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Analysis of chosen aspects of a tank gassing-up process on board liquefied petroleum gas carrier. Part II

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Abstract The paper presents a thermodynamic analysis of the removal of an inert gas from the tank using the vapor of liquefied petroleum gas cargo (called cargo tank gassing-up operation). For this purpose a thermodynamic model was created which considers two extreme cases of this process. The first is 'piston pushing' of inert gas using liquefied petroleum gas vapour. The second case is the complete mixing of both gases and removal the mixture from the tank to the atmosphere until desired concentration or amount of liquefied petroleum gas cargo in the tank is reached. On the example of nitrogen as inert gas and ethylene as a cargo, by thermodynamic analysis an attempt was made to determine the technical parameters of the process, i.e., pressure in the tank, temperature, time at which the operation would be carried out in an optimal way, minimizing the loss of cargo used for gassing-up. Calculations made it possible to determine the amount of ethylene used to complete the operation and its loss incurred as a result of total mixing of both gases.

Keywords: Filling the tank; Gassing-up; Ideal gas; Gas mixing; Ethylene; Nitrogen; Inert gas; Cargo vapour

1 Introduction

Ethylene carriers are highly advanced mostly semi-pressurized liquefied petroleum gas (LPG) ships designed to carry most of liquefied gas cargoes except liquefied natural gas (LNG). What is the most important, these

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vessels have a possibility to transport fully-refrigerated ethylene at atmospheric pressure boiling point of 169 K (–104 °C). Ethylene carriers have C type, bi-lobe, insulated, stainless or low temperature nickel steel tanks with no secondary barrier, withstanding ethylene temperature of 169 K [5].

Before loading a cargo, several operations must be carried out. The most important is inerting – removing oxygen from tanks by the use of an inert gas, nitrogen or carbon dioxide (mostly nitrogen) to prevent the formation of an explosive atmosphere in the tank and gassing-up – removing inert gas from cargo tanks by the use of cargo vapour because none of the gases, i.e. nitrogen or carbon dioxide, can be liquefied by the ship's reliquefaction plant [2]. This operation consists of introducing cargo vapour pushing out an inert gas from the tank at the same time. In case of ethylene that operation is the most difficult and demanding. For particular temperatures both have similar density, so both gas mix in tank making impossible to push the nitrogen out. The liquefaction temperature of nitrogen as well as carbon dioxide, is below the critical liquefaction temperature of ethylene [3].

The main problem associated with the condensation pressure of ethylene in the cascade cycle is the presence of nitrogen that has not been completely removed from the tank in the gassing-up process that significantly reduces the cooling capacity. The most important information is the acceptable limit of the possible amount of nitrogen present in the vapor mixture drawn by cargo compressors of which maximum working (discharge) pressure is 18–19 barg[1]. To prevent the compressors operating pressure from being exceeded, i.e., 18 barg during tanks cooling operation, when the permissible content of nitrogen is exceeded, the valves on the condenser are open, hot ethylene vapors are directed to the cargo tanks and warm up the cargo tank. An open valve significantly reduces the mass flow of condensed condensate and thus, also the cooling capacity. As the ethylene temperature decreases, the pressure in the tanks decreases, and thus the compressor suction, which causes a decrease in the cooling capacity of the cycle. For this reason, a thermodynamic model of the tank has been created together with its technical parameters based on the tank of the ethylene carrier [2,4].

[1]Barg is the unit for the measurement of gauge pressure used on board gas carriers for pressure reading during cargo operations. Gauge pressure (in units of bars) is measured against the ambient pressure. Therefore, it is equal to absolute pressure minus atmospheric pressure

2 Outline of theoretical computational model – tank gassing-up by the use of cargovapour

The purpose of the calculation model developed in part I of the paper, is to determine the optimal technical parameters at which gassing-up should be carried out, the amount of ethylene used in relation to various temperatures and pressures in the tank, cargo loss of gassing-up, and thus, the elimination of additional ethylene loss during tank cooling caused by improper gassing-up process, as well as to determine the time the operation will be carried out. The model consists of two stages. The first stage is to introduce the ethylene vapour into the tank filled with inert gas nitrogen. Gas A is under specified technical parameters, i.e., pressure and temperature. Ethylene is introduced into the tank with a defined mass flow rate until the desired pressure in the tank is reached. The second stage is the removal of nitrogen from the tank (completely or up to a certain concentration / mass of ethylene). Two cases of the second stage were considered, i.e. 'piston pushing' of nitrogen using ethylene and complete mixing of both gases and removal of the mixture from the tank until desired concentration or ethylene mass in the tank is achieved.

3 Calculations based on the theoretical model – tank gassing-up with ethylene vapour

3.1 Nitrogen 'piston pushing' by the use of ethylene vapour

Another process under consideration is the removal of nitrogen vapors from the tank on the basis of their 'piston pushing out' using ethylene vapors (Fig. 1). It was assumed that the tank is already filled with nitrogen to a pressure $p_{0z} = p_A$ equal to 0.015 barg with a temperature T_z of 293 K (an ambient temperature, which is close to the nitrogen temperature after inerting, it may vary depending on the geographical position of ship on which the process is carried out) [3]. The tank is filled with ethylene while removing nitrogen vapours, so there is no need to create cascade or introduce ethylene vapours into the tank to increase the pressure. To simplify calculations, following assumptions are made:

- atmospheric pressure p_{atm} equal to 101 325 Pa (1013.25 millibar);
- specific volume of nitrogen vapour, v_{inA}, for this pressure equal to 0.58 kg/m^3;

- ethylene mass flow rate introduced to the tank, $\dot{m}_{inE}$, is equal the nitrogen removal from the tank, $\dot{m}_{outA}$;
- other technical parameters of ethylene and nitrogen are assumed according to [5].

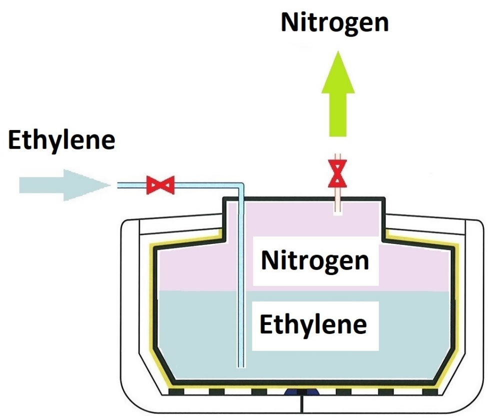

Figure 1: Nitrogen 'pushing out'.

Using the theoretical model developed, the cross-sectional area of the valve opening on the nitrogen vapor removal pipeline, f_{outA}, was calculated. On this basis, the diameter of this opening was calculated, which is 0.08 m. Figure 2 shows the change in the amount of nitrogen vapours in the tank

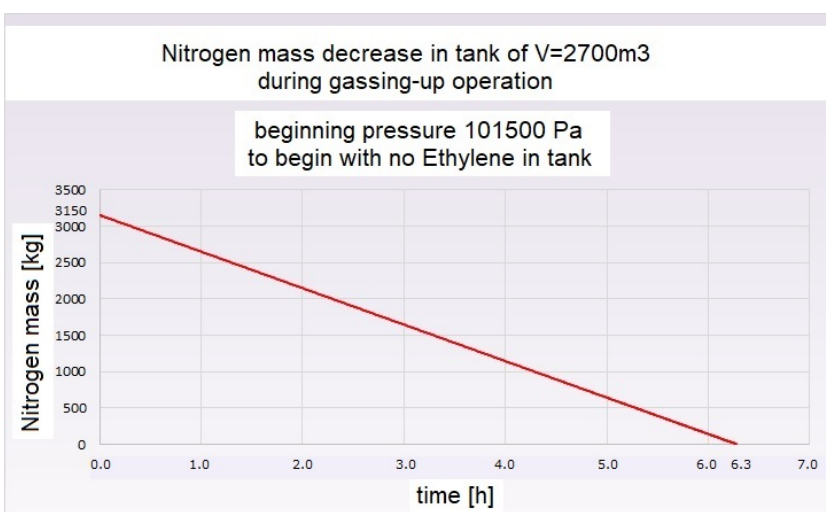

Figure 2: Decrease of nitrogen amount in tank as a function of gassing-up operation time.

relative to the gassing-up time. According to calculations, 3151 kg of cargo vapour was used to commence gassing-up of the tank with ethylene vapors for the case of ‘piston pushing’ of the nitrogen. As shown in figure, the amount of nitrogen in the tank decreases linearly for the assumed ethylene mass flow of 0.15 kg/s.

3.2 Gassing-up operation in case of total mixing of ethylene and nitrogen

The third and final part of the calculations is to remove nitrogen from the tank when nitrogen and ethylene vapours are completely mixed (Fig. 3). In order to simplify the calculations, it was assumed that:

- tank temperature does not change, it is equal to the nitrogen temperature throughout the operation, $T_z = T_A = 293$ K;
- pressure in inerted tank is equal to the initial gassing-up pressure $p_{0z} = p_A = 0.015$ barg;
- ethylene mass flow rate introduced to the tank $\dot{m}_{inE}$ is equal to removed mass flow rate of mixture $\dot{m}_{outm}$;
- values of the ethylene vapour mass flow introduced to the tank and the mixture removed from the tank are determined – 0.15 kg/s (the average value at which it is generally recommended on ships during gassing-up) and also 0.01 kg/s and 0.05 kg/s (experimental values for calculations).

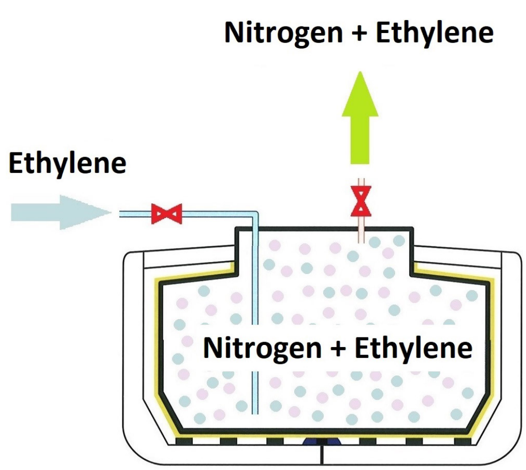

Figure 3: Removing the nitrogen by total mixing of nitrogen and ethylene.

3.2.1 Case I

It assumes that there are only nitrogen vapors in the tank (the pressure in the tank was not increased by means of ethylene vapors, i.e., at the same time the valve introducing ethylene vapor into the tank and removing the mixture of ethylene and nitrogen vapors from the tank was opened) – immediate tank rinsing. The increase in the amount of ethylene vapor relative to the gassing time for a flow rate of 0.15 kg/s used on gas carriers is shown in Fig. 4. Gassing-up the tank for the minimum ethylene mass flow rate value $\dot{m}_{inE}$ recommended on ships equals to 0.15 kg/s and takes about 27 h to reach 99% of ethylene in the tank. Based on the graph, it can be concluded that removing of the last 10% of nitrogen still remaining in the tank takes approximately half of the entire operation time.

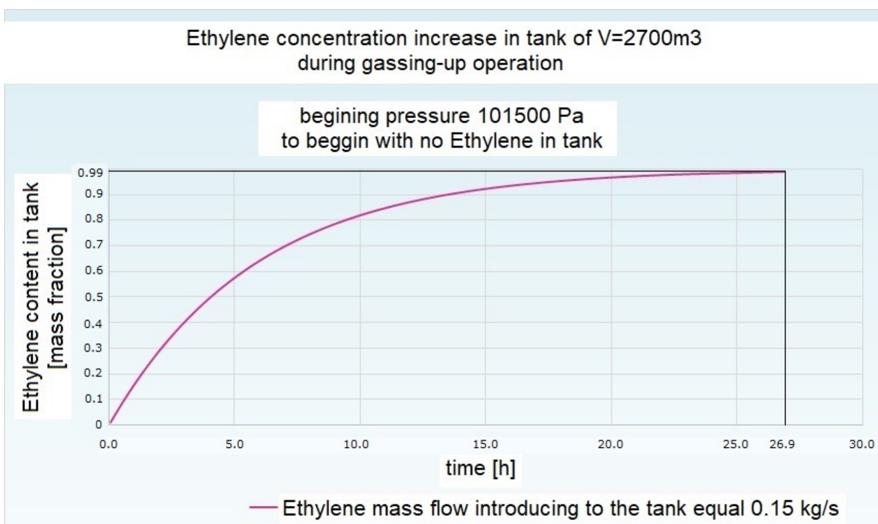

Figure 4: Increasing the amount of ethylene in the tank as a function of gassing-up time (without increasing the tank pressure by introducing the ethylene vapour).

Figure 5 illustrates the different values of time to commence the operation relative to the gassing-up time. For $\dot{m}$ equal to 0.1 kg/s, gassing-up takes over 40 h, while for $\dot{m}$ equal to 0.5 kg/s, about 8 h respectively. For comparison, Fig. 6 shows the ethylene content in the tank during its gassing-up as a function of time for different tank volume values, V_z. The mass fraction of ethylene in the tank increases in the direct proportion to its volume. For a larger tank volume of 2400 m^3 the time of the operation is

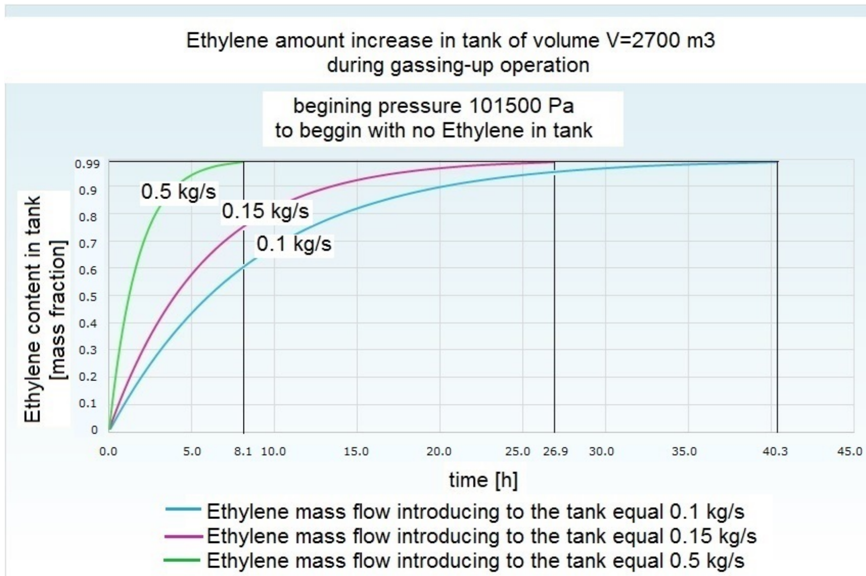

Figure 5: Increasing the amount of ethylene in the tank as a function of gassing-up time for different mass flow values (without increasing the tank pressure by introducing the ethylene vapour).

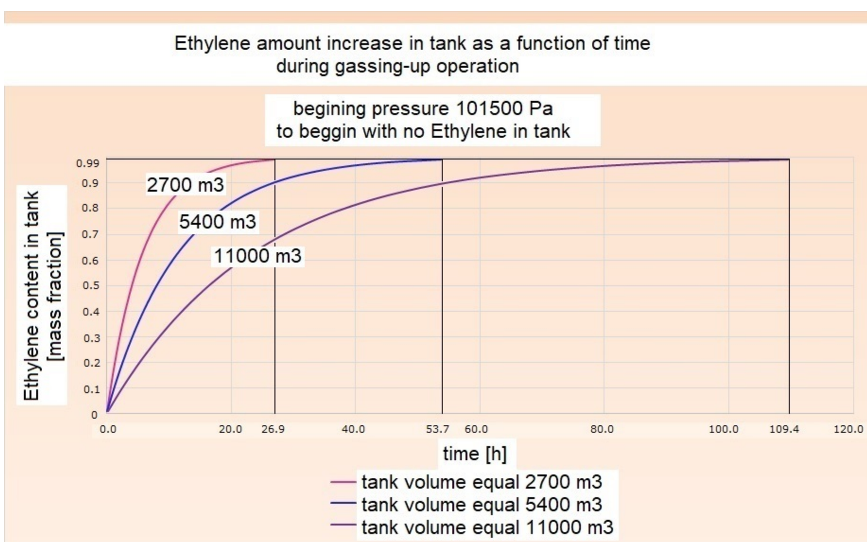

Figure 6: The increase of the amount of ethylene in the tank as a function of time of gassing-up for different values of the tank volume, V_z, without increasing the tank pressure by introducing the ethylene vapour.

about 27 h, whereas for a tank volume of 11 000 m^3 the gassing-up time is over 109 h.

Figure 7 shows the mass of ethylene used in the gassing-up process relative to the time of the entire operation. Based on the curve in Fig. 4, it can be read that after 13 h of gassing-up, the last 10% of nitrogen starts being removed from the tank, therefore it can be concluded that half of the ethylene mass used to gassing-up is intended to remove the last 10% of nitrogen.

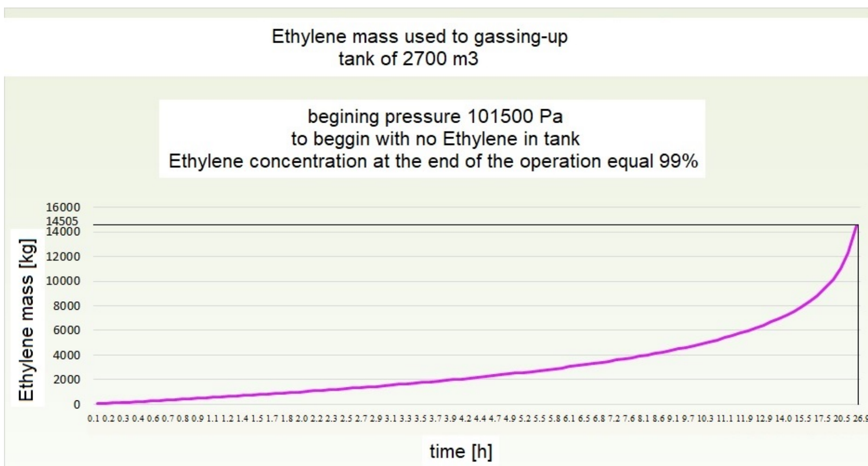

Figure 7: The amount of ethylene used to carry out the gassing-up process as a function of time (without increasing the tank pressure by introducing the ethylene vapour).

Based on the calculation model, ethylene loss were determined depending on the pressure at which the cargo tank gassing-up process is carried out for complete mixing of the cargo and inert gas. The results are shown in Fig. 8. Calculations confirm that the smallest cargo loss occur while maintaining the minimum tank overpressure.

3.2.2 Case II

Analysis of this case assumes that to begin the operation the certain amount of ethylene is introduced to the tank, m_{Ex}, (to maintain a minimum overpressure it is equal to 264 kg). That allows to increase the tank pressure to 0.1 barg. Subsequently the valve to remove the mixture to the atmosphere is opened (from this moment both valves are open, the mixture is removing

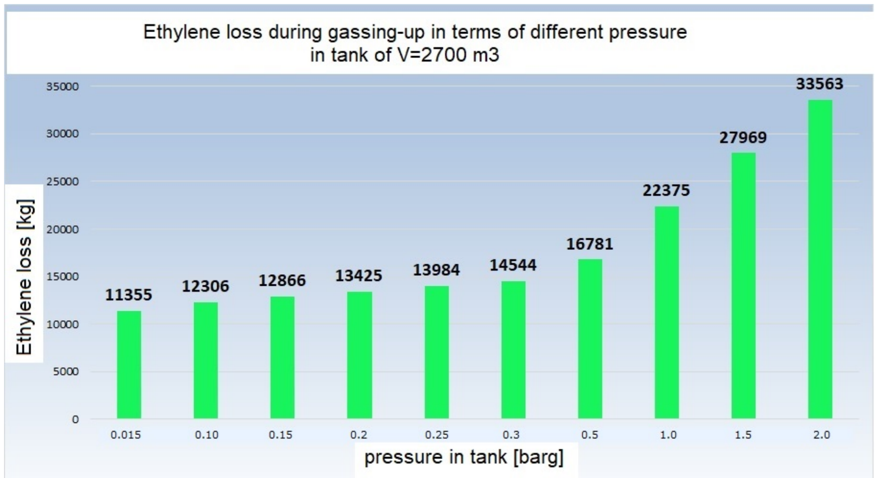

Figure 8: Ethylene loss during the tank gassing-up relative to different tank pressures, at which the process is carried out.

from the tank until it receives 99% of the ethylene). The increase in the amount of ethylene as a function of gassing-up time is shown in Fig. 9. It took nearly 30 h to reach 99% of ethylene in the tank. As the curve in the graph proves, in this case the removal of the last 10% of nitrogen vapour

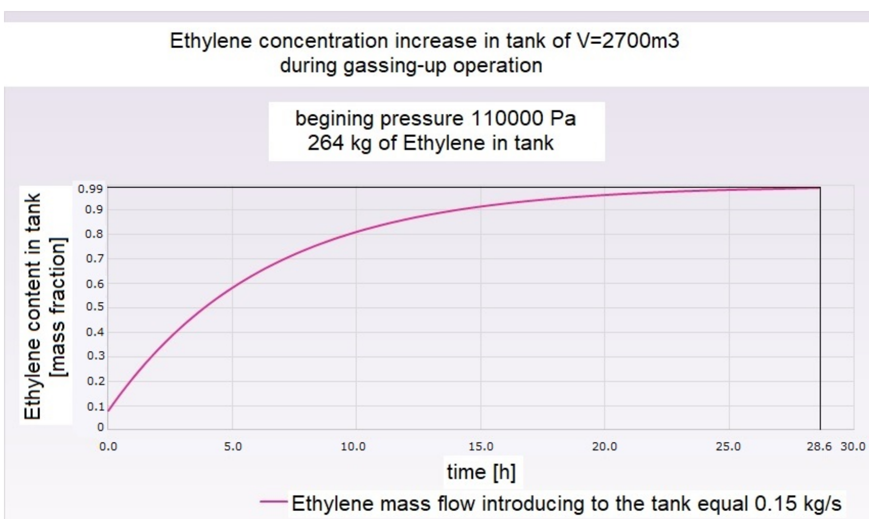

Figure 9: Ethylene amount increase in tank as a function of time (after introducing 264 kg of ethylene to increase the tank pressure).

also is the most time consuming – it took almost half of the entire time of the operation.

The curve in Fig. 10 characterizes the mass increase of the amount of ethylene used in the gassing-up process relative to the time (after an earlier increase of the tank pressure to 0.1 barg using cargo vapours). After over 26 h of gassing-up process, reaching ethylene concentration of 99%, 15 446 kg of the ethylene cargo is used to finish the operation.

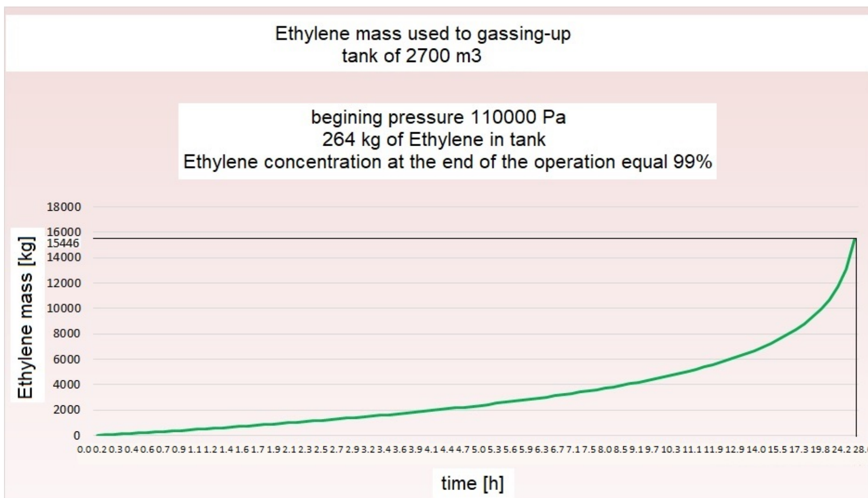

Figure 10: The amount of ethylene used to carry out the gassing-up process as a function of time (after introducing 264 kg of ethylene to increase the tank pressure).

4 Conclusions

Considering the gassing-up operation in a cascade made of two tanks, at which it is necessary to increase the pressure in the first tank of a cascade by introducing cargo vapors, the most beneficial for this operation is to inert the tank to the level of minimum overpressure, then increase the pressure by 0.1 barg with ethylene vapours and commence the operation of gassing-up process to remove nitrogen. This will allow to use the minimum amount of cargo in the shortest possible time.

In case of nitrogen 'piston pushing' by the use of ethylene vapors and complete mixing of both gases, inerting the tank to the minimum overpressure is also the most advantageous option from the point of view of the amount of cargo used to commence the operation.

From the mathematical point of view, the mass flow of introducing cargo and removing mixture should be as high as possible and has no effect on the loss of a cargo, which allows for a significant reduction of time of the operation. Nevertheless, further experiments will verify the values assumed in the calculations. The carried out calculations show that the removing of the last 10% of nitrogen vapour from the tank is the most time consuming and uses for this purpose an estimated half of the mass of the cargo used in discussed process.

Real loss, according to calculations results, show that there is a stratification of both gases in the cargo tank.

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