In the simulations, the ambient temperature was assumed to be constant with no variation during the day. The effect of the initial LNG loading temperature on the holding time, with constant ambient temperature, is shown in Figure 3 for tank sizes of 23, 75 and 150 m^3, respectively. These graphs also show the effect on the holding time of increasing the ambient air temperature from 5 to 25 °C.

As shown in Figure 3, when increasing the ambient temperature from 5 to 25 °C, the holding time is reduced by around 3 days for the tanks of 75 and 150 m^3 volume. For the smaller tank of 23 m^3, the reduction in holding time with the increased ambient temperature is only around 1 day. However, in this tank, the holding time was already half of that of the two bigger tanks. As compared to the holding time with 5 °C ambient temperature, the reduction of holding time in the case of 25 °C ambient temperature was 11 % for the 23 m^3 tank and 16−18 % for the bigger tanks.

If the LNG temperature at loading is increased from −164 °C to −140 °C, i.e. an increase of 24 °C, the effect on the holding time is more pronounced. For the 23 m^3 tank the holding time is reduced by around 5 days, by 10 days for the 75 m^3 tank, and by 11 days for the 150 m^3 tank. This can be explained as an increasing boil-off rate with increasing LNG temperature.

For comparing the effect of tank size/geometry, the holding time for the three tanks is shown in Figure 4 with −164 °C

Table 2: Overview of the tank dimensions and specifications used in the analyses.

Parameter	**Tank description**			**Unit**	**Comments and References**
Inner Volume (V_T)	23	75	150	m^3	
Inner Diameter (D_I)	1.55	2.77	3.01	m	Based on Chart-Ferox 2023
Outer Diameter (D_O)	2.18	3.40	3.65	m	Based on Chart-Ferox 2023
Tank head height	0.39	0.69	0.75	m	Inner diameter/4. Barderas et al. 2015
Inner cylinder length (L_{IC})	11.71	11.54	20.02	-	From BoilFAST
D_I/L_{IC}	0.13	0.25	0.15	m	From BoilFAST
Inner tank thickness	10			mm	Assumed thickness
Outer tank thickness	8			mm	Assumed thickness
Perlite layer thickness	300			mm	Assumed thickness
Perlite heat cond.	0.038			W/mK	Wlodek 2019
Outer tank heat cond.	42.6			W/mK	Carbon steel Wlodek 2019
Inner tank heat cond.	27			W/mK	405 stainless steel, 0-100°C AZO-Materials 2023
Outer heat convection	10			W/m^2K	Wlodek 2019
Inner heat convection	35			W/m^2K	Wlodek 2019
Heat transfer coeff.	0.12			W/m^2K	Calculated

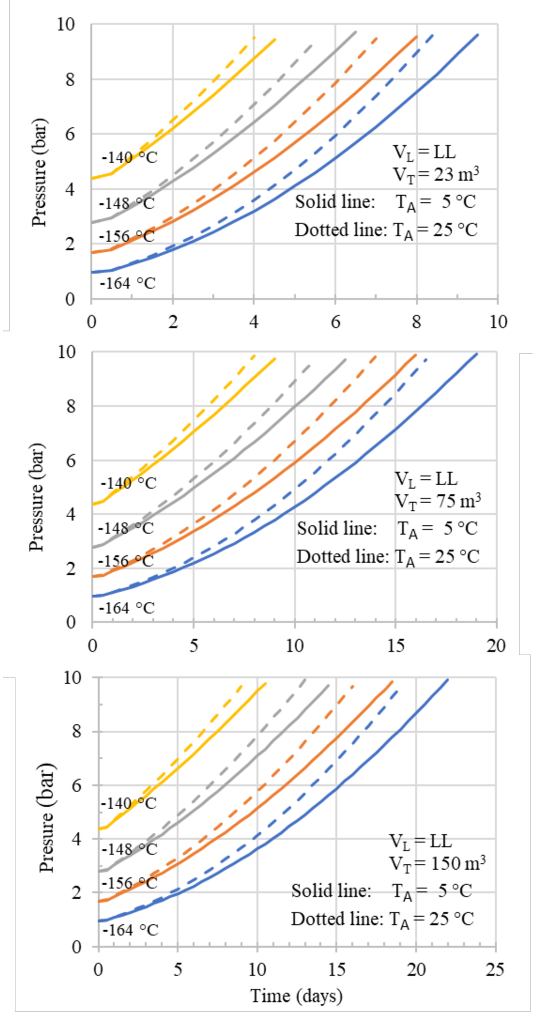

Figure 3: Upper to lower graphs show results for tank volumes (V_T) of 23, 75 and 150 m^3, respectively, and initial filling level (V_L)equal to the loading limit (LL). Loading temperatures are given to the right of the vertical axis.

Table 3: Overview of the various simulations that have been performed, where LL denotes the maximum allowable loading limit at the given temperature.

V_T	V_L	T_L	T_A
Tank Volume (m^3)	**Loading Volume (m^3)**	**Loading Temp. (°C)**	**Ambient Temp. (°C)**
23	LL	-164/ -156/ -148/ -140	5/ 15/ 25
23	50 %		
75	LL		
75	50 %		
196	LL		
196	50 %		

LNG loading temperature, 5 °C ambient temperature, and two different filling levels of the tanks. The solid lines in the figure represent results with an LNG filling level equal to the loading limit (LL) of 84.5 % at the given temperature, while the dotted lines represent 50 % filling volume of the tank. Similar trends were found for other LNG loading temperatures as well, but the loading temperature of −164 °C was chosen as a representative example.

As illustrated in Figure 4, the 23 m^3 tank has a significantly higher pressure increase and shorter holding time than the 75 and 150 m^3 tanks. Also, as can be seen from the figure, the holding time is not a linear function of the tank volume. The ratio of the inner diameter to the inner cylinder length (D_I/L_{IC}) of the various tanks is given in Table 2, and is largest for the 75 m^3 tank. Hence, the D_I/L_{IC} ratio cannot explain the holding time differences. The relative placement of the holding times of the various tanks seems to be connected to the gas cap volume and LNG surface area in the tank. The volume-to-surface-area ratios for the three tanks have similar relative distribution as the ratios of the holding times in Figure 4. However, this needs to be investigated further from a theoretical approach, but was not within the scope of the present work.

In Figure 4, the graph for the 23 m^3 tank with 50 % filling volume has a cut-off below 10 bar pressure. This is due to the time step in the simulations and the rapid pressure increase. By reducing the time step from 12 to e.g. 1 h, more data points could have been obtained, with a cut-off closer to 10 bar. However, regardless of this cut-off, it is clear that this case does not fulfill the holding time requirement, and further analyses with smaller time steps were therefore not found necessary.

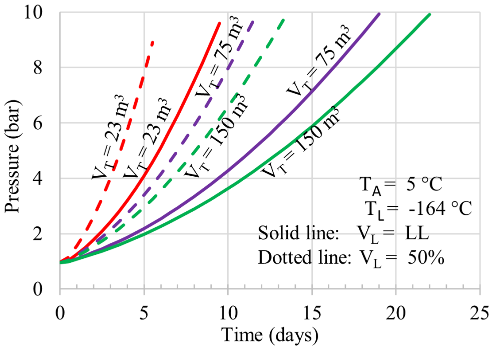

Figure 4: Results for tank volume (V_T) of 23, 75, and 150 m^3, respectively, with LNG filling corresponding to loading limit (LL) and 50 %.

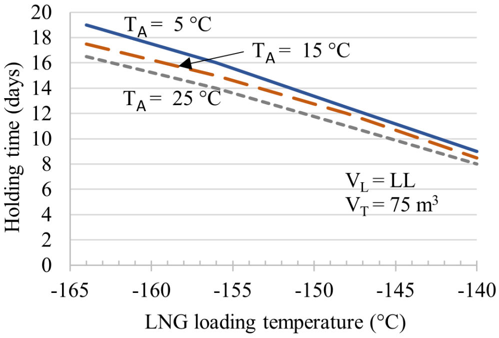

Figure 5: Holding time in the 75 m^3 tank as a function of loading temperature (T_L) of the LNG.

The results show that both the loading volume (V_L) and the LNG temperature at loading (T_L) have a great impact on the holding time of the given LNG tank. Maximum boil-off rates were found in the cases with 50 % filling of the tank and with a loading temperature of −140 °C. The maximum boil-off rates were 0.03, 0.04, and 0.08 mol/s for the tanks of volume 23, 75, and 150 m^3, respectively. These results comply with results by others (Kalikatzarakis et al. 2022). This would correspond to power consumption in the range 28 - 75 kW, assuming a molar mass of 17 g/mol and a lower heating value of 50 MJ/kg (Nerheim et al. 2021). Hence, with LNG volumes corresponding to the loading limit and 50 % filling of the tank, the entire boil-off gas volume can be removed from the tank and used for supplying the hotel load. This would prevent any pressure build-up in the tank. However, the boil-off rate probably increases with decreasing tank filling degree, since the LNG then (in normal operation) is at a higher temperature, and there is more gas cap volume to fill.

At high filling degrees, a large volume of LNG must be heated to produce boil-off gas. Also, the simulations show that the smaller tank sizes have shorter holding time than the bigger tanks with a similar ratio of inner diameter to inner cylinder length (D_I/L_{IC}). Due to the geometry of the smallest tanks, with smaller gas cap volume at high LNG filling degrees, the pressure increase is more rapid even at low boil-off rates.

In the simulations a time step of 12 hours was used. Initially, this was thought to be sufficient for a slow process as boil-off from a static tank. However, the large time step results in some "gaps" in the data, as indicated by curves with maximum pressure plotted significantly lower than 10 bar. In future analyses, the time step should therefore be smaller, but this also gives longer run time for the simulations.

For the tank of volume 75 m^3 the holding time as a function of LNG loading temperature is plotted in Figure 5. Three different ambient temperatures were used. The ambient temperature in the three simulation series is seen to have the most impact on the holding time at low LNG temperatures. Similar results were also obtained for the tanks of 23 m^3 and 150 m^3 volumes.

In real LNG fuel systems, the tank is not static but is subject to the ship's movements. Hence, there will be mixing of the two phases in the tank, and the heat conduction into the tank will be more efficient, which probably will increase the boil-off rate (Wu and Ju 2021). In this study, the 23 m^3 tank never obtained a holding time in accordance with the requirements of 15 days. However, these analyses did not include the allowed consumption for the hotel load on board. If this had been included in the study, the holding time would increase. However, this was not within the current scope.

As shown in Figure 3 the holding time requirement can be fulfilled for given tank geometries, even if the LNG is heated before loading into the storage tank. In the 150 m^3 tank, when filling up to the loading limit, the holding time requirement can be fulfilled up to a loading temperature of approximately −148 °C. This would give an equilibrium pressure in the tank of around 3 bar, which is in the lower range of the gas engine supply pressure requirement. If the engine can run at this gas pressure, an LNG loading temperature of −148 °C would therefore improve the robustness of the fuel system by preventing the pressure from dropping below 3 bar during sloshing conditions in the tank at sea.

The holding time results do not take into account any consumption for the hotel load on board the vessel. Hence, the present holding time results are "worst-case" scenarios. If this consumption was included, the resulting holding time would be longer. For investigating the effect of temperature and filling volume on the holding time in general the hotel load can be neglected. However, when dimensioning and designing an LNG tank for a specific maritime vessel, the hotel load should be included.

The simulations show reasonable results, and they demonstrate how BoilFAST can be used as a tool to give support to dimensioning and design of the optimal geometry of an LNG tank for a given vessel. However, these results are yet to be validated through real testing e.g. using operational data from stationary LNG storages.

CONCLUSIONS

Simulations using BoilFAST have been used to illustrate the process of boil-off in LNG storage tanks. This study has demonstrated how BoilFAST can be used as a tool in designing LNG fuel systems for small to medium-sized vessels. Using this tool, various geometries can be evaluated, as well as loading temperatures and filling degrees, so that a tank can be dimensioned and designed in accordance with the IMO regulations on holding time. The simulations can also provide support for operational procedures, e.g. loading temperatures, and it can be used in the evaluation of alternative designs of the LNG fuel processing system on board. However, assessment of the validity of the model using real data from static LNG storage tanks is yet to be documented.

BoilFAST simulations of the holding time in LNG storage tanks of 23, 75, and 150 m^3 volumes, showed that the boil-off rate is affected by the geometry of the tank, and not only the volume of the tank. Furthermore, the boil-off rate was found to depend on the filling degree in the tank, the ambient temperature, and the loading temperature of the LNG. The analyses show that, for given tank geometries, heating of the LNG prior to filling into the storage tank does not compromise the requirement of the holding time. Hence, heating the LNG can be used as a means to prevent pressure drops due to sloshing in maritime LNG fuel systems. This method would save costs and space on board the vessel, as compared to today's pumped systems, and would make LNG a more feasible alternative also for small to medium-sized vessels. However, heating of the LNG prior to filling into the storage tank onboard the vessel must be tested in practice before a final conclusion can be drawn. The present analyses were performed assuming a static tank. In a ship, the tank will not be static, and the resulting fluid mixing in the tank will affect the boil-off rate. Further analyses need to take this effect into account.

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NOMENCLATURE

Acronym	**Description**
BOG	Boil-Off-Gas
IMO	International Maritime Organization
LL	Loading Limit (%)
LNG	Liquefied Natural Gas
NG	Natural Gas
PBU	Pressure Build-up Unit
D_I	Inner Diameter (m)
D_O	Outer Diameter (m)
L_{IC}	Inner Cylinder Length (m)
T_A	Ambient temperature (°C)
T_L	Loading temperature of the LNG (°C)
V_L	Loading volume of LNG (m^3)
V_T	Volume of storage tank (m^3)

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