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**STUDY OF THE EFFECT OF GEOMETRICAL PARAMETERS  
OF THE LNG STORAGE TANKS  
ON THE PROCESS OF EVAPORATION  
OF LIQUEFIED NATURAL GAS**

**1. INTRODUCTION**

LNG has a very low temperature (-162 °C) therefore is stored in special thermally insulated tanks to protect its against heating and consequently evaporation. The tanks are always made of the best construction and insulating materials. Even so, some part of the heat escapes through the walls, top and bottom of the tank. The top of the LNG tank is exposed to the constant operation of the sun during the day, as a result of which the fluid is heated up to quite high temperatures. The surface of the tank's walls is very extensive, therefore most of the heat can be lost through them.

Even smallest amount of heat inflowing to the stored LNG causes an increase of its inner energy, which in turn leads to the evaporation of some amount of LNG. Evaporation of LNG inside the tank should be avoided. A change of the state of even a small quantity of fluid results in a change of composition and density of LNG. Any change of LNG density is the least desired process, potentially leading to stratification of the fluid in the tank.

Knowing about the impact of the geometry of the storing tank on evaporation of natural gas inside of it, one can very precisely design the process of LNG storing, and minimize gas losses caused by heat transfer.

**2. CALCULATION OF AMOUNT OF HEAT TRANSFER TO THE TANK**

The method of calculating the amount of heat transfer to the tank is based on two phenomena: thermal conductivity and heat transfer. Thermal conductivity is defined as a process

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of heat exchange between bodies of different temperature which are in direct contact. This can be described with the following equation [1]:

$$Q = -k \cdot A \frac{dT}{dX}, \quad (1)$$

where

- Q – heat ingress, W;
- A – surface of heat exchange, m<sup>2</sup>;
- k – thermal conductivity, W/mK.

Heat transfer is understood as a process of heat flow through thermal boundaries (in the case of LNG storages these are insulation layers). This process is defined with the following equation [1]:

$$Q = \lambda \cdot A \cdot (T_L - T_s), \quad (2)$$

where

- Q – heat transfer rate, W;
- A – surface of heat exchange, m<sup>2</sup>;
- λ – coefficient of heat transfer, W/m<sup>2</sup>·K;
- T<sub>L</sub> – LNG temperature, K;
- T<sub>s</sub> – ambient temperature, K.

In the case of LNG storage tanks heat is transferred in two directions, i.e. larger part of thermal energy goes inside the tank through the cylindrical walls, and smaller amount through the top. The amount of heat transferred through cylindrical walls of the storage tank can be calculated from the formula [1]

$$Q_w = -2 \cdot \pi \cdot H \cdot \Delta T \left( \frac{1}{r_i \cdot \lambda} + \frac{1}{k_1} \cdot \ln \frac{r_1}{r_i} + \frac{1}{k_2} \cdot \ln \frac{r_2}{r_1} + \dots + \frac{1}{k_n} \cdot \ln \frac{r_n}{r_{n-1}} + \frac{1}{r_o \cdot \lambda_o} \right), \quad (3)$$

where: H – height of the tank, m.

The amount of heat penetrating the top of the tank can be calculated from the dependence

$$Q_r = -2 \cdot \pi \cdot H \cdot \Delta T \left( \frac{1}{r_i^2 \cdot \lambda_i} + \frac{1}{k_1} \cdot \left( \frac{1}{r_i} - \frac{1}{r_1} \right) + \dots + \frac{1}{k_n} \cdot \left( \frac{1}{r_{n-1}} - \frac{1}{r_n} \right) \cdot \frac{1}{r_o^2 \cdot \lambda_o} \right), \quad (4)$$

The total heat delivered to the tank is a sum of heat transferred through the wall and through the top of the storage.

$$Q = Q_w + Q_r, \quad (5)$$

Knowing the amount of heat transferred through the insulation and heating the LNG inside, we can calculate the amount of LNG which may evaporate

$$BOG = \frac{Q}{h} \cdot 3600 \cdot 24, \quad (6)$$

where:  $h$  – LNG latent heat of vaporization (enthalpy at storage temperature), J/kg;

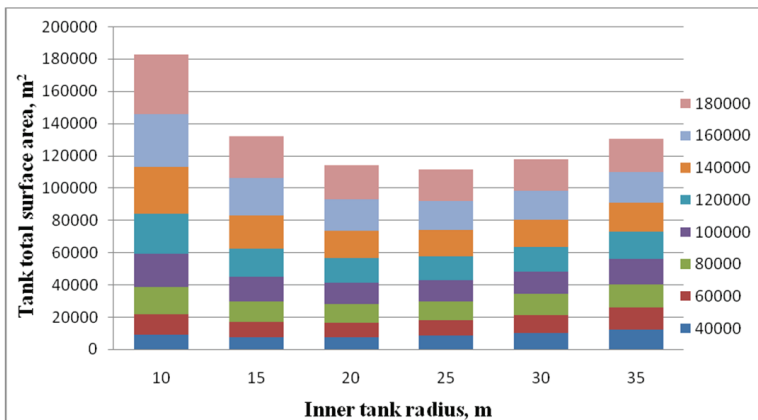
### 3. CALCULATION ASSUMPTIONS

It was assumed for particular types of tanks that their volume capacity would be constant and calculations made for six diameters, i.e. 10, 15, 20, 25, 30 and 35 m. The height of the tank was assumed to be variable, depending on the capacity and diameter of the tank.

The following constants were assumed for the model:

- inner tank wall is made of 9% nickel steel 0.229 m thick;
- outer tank wall is made of carbon steel 0.152 m thick;
- original insulation is made of perlite 0.6 m thick;
- secondary insulation is made of polyurethane 0.6 m thick;
- thermal conductivity for:
  - 9% nickel steel: 90.9 W/m K;
  - carbon steel: 35 W/m K;
  - perlite: 0.038 W/m K;
  - polyurethane: 0.0208 W/m K.
- coefficient of heat transfer,
  - inner surface: 50 W/m<sup>2</sup>·K;
  - outer surface: 80 W/m<sup>2</sup>·K.
- LNG temperature: 162 °C;
- ambient temperature: 0 °C;
- LNG latent heat of vaporization: 370,667 J/kg.

The results of calculations are presented in figures 1 to 4.



**Fig. 1.** Tank surface area versus its capacity and diameter

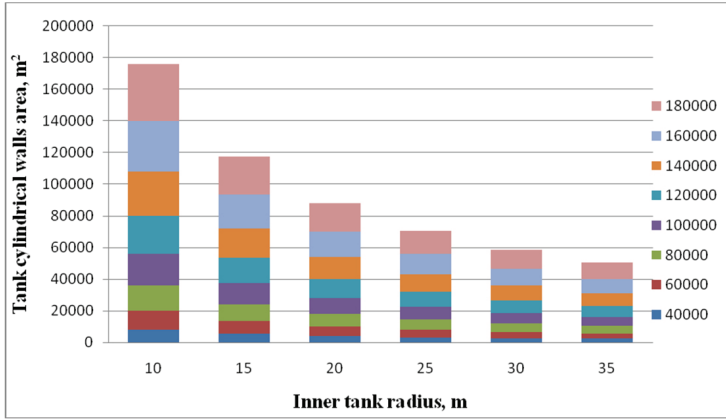


Fig. 2. Tank surface area versus its capacity and diameter

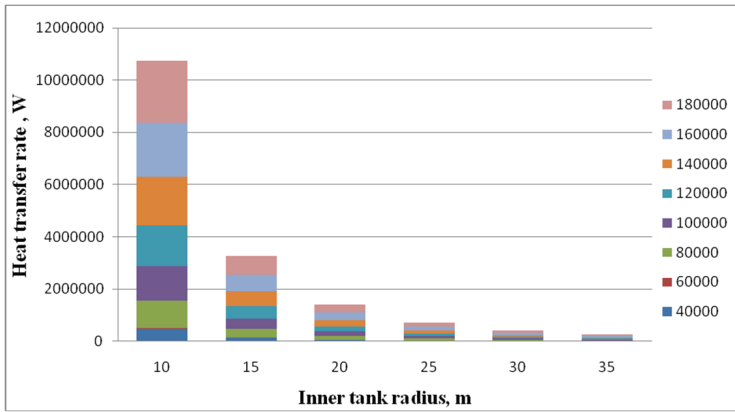


Fig. 3. Amount of heat transfer on tank capacity and diameter

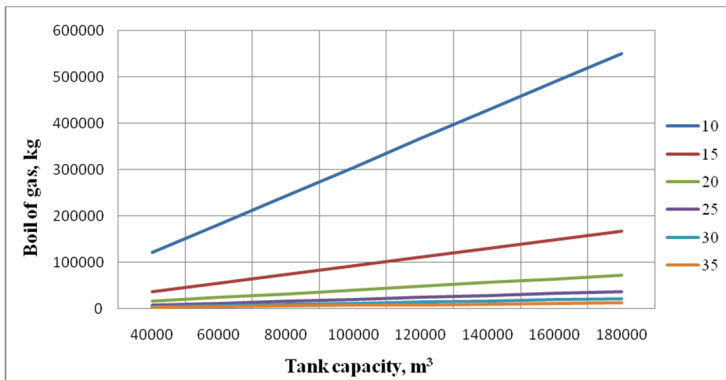


Fig. 4. Amount of BOG on tank capacity and diameter

The analysis of calculation results reveals that the amount of heat energy supplied to the tank and so the amount of boil-off gas directly depend on the geometrical parameters of the storage, especially its diameter and capacity. The plots show that the amount of transferred heat does not depend on the total surface area of the tank, but mainly on its side walls. The top of the tank is negligibly small as compared to the wall surface, therefore majority of heat escapes through the side walls.

Bearing in mind the amount of boiled off LNG as a percentage of total stored fluid, this parameter practically does not change with the increase of storage capacity of the tank. With the higher storing capacity it is also the amount of boiled off LNG which increases, though the ratio of these parameters remains almost the same.

#### 4. ANALYSIS OF CHANGES OF STORED LNG PARAMETERS

Heat transfer inside the tank results in the increase of LNG temperature, which consequently causes evaporation of some amount of stored medium. For analyzing processes taking place inside the tank, calculations were performed for two different LNGs. The first of them did not contain nitrogen, and the other one contained high admissible nitrogen content. Nitrogen-free fluid was labelled as “LNG 1”, and the other one “LNG 2”. The content was so composed as to best illustrate the difference in the evaporation of various LNGs.

Molar and mass compositions of both LNG variants are presented in table 1.

**Table 1**  
LNG compositions

| Component | Mass composition | Molar composition |          |           |
|-----------|------------------|-------------------|----------|-----------|
|           | LNG 1            | LNG 2             | LNG 1    | LNG 2     |
| Methane   | 0.89             | 0.89              | 0.9432   | 0.93904   |
| Ethane    | 0.08             | 0.08              | 0.045234 | 0.045035  |
| Propane   | 0.03             | 0.01              | 0.011567 | 0.0038387 |
| Nitrogen  | 0.00             | 0.02              | 0.00     | 0.012085  |

Calculations were conducted for conditions that may theoretically occur during LNG storage. The temperature ranges between 107 and 118 K, the pressure in the tank did not change and equaled to 0.10133 MPa. The density of liquid and gaseous phases present inside the tank were determined for molar and mass concentrations in the above range of temperatures.

The calculated temperature at which gaseous phase starts to be generated was equal to 112.36 K for LNG 1. At higher temperatures LNG begins to boil off causing changes in its composition. With the growing temperature it is not only the liquid phase of LNG which changes, but also the gaseous phase (natural gas).

The course of changes in the mass composition of liquid phase is presented in figure 5 and 6.

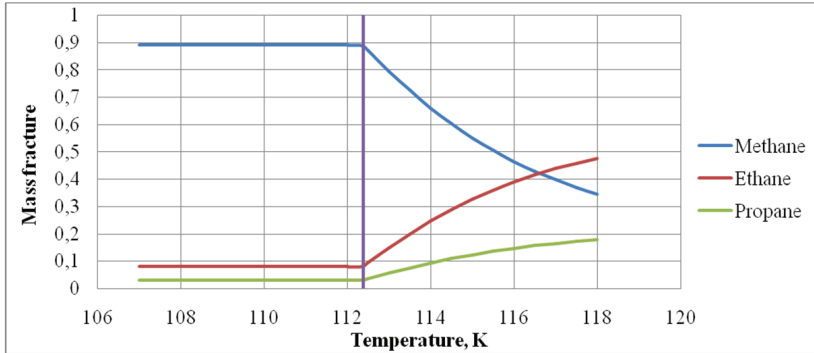


Fig. 5. Change of mass composition of liquid phase

As can be seen from the figure, the composition does not change unless a critical temperature of fluid is reached, i.e. 112.6 K. At the critical temperature, methane, which is the lightest element in the mixture, starts to evaporate as first.

Lowering the amount of methane in fluid results in the increased share of other components, mostly ethane, and propane to a smaller degree. At a temperature of about 116.5 the mass of methane and ethane in the stored LNG equalize. Then the ethane content starts to gradually exceed the methane content.

The increase of temperature and the resulting changes in the liquid and gaseous phase composition result in density changes. The change of density of the liquid phase is presented in figure 6.

The analysis of the calculation results reveals that the density of liquid phase decreases with the increase of temperature till the moment the stored medium reaches a critical temperature. This effect is both logical and understandable. This happens because the inflowing heat increases inner energy of the LNG and expands it. The LNG mass does not change over the time of storage, therefore the volume increase for the same mass reduces mixture's density.

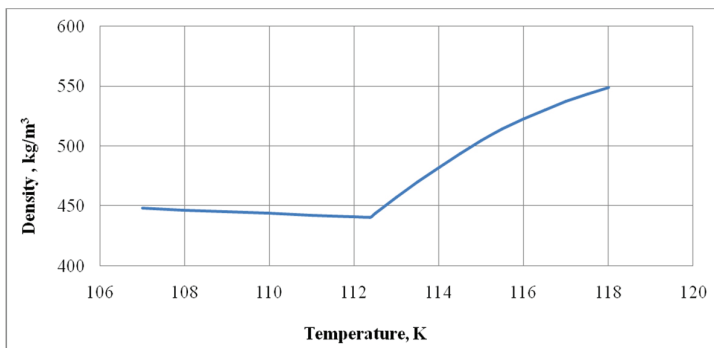
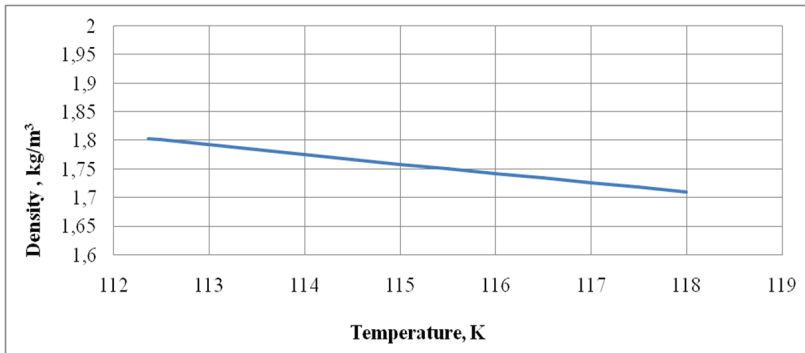


Fig. 6. Change of liquid phase density

Since the moment the critical temperature (initial temperature of evaporation) has been reached, the density of the fluid starts to increase. This effect can be explained by the fact that methane evaporates in the beginning. Methane is the lightest of other LNG components. Therefore, after methane has permanently evaporated, only heavier hydrocarbons, i.e. ethane and propane are left in the fluid, increasing its density.

The density of natural gas evaporation (mainly methane) at the increasing temperature quickly drops down. This can be explained by the same phenomenon as for fluids. The temperature increase causes an increase of gas volume, which in turn results in a decrease of its density. It cannot be ignored, however, that heavy hydrocarbons start to evaporate more intensely with time, and the density drop curve has a more lenient course.



**Fig. 7.** Change of density of gaseous phase

Analogous calculations were performed for the other LNG composition. LNG 2 differs from LNG 1 with the high nitrogen content.

Nitrogen is an undesired LNG component because it has a considerably low boiling point and is heavier than most of other constituents. Very low boiling point of nitrogen causes that LNG starts evaporating at even small amounts of the incoming heat. This is very bad for the tank and the analysis of changes taking place in the composition of gas and fluid is presented in the paper. The obtained results show that the critical temperature for LNG 2 is 108.34 K, therefore 4 K less than for LNG 1. This is caused by the presence of large quantities of nitrogen in the other fluid.

The analysis of the obtained calculation results shows that at the critical temperature nitrogen starts to very actively evaporate increasing share of other components in the mixture. The participation of light methane slightly increases till the moment the nitrogen content in LNG lowers down to 1.14 %. With the decrease of nitrogen level in active fluid, methane starts to evaporate while ethane and propane contents continue to increase. The changes in LNG 2 composition at higher temperatures are visualized in figure 8.

When the stored medium is heated to a temperature of 116 K nearly all nitrogen evaporates, making also methane evaporate at a higher rate. After the liquid reaches a temperature of 116.5 K the quantity of produced ethane will exceed that of methane.

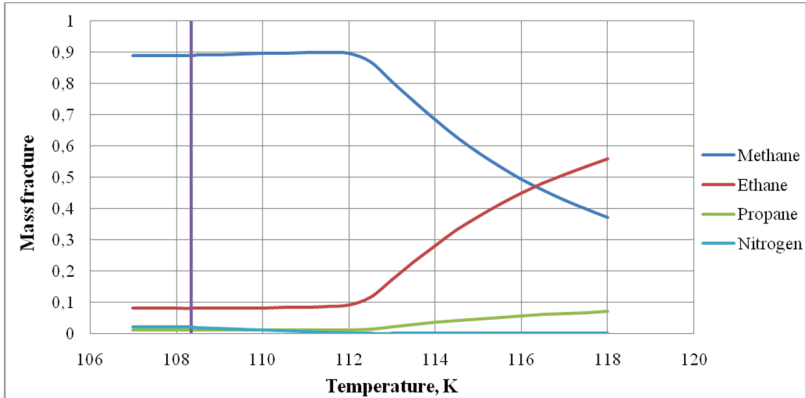


Fig. 8. Change of mass composition of liquid phase

Similarly, the molar composition of LNG changes, except that all changes are slower as compared to the mass composition.

At the initial stage of gaseous phase formation nitrogen constituted even 40 % of mass composition and 28 % of molar composition. At the successive temperature increase this share decreases as more methane is evaporated. The nitrogen content decreases twice when the fluid temperature increases to 2 K. For a temperature of about 113 K the nitrogen content becomes negligible.

The quantities of heavier hydrocarbons, e.g. ethane and propane also are negligible in the gaseous phase. This is caused by the fact that their boiling points are much higher than that of methane, and so of nitrogen. The amount of ethane and propane in the gaseous phase increases with each temperature growth. The analysis of the obtained results may suggest that after most of the methane has evaporated, ethane and then propane will also start to actively evaporate. In such a case the mass and molar composition of gaseous phase change through the decreased participation of methane and increased share of ethane and, to a smaller extent, propane.

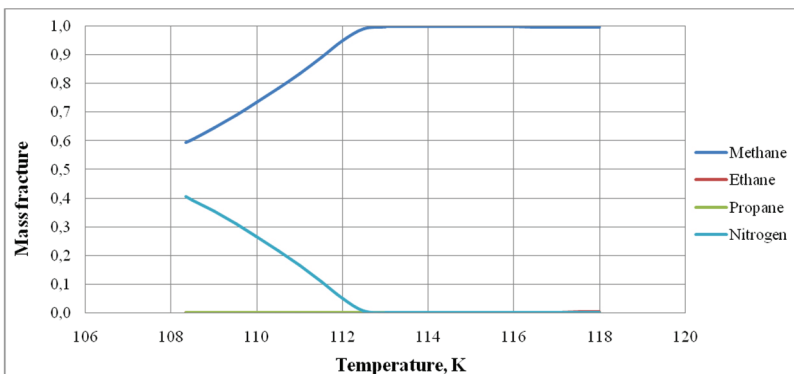


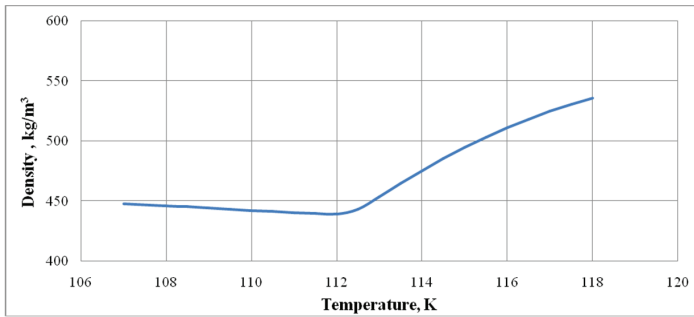
Fig. 9. Change of mass composition of gaseous phase



The density of liquid phase changes unevenly. With the temperature increase from 107 K to the critical temperature 108.34 K the density of LNG decreases due to the thermal expansion of fluid. This drop has a relatively gentle course.

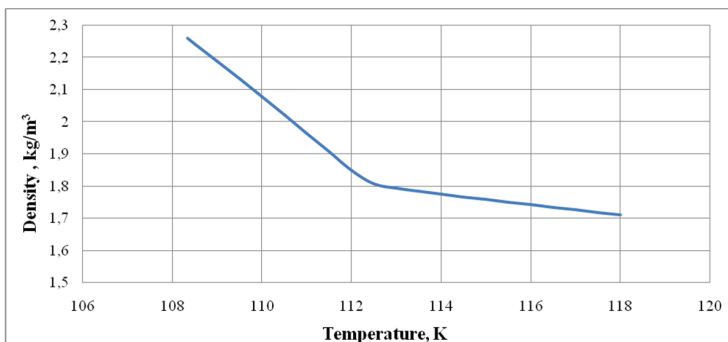
Condensed nitrogen is nearly twice as heavy as methane. This continues till the moment nitrogen starts to evaporate and the density of the fluid gradually decreases. After evaporating all the nitrogen (112.5 K) from LNG, it is also methane which starts to evaporate. Methane is lighter than the remaining components, ethane and propane, therefore the density of the stored medium rapidly increases.

The course of this process is visualized in figure 10.



**Fig. 10.** Change of liquid phase density

The density of gaseous phase changes inversely. At the initial stage the gaseous phase is quite dense and this is caused by the fact that the temperature of gas is very low and the mass content of nitrogen is about 40 %. Gaseous nitrogen is nearly twice as heavy as methane. With the increase of temperature in the tank the nitrogen content in BOG decreases as more and more methane is evaporated. This causes that gas density quickly decreases till the moment nitrogen becomes negligible in the mixture. This causes that the gas density lowers very rapidly. This continues till the moment nitrogen becomes negligible in the gaseous phase and simultaneously the temperature growth causes more active evaporation of heavier elements, i.e. ethane with propane.



**Fig. 11.** Change of gaseous phase density

All these factors add to the decrease of density of the gaseous phase. At the successive temperature increase the density will lower down, though this will be a slower process due to the increasing share of heavier hydrocarbons.

The LNG composition is a very important parameter because even the smallest contents of certain constituents may significantly affect the behavior of entire LNG while it is stored in the tank.

## 5. CONCLUSIONS

- The amount of heat transported inside the tank greatly depends on the geometrical parameters of the tank, especially the surface area of side walls. The bigger is the storing capacity of the tank, the bigger is the surface of the walls and the bigger is the amount of heat delivered to the stored LNG. As a consequence the process of natural gas evaporation is activated.
- The analysis of calculations reveals that the composition of particular components in the mixture has a great influence on the course of the process of LNG evaporation inside the storage. Components having the lowest boiling point (methane) change their state to gaseous as first, then follow heavier hydrocarbons, making the fluid denser and heavier. The course of the process in which density changes, has a gentle character here. The opposite takes place for LNG evaporation. LNG contains nitrogen which has a lower boiling point than methane, but is heavier almost twice. Therefore in the course of heating and evaporation, the density of LNG initially decreases, to grow after a greater quantity of nitrogen has evaporated.
- Long-term LNG storage is aimed at covering seasonal differences in gas consumption but this results in changes of the composition of the stored medium. Changes in the composition and density may contribute to stratification of LNG inside the tank.
- Knowing the process of heating and evaporation of different kinds of LNG one may predict and counteract potential risks related to it.
- During LNG storing a certain amount of fluid will be always evaporated due to the heat transport into the tank, which cannot be fought by the use of any thermal insulation materials.

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