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Estimation of Evaporation Losses of Bunker LNG



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ABSTRACT

Analysis of efficiency of transport systems using liquefied natural gas (LNG) as fuel is impossible without a comprehensive understanding of the volumes of fuel LNG losses from evaporation during main technological operations: transportation (storage), bunkering, and cool-down of fuel tanks. Despite active development of water and land natural gas vehicles, practical approaches for obtaining appropriate estimates in a wide range of characteristics of cargo tanks have not been previously published.

The objective of this work is to analyze LNG losses in road, rail and ship tanks (with a capacity of up to 5600 m^3), as well as in tank containers, provided that LNG is stored with an overpressure of about 5–7 atmospheres.

In the work, numerical modelling was used as a method. The evaporation process of LNG is described using models of heat exchange between the liquid phase of LNG, its vapours, as well as a cargo tank and the external environment. This makes it possible to simulate the behaviour and phase transformations of LNG during its storage in a tank, as well as during main technological operations. Numerical modelling of thermodynamic processes during storage of LNG is performed using a computer simulation model implemented in AnyLogic environment. Quantitative estimates of LNG losses during bunkering and cool-down of fuel tanks were obtained based on analytical calculations.

An analysis of sensitivity of the created models to various parameters, as well as massive numerical calculations, made it possible to construct regression relationships to determine LNG losses during operations under consideration. The obtained dependencies can be used to search for the most effective configurations of the system for low-tonnage LNG transportation, as well as to perform economic assessments of feasibility of using LNG as fuel for water and land transport.

Keywords: sea transportation, liquefied natural gas (LNG), evaporation losses of LNG, LNG bunkering vessel, LNG bunkering, fuel tank cooling, simulation thermodynamic model, regression analysis.

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Background.

Liquefied natural gas (LNG) is increasingly being used as fuel for vehicles of various modes of transport. However, a number of aspects of use of this atypical type of fuel are currently poorly studied. In particular, an urgent practical task is to study the issues of LNG losses during its transportation and performing a number of technological operations, such as cooling down (lowering the temperature of the cargo tank to -130°C before direct supply of LNG to it) and bunkering of cargo tanks (moving LNG from the tank-source into the tank-recipient with cool-down of LNG residues in the receiving tank).

To solve the tasks of a feasibility study and optimization of LNG transportation systems, it is necessary to get fairly simple calculated dependencies that allow one to estimate the volume of cargo losses during transportation in the form of functions of trip's duration, insulation characteristics, ambient temperature and other factors that affect the evaporation rate. Similar dependencies are required to determine LNG losses during cool-down and bunkering of cargo tanks. The presence of such dependencies will make it possible to reasonably approach both the issue of designing vehicles for delivery of LNG (the choice of design delivery speed, cost/efficiency ratio of the used insulation material, etc.), and for forecasting LNG losses when solving planning problems of operation of vehicles (scheduling of movement, forecast of cargo parameters at the point of delivery, and others). The development of such dependencies is the *objective* of this study.

It should be noted that the authors were unable to find such studies either among the domestic or foreign publications, which is obviously due to novelty of this topic as a whole. Many foreign studies are focused on thermodynamic modelling of LNG storage process at atmospheric pressure [1; 2]. This method of storing and transporting LNG is predominant in terms of traffic volumes, therefore the issue of analyzing and predicting losses from evaporation along the entire supply chain [3] is quite important. However, in this case, as a rule, the simplest methods of determining daily LNG losses, based on statistical data, are used. For example, LNG losses during transportation by sea-going gas carriers amount to 0,10–0,15 % of the vessel's capacity when moving in cargo, and 0,06–0,10 % when moving in ballast [4]. The few studies that address the issue of LNG losses during storage under conditions of an excess pressure of 5–7 atmospheres are mainly focused on the operational aspect, for example, on operation of bunkering vessels [5]. Thus, implementation of this study is relevant.

1. Design models for determining LNG losses

To solve the problem, special thermodynamic models were created that allow describing the processes of LNG storage, bunkering and cooling of tanks, and a stochastic model of the dynamics of air temperatures during the voyage was developed as well. A detailed description of the calculated relationships of thermodynamic models, as well as functional dependences of natural gas parameters on temperature and pressure are given in the monograph [6]. Here, we note only the basic design ratios and the accepted assumptions.

1.1. Thermodynamic model for estimating LNG storage losses

The heat exchange between the two-phase medium contained in the tank in a state of saturation with temperature T and the environment with temperature T_0 is described by the heat transfer equation:

$$dQ/dt = k \cdot (T_0 - T) \cdot F, \quad (1)$$

where Q is incoming heat, J;

t is time, s;

k is heat transfer coefficient W/m^2 • K;

F is heat exchange surface area, m^2.

When using formula (1), heat flows Q_1 and Q_2 from the external environment to the liquid and gaseous phases, respectively, are considered. These flows are determined by the areas of heat exchange between liquid and the external environment F_1, and between vapour and the external environment F_2. The ambient temperature T_0 is considered as an external dynamic parameter. The heat transfer coefficient k for a wall consisting of layers of steel and thermal insulation is determined by standard dependencies [6, p. 69].

Heat transfer between liquid and gas at different temperatures across the interface obeys the Newton–Richmann equation:

$$Q = \alpha \cdot (T_2 - T_1) \cdot F_3, \quad (2)$$

where Q is amount of heat, W;

α is heat transfer coefficient, W/m^2 • K;

T_1 and T_2 are temperatures of liquid and gas phases, respectively;

F_3 is surface area of the interface, m^2.

Pic: 1. Determination of the main characteristics of cryogenic containers in SolidWorks environment. View of the screen when implementing SolidWorks software.

Phase transitions between states of aggregation (liquid evaporation and gas condensation) lead to a change in the pressure of the gas cushion above the liquid surface and, accordingly, to a change in thermodynamic parameters (boiling point, heat capacity, and others). When heat is supplied to the liquid phase for transition to a new saturation state, the liquid evaporates, and heat is taken from it. This evaporation process in the model is described by the ratio:

$dM = dQ/r,$ (3)

where dM is increment in mass (kg) of the vapour phase when heat dQ (J) is supplied to the liquid phase in a state of saturation;

r is heat of vaporization of LNG, which is a function of saturation temperature (and, thus, saturation pressure), J/kg.

When heat is supplied to the vapour phase or in the presence of a subcooled liquid and to reach the saturation state, vapour condensation occurs: the liquid perceives heat of the gas phase. This process is described by the heat balance equation describing the balance between the heat transferred from vapour and received by the liquid:

$\alpha \cdot (T_2 - T_1) \cdot F_3 \cdot dt = G \cdot di,$ (4)

where G is mass of the precipitated condensate, kg;

di is difference between the enthalpies of superheated vapour and liquid in a state of saturation, J/kg.

The use of the given dependences makes it possible to implement an algorithm for sequential recalculation of the characteristics of the state of liquid and gas inside the tank. In this work, such an algorithm was implemented using a modification of the computer simulation model of system dynamics developed earlier in *AnyLogic* environment [7], which also integrates a stochastic generator of ambient temperature. Let us note several aspects of implementation of the simulation model.

The vapour pressure inside the tank cannot exceed a certain maximum pressure allowed by design of the tank and the pressure of the control valve. Therefore, when the pressure rises above the maximum, some small mass of LNG vapour is released, which is interpreted as an irrecoverable loss. In numerical implementation of the model, a one-time discharge of 5 kg of vapour is assumed, which is by 3–4 orders of magnitude less than the mass of LNG in the tank and allows us to consider release of excess vapours almost uniform. The indicated vapour mass loss allows maintaining the equilibrium state of the «liquid–vapour» system inside the cargo tank, but at the same time there is an abrupt change in temperature and mass of the vapour and liquid phases. Modelling of such an event is based on the assumption of dynamic rigidity of the system. According to this assumption, time of transient processes of temperature equalization in the layers of the liquid phase and return of the system to the equilibrium saturated state with an abrupt change in conditions is assumed to be small in comparison with the dynamics of the background process of heat exchange with the environment.

Practical calculations were based on specific types of cryogenic containers: tank truck GT7 PPCT-60, tank car 15-5106 and LNG tank container of type KCM 40/0,7. Cylindrical type C LNG ships with a capacity of 1700 m^3, 2800 m^3 and 5600 m^3 were also considered. Since not all the necessary technical parameters of these containers are available in the public domain, their three-dimensional models were created in *SolidWorks* environment (Pic. 1), which made it possible to obtain all the necessary geometric and mass parameters (Table 1).

In addition, on the basis of 3D models of tanks, the dependences of the dimensionless

Table 1

Main characteristics of the containers under consideration, obtained based on the analysis of open access materials

Tank type	Geometric volume, m^3	Maximum permissible pressure inside the tank, bar	Initial LNG volume, m^3	Initial LNG mass, t	Type of insulation (SV – screen-vacuum, FV – fiber-vacuum, P – polyurethane foam)	Coefficient of thermal conductivity W/m^2	Insulation layer thickness, m	Heat transfer coefficient, $W/m^2 \cdot K$
Tank truck GT7 LNG PPCT-60	60,0	7	54,0	23,2	SV	0,00145	0,12	0,012
Tank car 15-5106	65,4	5	58,2	25,0	FV	0,002	0,14	0,014
Container KCM-40	39,2	7	34,9	15,0	SV	0,00145	0,10	0,015
Ship tank 1700 m^3	1685	5	1500	645	P	0,024	0,60	0,040
Ship tank 2800 m^3	2809	5	2500	1075	P	0,024	0,60	0,040
Ship tank 5600 m^3	5618	5	5000	2150	P	0,024	0,60	0,040

values of the characteristic areas F_1, F_2 and F_3 were also plotted as a function of the filling level. These dependencies were further used when performing calculations.

1.2. Thermodynamic models for assessing LNG losses during cooling and bunkering of fuel tanks

Cooling down a fuel tank assumes its cooling from a certain temperature $T_0 \geq 143$ K (≈ -130ºC) to a temperature $T_{z0} = 143$ K by supplying small portions of LNG. The uniformity of cooling is ensured by operation of spray nozzles inside the tank. The LNG droplets obtained as a result of spraying evaporate, taking heat away from the metal structures and insulation of the tank; therefore, cooling is accompanied by intense vaporization.

To reduce the tank temperature, it is necessary to evaporate LNG mass:

$$M_{z\_1} = (\Sigma M_i \cdot c_i) \cdot \Delta T/r, \quad (5)$$

where M_i is mass of the liquid and gas phases of LNG in the tank at the beginning of the cooling process, as well as mass of walls and thermal insulation of the cryogenic tank, kg;

c_i is heat capacity of cooled masses, J/kg • K;

$\Delta T = (T_{z0} - T_0)$ is temperature gradient, which is the difference between the tank temperature at the beginning of T_0 and at the end of T_{z0} of cooling down, K.

The cool-down rate υ_3 is determined by the permissible thermal stresses of the cargo tank structures and is, as a rule, 5 ... 10 K/h [8]. The cool-down time t_z can be determined by the ratio:

$$T_z = \Delta T/\upsilon_z. \quad (6)$$

During this time, heat enters the tank through the insulation, which must also be compensated for by injecting liquid LNG with a mass of M_{z_2}. Determining the amount of LNG required to compensate for the heat supplied during time t_3 is performed on the basis of formulas (1)–(4).

Thus, the mass of LNG consumed for cooling the tank is determined by the ratio:

$$M_z = M_{z\_1} + M_{z\_2}, \quad (7)$$

LNG losses during bunkering of a tank, pre-cooled to a temperature $T_z \leq T_{z0}$, with liquefied natural gas supplied at a temperature of $T_{LNG} = 110$ K, can be calculated in a similar way, that is, as the sum of losses caused by two processes:

- cooling of metal structures, liquid and vapour inside the cargo tank from the temperature T_z to the temperature T_{LNG}
- heat input through the cargo tank insulation.

The description of the corresponding differential equation, which makes it possible to determine temperature of the cargo tank and its contents at each moment of the bunkering operation, is given in [6, p. 84]. The analysis of this calculation model showed that the component of LNG losses due to heat input from outside the cargo tank can be neglected, since for the characteristic values of thermal conductivity of insulation (k = 0,01... 0,04 W/m^2 • K) and bunkering duration (2 ... 4 hours), its share in total losses does not exceed 1 %. Note that in case of a cargo tank cooling, it is undesirable to neglect this component, because duration of the operation can reach 30 hours, and the relative share of losses due to heat exchange with the external environment is 7 ... 10 %.

So, with an accuracy sufficient for solving practical problems, it is possible to determine LNG losses during bunkering by relation (5), in which the value of the temperature gradient is taken equal to $\Delta T = T_z - T_{LNG}$.

1.3. Stochastic outboard temperature dynamics generator

Simulation of a fictitious voyage of a vehicle carrying LNG is carried out on the assumption of a stochastically varying ambient temperature. In this case, an approach is used that allows one to simulate the dynamics of temperature fluctuations as a random process with given autocorrelation properties. To do this, at the conditional points of departure and destination, at each step of model time, the current value of air temperature is calculated, which is determined as the value of the deterministic time trend plus a random addition, modeled using a scalar shaping filter of the first order (one-dimensional stochastic weather generator) [9]. The time trend of temperature at both points is described as a superposition of two harmonic functions, which represent the annual variation of average daily temperature and daily variation of temperature.

Thus, the current ambient temperature T at the points of departure (T_{dep}) and destination (T_{des}) is calculated for each hour of model time t by the ratio:

$$T = T_d + 0{,}5 \cdot R_d \cdot \cos(2\pi/24 \cdot (h - 14)) + D \cdot x_h, \quad (8)$$

where R_d is given amplitude of the daily temperature variation;

h is current time of day in hours (0 ... 24);

D is standard deviation of the current temperature from the average trend, taking into account the annual and daily variations;

T_d is average daily temperature at a given geographic point for a given day of the calendar year;

x_h is random centered normalized addition to temperature (stochastic disturbance of the mean trend).

The change in average daily temperatures T_d at the point of departure or destination is modeled by the ratio:

$$T_d = T_{ave} + 0{,}5 \cdot R_y \cdot cos(2\pi/365 \cdot (d - 200)), \quad (9)$$

where R_y *is the* amplitude of the annual variation of the average daily temperature;

T_{ave} is averaged annual temperature;

d is number of the current day in the year, counted from January 1.

The value x_h is calculated using a first-order scalar shaping filter, which makes it possible to reflect the autocorrelation properties of the dynamics of temperature anomalies as a random process:

$$x_h = \rho \cdot x_{(h-1)} + \sqrt{(1 - \rho^2)} \cdot \varepsilon;$$

$$x_h = \rho \cdot x_{h-1} + \sqrt{1-\rho^2} \cdot \varepsilon, \quad (10)$$

where ε is random standardized normal value.

The values T_{ave}, R_y and R_d are set separately for the geographic points of departure and destination, while ρ and D are considered common parameters of the weather generator.

The temperature T_0 outside the vehicle is determined by a linear approximation between the simulated temperatures between departure T_{dep} and destination T_{des}, based on the known voyage time.

$$T_0 = T_{dep} . (1 - t/t_\upsilon) + T_{des} \cdot (t/t_\upsilon), \quad (11)$$

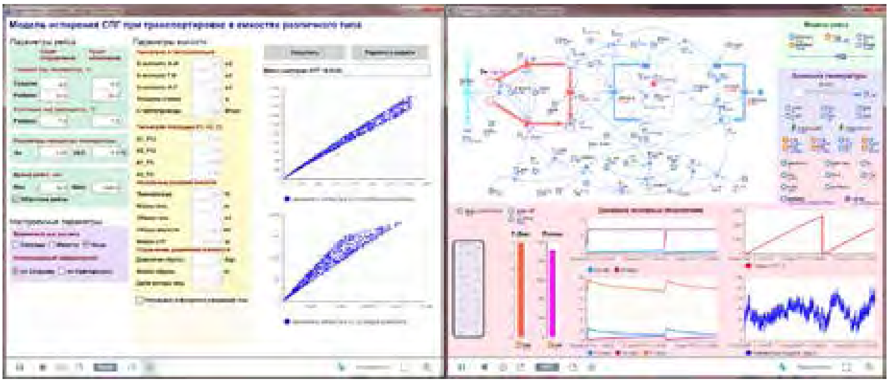
where t is time from the start of the voyage;

t_υ is total voyage time.

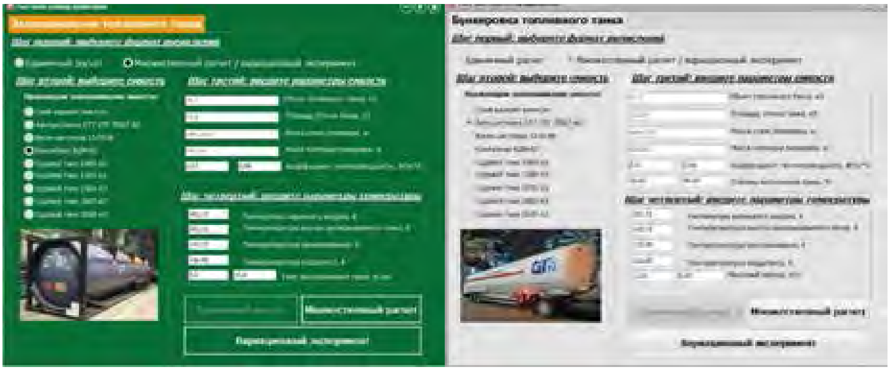
To identify the parameters of the air temperature generator, we used data of long-term historical observations in the territory of Russia [10]. A certain conditional voyage of a vehicle between the cities of Moscow, St. Petersburg, Rostov-on-Don, Volgograd, Kazan was considered. As a result, it was accepted that T_{ave} = 4 ... 8 ≈ 6°C, R_y = 24 ... 28 ≈ 26°C, R_d = 5 ... 12 ≈ 7°C. The parameters ρ and D were determined from the results of processing long-term data of actual temperature measurements for the reference meteorological stations Belogorka (Leningrad region) and Saratov. In general, we can conclude that the characteristic values of these parameters in the territory of central Russia are quite stable: ρ ≈ 0,98 (at the hourly step of the generator), D = 3,1 ... 7,8 ≈ 5°C.

2. Program implementation of computational models

The model of thermodynamic processes occurring during LNG storage has a dynamic character, so it was implemented in *AnyLogic*



Pic. 2. Main window of the simulation experiment (left) and thermodynamic model of LNG evapouration (right) in AnyLogic environment. View of the screen of AnyLogic program.



Pic. 3. User interface of software applications for calculating cooling (left) and bunkering (right) of LNG tanks. View of the screen of Embarcadero Delphi program.

environment together with a stochastic outboard temperature model. The models for determining LNG losses during bunkering and cooling are static, therefore they were implemented in the form of standard software applications that support the functions of a single or multiple calculation based on a set of input parameters.

In the graphical interface of the simulation experiment (Pic. 2), the parameters of the current calculation option are set (duration of the voyage, characteristics of the cargo tank, dynamics of temperature changes during the voyage), the main results are tracked, and the progress of execution is displayed [11].

Software applications for calculating LNG losses during cooling and bunkering of a fuel tank are similar in functionality and represent computational models implemented by *Embarcadero Delphi* tools (Pic. 3). The graphical interface allows us to configure the type of containers and the initial conditions for performing calculations.

3. Regression model for estimating LNG storage losses

A series of massive numerical experiments was performed to obtain the desired regression dependences that allow determining the evaporation losses of LNG during the voyage of gas-fuel vehicles. The initial temperature of the cargo tank and its contents was set equal to T = 110 K, and pressure in the tank at the beginning of the simulation experiment was assumed to be equal to atmospheric.

In the course of a series of simulation experiments based on Table 1 of the standard-size range of fuel tanks, the influence on final LNG losses of such factors as tank volume, heat transfer coefficient of insulation, voyage duration, average-trip ambient temperature and others was analyzed. In total, more than 50 design cases were considered, for each of which at least 3000 conditional vehicle voyages were performed, which made it possible to achieve statistical representativeness of modelling results.

Table 2

Calculations of LNG losses for the tanker type GT7 PPCT-60 vehicle

No.	Voyage start date	Duration, days	Sum of degree-days, °C (counting from -40°C)	Average temperature per voyage, °C	Lost LNG, kg
Constant voyage duration, constant degree-days					
1	Jan 11	4,17	156,0	-2,55	320,2
2	March 22	4,17	156,2	-2,52	320,4
3	Apr 2	4,17	156,8	-2,36	320,6
4	Nov 1	4,17	156,5	-2,43	320,5
5	Nov 19	4,17	156,4	-2,45	320,4
Variable voyage duration, constant degree-days					
6	Jan 10	4,83	156,3	-7,61	356,5
7	Jan 26	5,03	156,2	-8,94	367,7
8	Feb 4	5,37	156,6	-10,83	386,1
9	Feb 9	5,09	156,1	-9,34	370,8
10	Feb 8	2,83	156,4	15,21	247,8

First of all, an analysis was made of influence of dynamics of temperature changes during voyages of different duration on the resulting LNG losses. Examples of such calculations are given in Table 2, which displays a sample from the simulation results of the runs of the tanker type vehicle of GT7 PPCT-60 type with a close value of the sum of degree-days (when calculating the sum of degree-days, a temperature of -40°C is taken as the reference point).

In the first block of calculations, voyage time is constant and the sum of degree-days (or the average temperature during the voyage) is approximately the same, only the voyage start date and the associated temperature pattern changes. Despite different dates and obviously different temperature dynamics during the voyage, the mass of the lost LNG is practically the same and ranges from 320,2 to 320,6 kg. The second block of calculations is a sample of the results of calculations for the same tank truck, but with a variable duration of the voyage. From these data, an almost absolute correlation of LNG losses with duration of the voyage is visible, provided that the sum of degree-days is approximately the same. The longer is the voyage, the higher are the losses, with the average voyage temperature varying from -11°C to +15°C. These results indicate that the dynamics of temperatures during the voyage has a negligible effect on the values of resulting LNG losses, and it is the sum of degree days and duration of transportation that play a decisive role. In other words, when predicting the amount of LNG losses, it is sufficient to know voyage duration and average air temperature. This is due to the linear and additive nature of the considered thermodynamic process of LNG evaporation.

Based on these conclusions, as well as on the result of processing data of mass calculations, a regression dependence was proposed to determine mass of liquefied natural gas M_x lost during the voyage (or during stationary storage) as a function of four parameters: voyage duration, temperature during the voyage, heat transfer coefficient and mass of transported LNG. The dependence is as follows:

$$M_x = A \cdot k \cdot T_x^{0.884} \cdot t_{av}^{\ B}, \text{ kg,} \qquad (12)$$

where k is heat transfer coefficient of heat in LNG from the environment, W/m^2 • K;

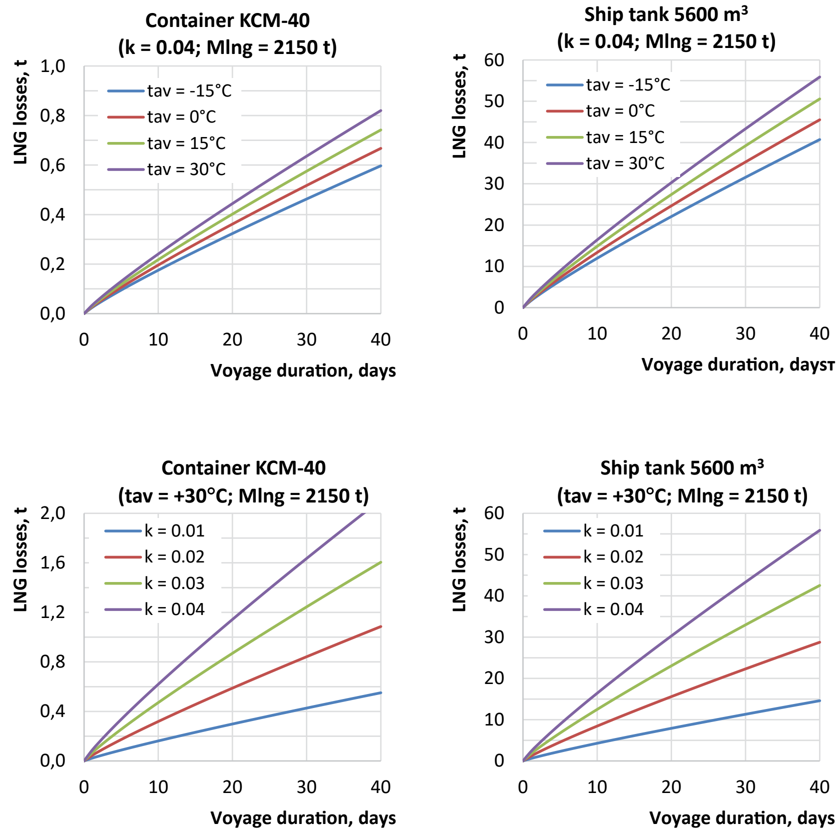
T_x is duration of LNG storage, hour;

t_{av} is average ambient air temperature, calculated by averaging temperatures during the voyage, K;

$A = A(M_{LNG})$ is regression coefficient depending on the initial mass of LNG in the cargo tank;

$B = B(k)$ is regression coefficient depending on the features of the tank thermal insulation.

It turned out that containers of different types are characterized by the same value of the regression coefficient, which stands as an exponent of the parameter T_x. This is probably due to the identical nature of physical processes occurring during evaporation of LNG in different containers. It was also found that the value of the coefficient A may be related to the amount of LNG transported. Either the volume of the container or mass of LNG transported in it can be taken as an indicator characterizing



Pic. 4. Calculation of LNG losses for various containers depending on voyage duration, average temperature during voyage and heat transfer coefficient.

the amount of LNG. The latter parameter is preferable because it allows to consider the constraints regarding the level of filling of the tank. The dependence for determining the coefficient A has the form:

$A = 2{,}76 \cdot 10^{-6} \cdot M_{LNG}^{0{,}66},\ R^2 = 0{,}999,$ (13)

where M_{LNG} is mass of LNG liquid and gas phases stored in the tank, kg;

R^2 is determination coefficient.

It should be borne in mind that the value M_{LNG} corresponds to the maximum filling level of the tank, which is about 90 % of the geometric volume. Application of dependence (12) at lower filling levels will lead to underestimation of the volume of LNG losses. The degree of this underestimation increases as the filling level decreases.

The dependence $B = B(k)$ was found by performing numerical experiments with a KCM-40/0,7 capacity with a change in k in the range from 0,002 to 0,150 W/m² • K. The resulting dependence turned out to be true for containers of other types:

$B = 1{,}98–0{,}253 \cdot k,\ R^2 = 0{,}9.$ (14)

The accuracy of approximation of the results of model calculations by dependence (12) turned out to be very high, the standard deviation of LNG losses was 0,007... 0,018 % of the initial mass for containers of all types considered. The largest relative errors are observed with a short voyage duration. An illustration of the values of LNG losses obtained on the basis of dependence (12) at various values of average trip temperatures and coefficient k is shown in Pic. 4.

To confirm accuracy of the estimates obtained, the calculated LNG losses were compared with the specification data of the KCM-40 tank container, according to which the maximum possible daily evaporation loss during stationary storage is 0,28 % at an outside temperature of 306 K (33°C) and with internal pressure of 0,1 MPa. The calculated value of the thermal conductivity coefficient for a tank of this type is $k = 0{,}015$ W/m² • K (obtained by the authors based on indirect data). According

Table 3

Calculations of LNG losses during cooling of KCM-40 container

No.	Tank temperature at the beginning of cooling down, T_0, K	Cooling rate, K/h	Heat transfer coefficient, W/m^2 • K	Lost LNG, kg
Constant heat transfer coefficient				
1	293,15	5,0	0,01	516
2	293,15	7,0	0,01	509
3	293,15	9,0	0,01	505
Constant cooling rate				
4	293,15	5,0	0,01	516
5	293,15	5,0	0,03	566
6	293,15	5,0	0,05	617

to dependence (12), during the first day of LNG storage at a temperature of 33°C, 32,1 kg of LNG will evaporate, which makes 0,21 % of the total amount of LNG. The result obtained is in good agreement with field data, especially if we take into account that specification data are usually indicated with a certain margin, and also that the actual value of the thermal conductivity coefficient for tanks of this type may differ from that accepted in the calculations.

4. Regression model for estimating LNG losses during cooling

When studying the process of cooling down the fuel tank, we took into account such factors as initial temperature inside the tank T_0, its own weight, thermal conductivity of insulation and the rate of cooling. The results of calculations indicate that the last parameter has a rather weak effect on the amount of LNG lost. As an example, Table 3 shows the results of calculating cooling of KCM-40 tank container at a constant temperature of the fuel tank at the beginning and at the end of this process. It can be seen that despite the change in the cooling rate in the range from 5 to 9 K/h, the mass of the lost LNG at constant k changes by only 2 %. Also, Table 3 shows the results of calculations for a variable heat transfer coefficient and a constant cool-down rate. In this case, there is a strong correlation between LNG losses and heat transfer coefficient.

As a result, the following regression dependence was proposed to determine the mass of liquefied gas M_z, lost when the tank cools down to a temperature of T_{z0} = 143 K:

$$M_z = C \cdot k^D \cdot (M_{st} + M_{is}),\ \text{kg}, \qquad (15)$$

where M_{st} is mass of the cryogenic container steel, kg;

M_{is} is mass of container insulation, kg;

$C = C(T_0)$ is regression coefficient depending on the temperature T_0 of the tank at the beginning of cooling;

$D = D\,(M_{st} + M_{is})$ is regression coefficient depending on mass of the container.

In the course of numerical experiments, the following dependences were obtained to determine the coefficients C and D:

$$C = 0{,}00131 \cdot T_0 - 0{,}187,\ R^2 = 0{,}999; \qquad (16)$$

$$D = 0{,}0046 \cdot \ln(M_{st} + M_{is}) + 0{,}02,\ R^2 = 0{,}978. \qquad (17)$$

For approximate estimates of the sum of masses M_{st} and M_{is} of ship cylindrical tanks with a known geometric volume V(m^3), the following approximate dependence was obtained, valid for the ratio of the length of the tank to the diameter in the range of 4,2 ... 5,0, the calculated overpressure of 4,5 atm and tank insulation made of 0,6 m thick polyurethane foam.

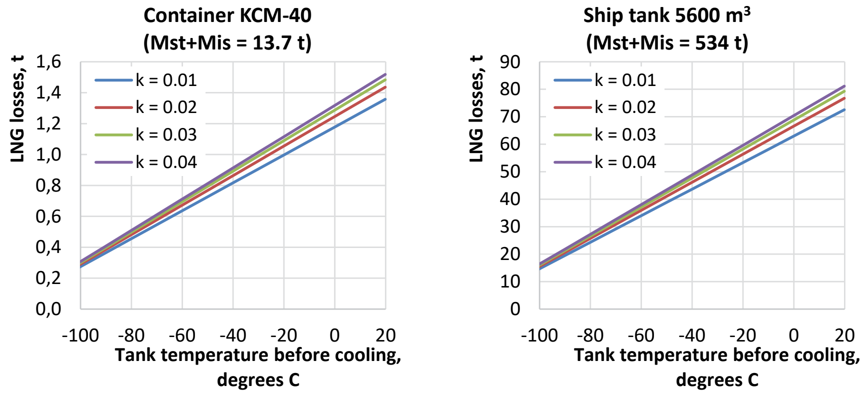
$$(M_{st}) + (M_{is}) = (60 \cdot V + 2900) + (620 \cdot V^{0.66}),\ \text{kg}. \qquad (18)$$

Examples of calculation results for this dependence are shown in Pic. 5. The mass of KCM-40 is taken according to the specification data equal to 13,7 tons. It can be seen from the picture that the value of the thermal conductivity coefficient k has little effect on the result, since the proportion of LNG losses due to external heat input is small.

The standard deviation of LNG loss calculated by formula (15) from the results of calculations based on exact algorithms is about 3 % ... 4 % of the total losses for cooling the tank, which indicates the sufficient accuracy of the approximate formula.

5. Regression model for estimating LNG losses during bunkering

When simulating the bunkering process of a tank precooled to a temperature $T_z \le T_{z0}$,



Pic. 5. Estimated values of LNG losses during cooling.

Table 4

Calculations of LNG losses during bunkering of a 1000 m³ ship tank

No.	Tank temperature at the beginning of bunkering, T, K	Performance of pumps, kg/h	Heat transfer coefficient, W/m² • K	LNG losses, kg
Constant heat transfer coefficient				
1	143,15	20,0	0,01	13065
2	143,15	75,5	0,01	13055
3	143,15	130,0	0,01	13053
Constant performance of pumps				
4	143,15	20,0	0,01	13065
5	143,15	20,0	0,03	13091
6	143,15	20,0	0,05	13118

several assumptions were made that correspond to the most probable operational scenario. It was believed that at the beginning of bunkering the fuel tank was filled to the minimum permissible level (from 10 to 50 % by volume), and temperature of the supplied bunker LNG was equal to T_{LNG} = -161ºC, and at the end of the bunkering process the contents of the tank had a temperature T_{LNG}. In addition, it was assumed that operation of the pumping equipment does not affect heating of LNG and does not significantly affect vaporization.

When analyzing the results of the calculations, it was found that duration of bunkering operations (i.e. performance of cargo pumps) practically does not affect the amount of the generated boil-off gas. The characteristics of thermal insulation and weight of the container also have little effect on gas losses. To illustrate these findings Table 4 shows the results of bunkering calculations for a ship's tank with a volume of 1000 m³ at a constant temperature of the fuel tank at the beginning of bunkering.

The main influence on mass of lost gas is exerted by initial temperature inside the fuel tank and the mass of LNG residues contained in it. The lower is temperature of LNG residue, the lower are bunkering losses. Likewise, the larger is the amount of residual LNG that needs to be cooled down to temperature T_{LNG}, the higher are losses.

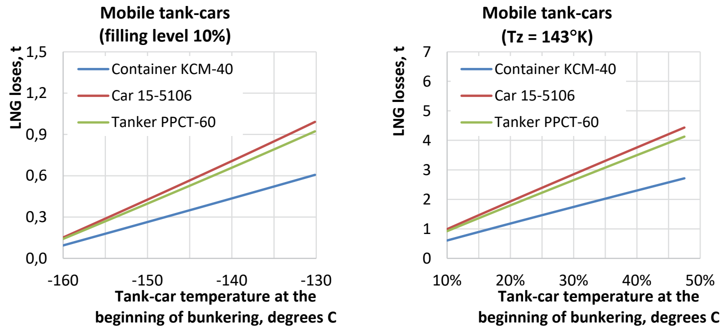
These results allowed us to form the following formula for determining LNG losses during bunkering:

$$M_b = E \cdot M_{LNG0}^{F}, \text{ kg}, \quad (19)$$

where M_{LNG0} is mass of LNG residues contained in the tank at the beginning of bunkering (from 10 to 50 % of filling), kg;

$T_z \leq 143$ K is temperature of the previously cooled tank, K;

$E = E(T_z)$, $F = F(T_z)$ are coefficients, depending on tank temperature at the beginning



Pic. 6. Estimated values of LNG losses during bunkering of mobile tank-cars.

of bunkering, obtained in the course of numerical experiments:

$$E = 0{,}0116 \cdot T_z - 1{,}248,\ R^2 = 0{,}999; \quad (20)$$

$$F = 1{,}895 \cdot 10^{-5} \cdot T_z^{\,2} - 3{,}91 \cdot 10^{-3} \cdot T_z + 1{,}133,\ R^2 = 0{,}999. \quad (21)$$

The root-mean-square deviation of regression values from model calculations is 0,2... 0,94 % of the amount of bunker LNG. An illustration of the calculated LNG losses obtained on the basis of calculations using formula (19) is shown in Pic. 6.

Conclusion. This article proposes simple regression relationships to estimate LNG losses during transportation (storage), bunkering, and cooling of various types of fuel tanks. The dependences were obtained by processing the results of a series of computer experiments with a simulation model and analytical calculations. They are applicable for containers with a maximum allowable pressure of up to 7 atmospheres at arbitrary values of the capacity. Despite the fact that initially, within the framework of the study, specific types of cargo tanks were considered, the analysis of the calculation results made it possible to propose universal formulas for estimating LNG losses, which can be used to perform estimated calculations for all types of cryogenic tanks. The results obtained can be used to optimize systems for low-tonnage LNG transportation, to design appropriate vehicles, as well as to perform various technical and economic assessments.

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