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Method of type-C liquefied natural gas tank modeling based on volume optimization for future “milk-run” exploitation

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Abstract

Common practice methods of tank design for transportation of liquefied natural gas don’t take into account the specifics of the gas carriers operation under the condition of partial filling of cryogenic tanks. A new method for designing of type-C tank is proposed. Method is based on solving the problem of increasing the volume of transported liquefied natural gas by small-scale inland carriers. The method is based on usage of a number of limiting parameters: minimal allowable ventless operation time, allowable values of the ship’s draft, and the actual duration of voyages between neighboring consumers. The method allows optimizing type, shape, wall thickness, and heat insulation thickness of cryogenic tank. The proposed method is aimed at enlargement of usage of the ship’s hull dimensions. This is achieved by changing the diameter, the distance between centers of the bi-lobe tank, the thickness of the insulation, and the maximum allowable working pressure. An increase in the volume of the tank is achieved by coordination such parameters as the maximum allowable draft of the vessel, the minimum time of ventless storage, and the time of ventless operation under partial filling conditions. The calculation of the ventless operation time is determined by the operating conditions of type-C tanks. The calculation of the heat ingress into the tank takes into account the contact area of liquefied gas and its vapors with the metal wall of the tank. The calculations do not take into account the assumption of thermal equilibrium between the liquid and vapor fractions, which leads to the need to take into account heat transfer from vapor to liquid. The implementation of the method is shown on the example of the modeling of the two-way river-sea type vessel. It is shown that optimization of tank parameters in accordance with proposed criteria can lead to an increase in the volume of transported natural gas by more than 4 %. The method can be used in the development of new and modernization of existing vessel projects to transportation of liquefied natural gas operating in water basins of Lena and Yenisei rivers in the East Siberian region. The described method can also be used in the design of road and rail tanks as well as small-scale bullet tanks for liquefied natural gas.

Keywords

cryogenic tank design, type-C tank, partial filling, tank optimization, inland carrier, small-scale tanker, liquiefied natural gas, ventless operation

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УДК 621.642.86

Метод моделирования резервуаров сжиженного природного газа типа С на основе оптимизации объема для будущей эксплуатации в режиме частичного заполнения

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Аннотация

Введение. Распространенные на практике методы проектирования танков для транспортировки сжиженного природного газа не учитывают специфики эксплуатации танкеров-газовозов при частичном заполнении криогенных резервуаров. Предложен новый метод проектирования судовых танков типа C, основанный на решении задачи увеличения объема перевозимого сжиженного природного газа речными малотоннажными речными танкерами. Метод основан на применении ряда ограничительных параметров: минимального допустимого времени бездренажного хранения криопродукта, допустимых значений осадки судна и реальной продолжительности переходов между соседними потребителями. Выполнена оптимизация типа, формы, толщины стенок и теплового ограждения криогенного танка. **Метод.** Предложенный метод направлен на увеличение использования габаритов корпуса судна. Это достигается изменением диаметра, расстояния между центрами двудольного танка, толщины изоляции и максимально допустимого давления. Увеличение объема танка обеспечено согласованием таких параметров, как максимально допустимая осадка судна, минимальное время бездренажного хранения и время бездренажного хранения при различном начальном уровне заполнения. Расчет времени бездренажного хранения определен условиями эксплуатации резервуаров типа С. Расчет подвода тепла к резервуару учитывает площадь контакта сжиженного газа и его паров со металлическими стенками резервуара. В расчетах не принимается допущение о тепловом равновесии между жидкой и паровой фракциями, что приводит к необходимости учета теплопередачи от пара к жидкости. **Основные результаты.** Реализация метода показана на примере расчета танков для судов типа река–море. Показано, что оптимизации параметров резервуаров в соответствии с предложенными критериями может привести к увеличению объема перевозимого природного сжиженного газа более чем на 4 %. **Обсуждение.** Метод может найти применение при разработке новых и модернизации существующих проектов судов для перевозки сжиженного природного газа, работающих в водных бассейнах рек Лена и Енисей Восточно-Сибирского региона. Описанный метод может быть использован при проектировании автомобильных и железнодорожных цистерн, а также стационарных малогабаритных цилиндрических цистерн для транспортировки и хранения сжиженного природного газа.

Ключевые слова

проектирование криогенного танка, танки типа С, частичное заполнение, оптимизация танка, речной газовоз, малотоннажный газовоз, сжиженный природный газ, бездренажное хранение

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Introduction

Liquefied Natural Gas (LNG) has become a new major clean energy source[1] [1]. Distant settlements are in need of fuel supply. Fuel supply chain in North-Eastern Siberia has name “Northern delivery”. Due to logistic problems, the fuel price transportation fee may be up to 70 % of total price [2]. Since in such places usually there are no developed railways or roads, the only reliable way of LNG transportation is naval one: by sea or river.

Due to multiple unique factors specific to North Siberia region, existing methods of technical analysis and optimization of LNG tanks are not effective. Such specific factors include: long distances between each point of LNG consumption, shallow draft on majority of waterways, and lack a single large consumers [3]. Based on analytical papers [4–6], the conception of “milk-run” delivery is the most rational solution. Milk Run concept means that LNG carrier moves along the distribution route and unloads parts of LNG. Afterwards, vessel continues movement with partial filled tanks. The main problem with partial filling is faster self-pressurization. When inner pressure reaches peak number of Maximum Allowable Working Pressure (MAWP) safety valve opens and Boil-Off Gas (BOG) is released. Discharge of BOG is a big problem that harms economic efficiency of LNG transportation and causes environmental damage.

Different method of modeling of small-scale LNG tank was developed. Paper [7] described an original method of projecting inland small-scale LNG carrier based on usage of standard ISO insulated LNG containers. Boundary conditions are selected by specific of a waterway of river Danube: ship’s length, breadth and draft. Maximum

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[1] GIIGNL. Annual Report. 2020 URL: https://giignl.org/document/giignl-2020-annual-report/ (accessed: 08.12.2021).

allowable draft defines maximum weight of cargo. Different variants of vessel hulls were analyzed to find the best one.

Although standard ISO[1] containers are reliable way of LNG storage, the coefficient of effective displacement usage is lower than any other Cargo Containment System (CCS). That's why this method cannot be used to design LNG carriers for main rivers. Also described method does not suit for reconstruction and modernization projects.

LNG carriers on Lena and Yenisei will be exploited in "milk-run" based logistics supply chain. By that reason the CCS for these vessels must be designed in view of this feature. Different models were already designed: for small pressurized vessels and large ones. For example, in [8] model, the case has been presented without phase-equilibrium between LNG and its vapor. Separated heat ingress is calculated towards vapor phase and liquid phase: vapor overheat in large LNG reservoir reaches up to 10 K. Heat transfer from vapor to liquid phase has been calculated by integrating the heat flux from the vapor phase to the vapor-liquid interface. The main mechanism of heat transfer is conduction. LNG is presented as multicomponent liquid. Although this method is reliable for the full-scale LNG reservoirs — for the small-scale ones it needs to be adjusted.

In paper [9], evaporation rate under different loading condition is calculated with ANSYS Fluent software. With assumption of different initial filling, the authors did not consider the change of the liquid level due to change in density of LNG due to the increase of temperature.

Lee et al. [10] present experimental data from nitrogen tank self-pressurization. This paper stated that equivalent thermal conductivity is a convenient calculation method of heat ingress through the wall to BOG and from BOG to LNG (if sloshing effect is neglected).

Ferrin et al. [11] calculated convective heat ingress under different filling conditions. The modeling object in this paper is small vertical cylinder tank. Although the described method of heat transfer calculation is accurate, it's hard to apply Computational Fluid Dynamics (CFD) calculations for the full-scale tank holding time calculation due to the necessity of high-performance computer.

Paper [12] presents the whole algorithm of calculation LNG evaporation from a reservoir. Heat transfer coefficient between BOG and LNG is presented as a steady number. Heat ingress rate is a steady number as well. REFPROP wrapper was used to perform the modeling. With static number of heat transfer coefficient, it is not reliable for the calculations with constant change in thermodynamic parameters of LNG and its vapor.

All the methods described above cannot be utilized effective enough under specific conditions that require taking into consideration partial filling of tank. Described methods include simplifications making obtainable data unusable in such conditions. Presented method is based on the usage of ship's hull parameters and drain-free operation time under different filling conditions, so it may be implemented in development of new ship and modernization of the existing ones. Method allows adjusting tank dimensions, volume, thickness of tank walls, and thermal insulation. Proposed method allows achieving enlargement of LNG volume and prevent LNG loss due to BOG discharge under any specific conditions of tank exploitation.

Model development

The enlargement of LNG tanks is achieved by optimization parameters of tank: its shape, length, diameter, thickness of wall, and insulation. Volume enlargement is achieved when following parameters are matched:

- Draft of the fully loaded vessel matches with maximum allowable draft for the unique waterway.
- Ventless operation holding time under maximum filling condition matches 15 days.
- Ventless operation holding time under partial filling condition is more than time set by operational conditions.

Current draft of vessel is determined by weight of the CCS. Weight is determined by volume of tanks and wall thickness. Type and shape of tank are determined by the available space in the ship's hull. Total weight of CCS is limited by maximum allowable draft:

$$Draft = f(W_{total}, L, B, H) \leq Maximum\ allowable\ draft,$$

where W_{total} — total weight of CCS; L — length of the ship; B — breadth; H — vessel's board height.

Total weight of CCS:

$$W_{total} = W_{LNG} + W_{tank},$$

where W_{LNG} — mass of LNG; W_{tank} — mass of tanks.

$$W_{LNG} = f(V, Fl, n);$$

$$W_{tank} = f(V, n, Wall, Ins),$$

where V — volume of tank; Fl — filling limit; n — number of tanks; $Wall$ — thickness of the tank walls; Ins — thickness of the tank insulation.

Volume of tank:

$$V = f(D_{\max}, l_t, Wall, Ins),$$

where $D_{\max}$ — overall diameter of the tank; l_t — tank's length.

MAWP is determined by the thickness of tank walls and volume of a tank. Ventless operation holding time is determined by MAWP, surface area of tank, and thickness of heat insulation. Second parameter of optimization determines thickness of heat insulation. If holding time is more than required 15 days, insulation thickness gets diminished, volume of tank increases, and thickness of tank walls gets calculated again. Holding time is limited by minimal ventless operation time and maximal time of voyage under partial filling conditions (MTPFC).

$$Holding\ time = f(V, Wall, Ins, MAWP, Fl) \geq required\ time.$$

Maximum allowable filling limit is 0.98. Maximum filling limit is one under which maximal ventless holding

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[1] ISO VAC 40 LNG: 40 ft LNG Iso Container. URL: https://wessingtoncryogenics.com/products/liquefied-natural-gas-containers/iso-vac-40-lng/ (accessed: 27.01.2023).

time is reached. For maximum filling level minimal required time is 15 days.

When second optimization parameter is matched, thickness of heat insulation is adjusted for partial filling conditions when minimal time is determined by the future of exploitation conditions.

Optimization of tank volume is achieved when all the following conditions are matched:

$$\begin{cases} \left.\begin{array}{l} \textit{Holding time} \geq \textit{15 days} \\ \textit{Holding time under partial filling} \geq \textit{MTPFC} \end{array}\right\} \begin{array}{l}\textit{whatever}\\ \textit{comes}\\ \textit{first}\end{array} \\ \textit{Draft} = \textit{Maximum allowable draft} \end{cases}$$

Overall algorithm of tank optimization is based on maximization of volume of LNG carried by the vessel. This algorithm is presented in Fig. 1.

A method for specifying the type-C tank shape was chosen based on paper [13]. Accessible space is determined by IGC and DNVGL codes regulation[1]. Upper-deck part of tank cannot be higher than 3 meters above the upper deck (or tank radius, whatever number is smaller). For bi-lobe tanks distance between cylinders centers is 0.35 r to 0.75 r [14].

Maximum diameter of type-C LNG tanks is the sum of below-deck space height (H_b) and upper (H_u) deck space height.

$$D_{\max} = H_b + H_u.$$

Hence, tank shape is chosen by the following conditions:

$$\frac{B}{D_{\max}} < 1.35 \text{ — cylinder shape of the tank;}$$

$$1.35 \leq \frac{B}{D_{\max}} < 1.8 \text{ — bi-lobe shape;}$$

$$\frac{B}{D_{\max}} \geq 1.8 \text{ — multi-lobe shape.}$$

Maximum tank length:

$$l_{\max} \leq 0.2L.$$

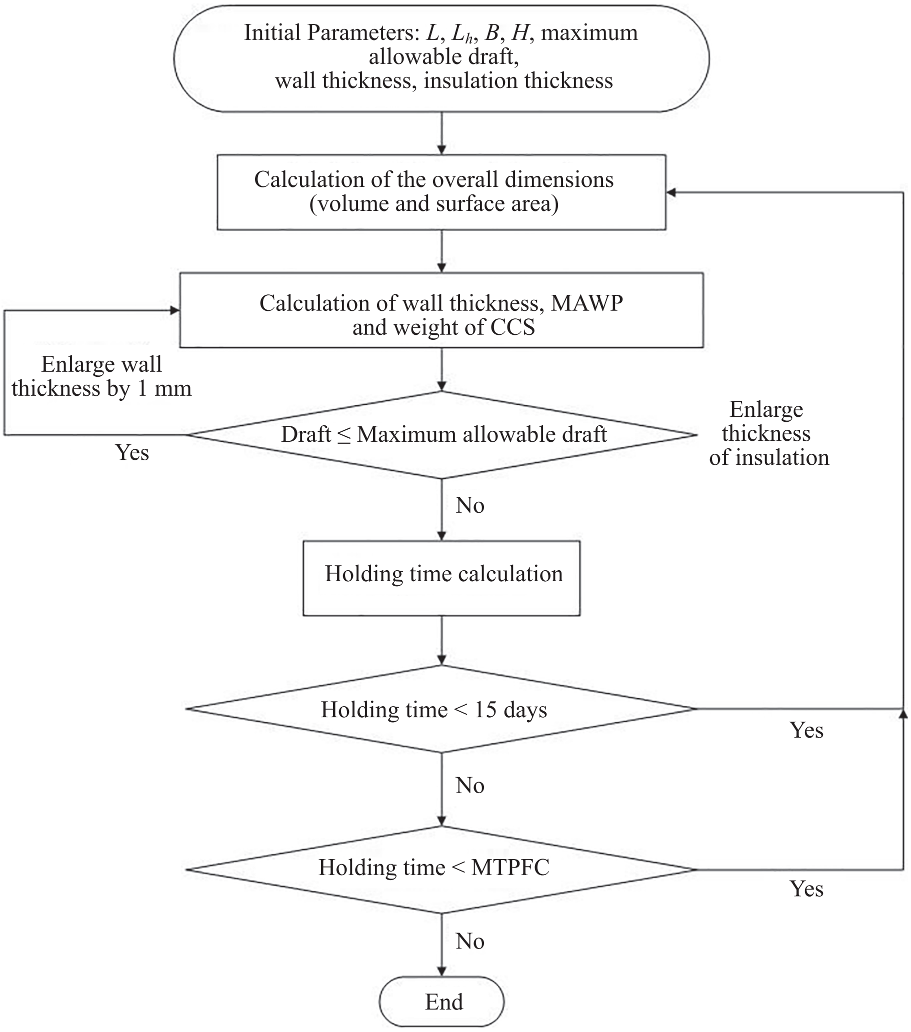

Fig. 1. Modeling algorithm

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[1] The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). URL: https://www.imo.org/en/OurWork/Environment/Pages/IGCCode.aspx (accessed: 27.01.2023).

Hence, number of tanks:

$$n = \frac{L_h}{l_{\max}}.$$

where L_h — length of the vessel's hull.

The number of tanks is obtained by rounding this number up.

Tank length:

$$l_t = \frac{L_h - 2l_{coff}}{n},$$

where l_{coff} — length of cofferdam.

Type-C tanks work under high pressure. MAWP is a function of tanks walls thickness. Therefore, maximum thickness of tanks walls is limited by maximum allowable weight of CCS. Weight of CCS is a sum of metal parts weight, insulation layer weight, and LNG stored in the tanks with maximum allowable filling. Tanks wall thickness is calculated by GNVGL guideline[1]. Sloshing effect is neglected due to the high thickness of the walls that cannot be damaged by LNG sloshing. Sloshing is taken under consideration only when dealing with membrane tanks.

Vessel lightweight (LWT) is calculated by the following formula [7]:

$$m_{LWT} = -4.44 \cdot 10^{-6}(LBH)^2 + 0.195LBH.$$

Deadweight (DWT) of vessel:

$$m_{DWT} = 1.2(m_t + m_{LNG}),$$

where m_{LNG} — mass of LNG stored in tanks; m_t — total mass of the tank; 1.2 is a coefficient that includes weight of the fuel, water supply, weight of the ship's crew, etc.

Therefore, total displacement of the vessel:

$$\Delta = m_{LWT} + m_{DWT}.$$

Loaded draft of the vessel:

$$Draft = \Delta(LBC_B p_w)^{-1},$$

where C_B — is cubic coefficient of vessels hull; p_w — relative density of water.

Second limiting parameter is minimum allowable holding time. This parameter is set by IGC code and equal to 15 days.

Assumption is made that LNG is pure methane. Heat ingress into the tank calculated as conduction only. Insulation is made from sprayed polyurethane foam (PUF). Density of PUF is 40 kg/m^3. Thermal conductivity is a function of temperature:

$$\lambda_{PUF} = -0.0003T_{PUF}^2 + 0.1908T_{PUF} - 4.2758.$$

This equation is based on experimental parameters [15], in range from 95 to 220 K. Mean deviation of presented polynomial equation from experimental results is $R^2 = 0.9983$. PUF temperature is average temperature between cold LNG side and warm outer side.

Type-C tank is made from 304L stainless steel. Since thermal conductivity does not change much, $\lambda_m = 24.21$ W/(m·K) is a constant.

Insulation layer is covered by a thin layer of coating that prevents water contact with PUF. Thickness of this layer is 5 mm and thermal conductivity is $\lambda_{coat} = 0.5$ W/(m·K).

Metal in contact with LNG assumed to have temperature of LNG. Metal in contact with BOG assumed to have temperature of BOG.

Fourier's law calculates heat ingress Q through insulation.

$$Q = \frac{T_{out} - T_{ins}}{\dfrac{d_m}{\lambda_m F_{m.av}} + \dfrac{d_{ins}}{\lambda_{PUF} F_{PUF.av}} + \dfrac{d_{coat}}{\lambda_{coat} F_{coat}}},$$

where d_m, d_{ins}, d_{coat} — thickness of metal layer, PUF insulation and primer coating; $F_{m.av}$ — mean contact surface between liquid and outer side of walls; $F_{PUF.av}$ — mean contact surface between outer surface of metal and outer surface of the heat insulation; F_{coat} — mean contact surface between outer surface of the heat insulation and outer surface of coating; T_{out} — temperature outside of the tank; T_{ins} — temperature inside the tank.

Heat ingress is calculated separately towards vapor phase and liquid phase. To calculate mean surface for cylinder tank body and hemisphere tank head following formulas were used:

$$F_{av.cil} = \frac{F_t + F_m}{2},$$

$$F_{av.hs} = \sqrt{F_t F_m},$$

where F_t — surface area of contact inside the tank; F_m — surface area of wall outside the tank.

Heat ingress to vapor and liquid phase are calculated separately since there is no equilibrium state and vapor phase is overheated.

Surface area is a variable parameter. Heat ingress towards liquid and vapor are different and based on the area of contact between fluid and tank wall. Since shape of a tank is not an ordinary vertical cylinder, contact surface calculation is a complicated task. Height of the interface between liquid and vapor allow calculating area of contact between liquid and tank wall. LNG and BOG liquid (ρ_L) and vapor (ρ_V) densities are functions of temperature and pressure:

$$\rho_L = f(P, T_L);$$

$$\rho_V = f(P, T_v).$$

Height of the interface is a function of liquid density:

$$h_{int} = f(\rho_L) \rightarrow f(P, T_L).$$

Hence, area of contact between wall and liquid:

$$F_L = f(h_{int}) \rightarrow f(\rho_L) \rightarrow f(P, T_L);$$

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[1] DNVGL-CG-0135 Liquified gas carriers with independent cylindrical tank of type C. 2016. URL: https://rules.dnvgl.com/docs/pdf/DNVGL/CG/2016-02/DNVGL-CG-0135.pdf (accessed: 08.12.2021).

$$F_V = F_{total} - F_L.$$

Evaporation heat is also a function of pressure and temperature:

$$H_{vap} = f(P, T_L).$$

Saturation temperature of liquid methane is a function of pressure:

$$T_{sat} = f(P).$$

Heat transfer from overheated BOG to liquid LNG is assumed by mechanism of conduction since convection part in negligible [9].

$$Q_{VL} = F_{VL}\lambda_V \left.\frac{\partial T_v}{\partial z}\right|_{z=0},$$

where $\frac{\partial T_v}{\partial z}$ — temperature gradient in the stratified vapor zone.

Vapor-liquid interface area is function of height of interface if sloshing effect is neglected. For the cases of vertical cylinder reservoirs, F_{VL} is constant.

$$F_{VL} = f(f(h_{int})) \to f(\rho_L) \to f(P, T_L).$$

Evaporation condition calculation algorithm follows.

If at the beginning of a time step $T_L < T_{sat}$, evaporation on this time step does not occur. Change of the masses of liquid and vapor are 0.

Temperature and density of liquid on the next time step:

$$T_L' = T_L + \frac{(Q_L + Q_{VL})\Delta t}{C_{p_L} m_L};$$

$$\rho_L' = f(T_L', P).$$

Volume of liquid on the next time step:

$$V_L' = \frac{m_L}{\rho_L'}.$$

Volume of vapor on the next time step:

$$V_V' = V_{total} - V_L'.$$

Temperature and density of vapor on next time step:

$$T_V' = T_V + \frac{(Q_V - Q_{VL})\Delta t}{C_{p_V} m_V};$$

$$\rho_V' = \frac{m_V}{V_V'}.$$

Enthalpy of vapor:

$$h_V' = \frac{h_V m_V + (Q_V - Q_{VL})\Delta t}{m_V}.$$

New pressure at the end of a time step:

$$P' = f(\rho_V', h_V').$$

If at the beginning of time step $T_L \geq T_{sat}$, evaporation occurs. Changes of masses on the next step:

$$\Delta m = \frac{(Q_L + Q_{VL})\Delta t}{H_{vap}}.$$

Enthalpy of liquid and vapor:

$$h_L' = \frac{(h_L m_L + (Q_L + Q_{VL})\Delta t - \Delta m H_{vap})}{m_L - \Delta m};$$

$$h_V' = \frac{(h_V m_V + (Q_V - Q_{VL})\Delta t + \Delta m H_{vap})}{m_V + \Delta m}.$$

If enthalpy of liquid on the next step is more than enthalpy of saturated liquid $h_L' > h_{sat}$:

$$\Delta m = \frac{(h_L' - h_{sat})m_L}{H_{vap}}.$$

And enthalpy and temperature of liquid on the next step is:

$$h_L' = h_{sat},$$

$$T_L' = T_{sat}.$$

Density of liquid on the next time step:

$$\rho_L' = \frac{m_L - \Delta m}{V_L}.$$

Therefore, volume of liquid and vapor:

$$V_L' = (m_L - \Delta m)\rho_L';$$

$$V_V' = V_{total} - V_L'.$$

Hence, density of vapor:

$$\rho_V' = \frac{m_V + \Delta m}{V_V'}.$$

Pressure on the next time step:

$$P' = f(\rho_V', h_V').$$

Calculation algorithm is based on one used in paper [12]. The main difference is calculation of changed surface area of tank contact with LNG and BOG and interface area between vapor and liquid phase.

Maximal holding time is obtained from calculated data under different initial filling level. The graph of changes in holding time dependent of filling limit is presented in Fig. 2.

Graph from the Fig. 2 repeats the pattern for self-pressurized cryogenic reservoirs from the book [16].

However, “milk-run” transportation requires partial filling conditions. Since holding time of partially filled tank is much lower than fully filled, it is necessary to calculate drainless time under partial filling conditions. Such conditions depend on logistics: future area of work of the vessel. To prevent LNG loss by BOG discharge, such modes of operation must be taken into account.

Results and discussion

As an example of this method usage, vessel RSD62 was set as a case. RSD62 is small-scale inland oil carrier

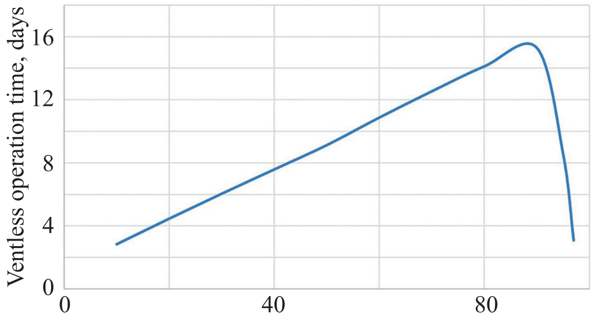

Fig. 2. Holding time under different filling conditions

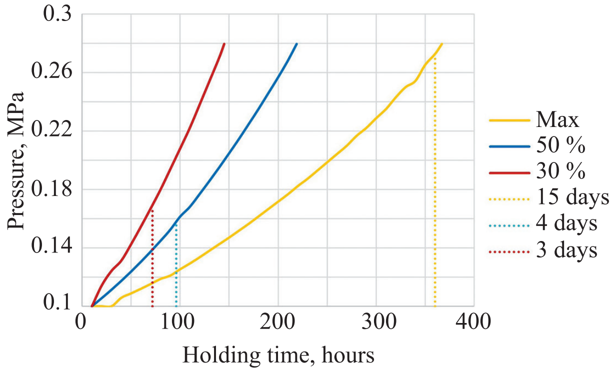

Fig. 3. Pressure build-up under different filling conditions

Table. Parameters of CCS

Step	Tank Volume, V, m^3	Total Volume, V_{total}, m^3	Wall thickness, *Wall*, mm	Insulation thickness, *Ins*, mm	*MAWP*, MPa	Holding time, days	
						Fl, %	Ventless operation time, days
1	1769.1	7076.5	31.94	300	0.34	91.8	24.46
						50	19.12
						30	12.87
2	1826.6	7306.5	29.43	200	0.29	92.8	17.46
						50	11.50
						30	7.62
3	1880.8	7523.4	25.43	100	0.25	93.6	6.46
						50	5.17
						30	3.33
4	1837.7	7350.8	27.68	180	0.28	93	16.17
						50	10.17
						30	6.75
5	1845.9	7383.9	27.16	165	0.27	93.2	15.29
						50	9.12
						30	6.04

used for northern delivery in North-Eastern Siberia. Main dimensions of this vessel are *L* — 141 m, *B* — 16,92 m, *H* — 6,3 m, L_h — 100 m, *Draft* — 3,5 m[1].

For the initial cycle of tank modeling, volume of a tank is set as 1200 m^3. Initial insulation thickness is set as 300 mm.

To obtain thermodynamic properties of liquid methane and its vapor, CoolProp wrapper for Python was utilized. All parts of the algorithm were realized with Python programming.

Initial conditions for modeling are: LNG temperature is 110 K and vapor temperature is 112 K. Before loading, LNG tank is cooled with methane vapor and after loading of LNG its vapor is slightly overheated. Environment temperature is 290 K.

Partially loaded tank conditions were analyzed. Longest trip with 50 % filling is 4 days. Longest trip with 30 % filling is 3 days.

After the modeling, the preferable tank shape appeared to be bi-lobe one. Maximal filling level is 93.2 %. All iterations of calculated CCS are presented in Table.

After modeling, it was investigated that optimal design is tank with insulation thickness of 165 mm. Fig. 3 shows pressure build-up inside the tank under different filling conditions of the tank after last iteration.

With presented method, on the first iteration total volume of LNG carried by vessel is 7076.5 m^3. After volume optimization this number was increased to 7383.8 m^3. Extra 307.3 m^3 generate additional positive economic effect on whole vessel project.

Conclusion

This paper presented new method of type-C LNG tank modeling. Proposed method is easy to use and it may be

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[1] Project RSD62. Dry-cargo vessel of river and mixed (river-sea) with a deadweight of 5640 tons URL: https://www.meb.com.ua/dry/RSD62.html (accessed: 12.10.2022).

completely automated. New method is not only suitable for new vessel projects but also for reconstruction and modernization projects. Optimization is based on the maximal usage of allowable space in vessel's hull and a close approximation of draft of fully loaded vessel up to maximum allowable draft on the waterway. Heat insulation is modeled to match minimum requirement of holding time according to IGC code, but also specific regimes of future exploitation were taken into account. With modeling of specific partially filling conditions of "milk-run" logistics, drainless operation mode on whole route of LNG distribution is preserved. This specific modeling prevents BOG discharge into the environment and economic losses due to loss of cargo.

References

1. Lee S., Seo Y., Lee J., Chang D. Economic evaluation of pressurized LNG supply chain. *Journal of Natural Gas Science and Engineering*, 2016, vol. 33, pp. 405–418. https://doi.org/10.1016/j.jngse.2016.05.039
2. Knizhnikov A.Yu., Klimentiev A.Yu. Perspective and opportunities of usage of LNG in arctic regions of Russia. *Conference WWF View Russia*, 2018, Moscow.
3. Ivanov L.V., Baranov A.Yu. Analysis of technical and logistic solutions used in the inland transportation by small-scale LNG carriers. *Gas Industry*, 2021, no. 4(815), pp. 80–86. (in Russian)
4. Budiyanto M.A., Pamitran A.S., Yusman T. Optimization of the route of distribution of LNG using small scale LNG carrier: a case study of a gas power plant in the Sumatra region, Indonesia. *International Journal of Energy Economics and Policy*, 2019, vol. 9, no 6, pp. 179–187. https://doi.org/10.32479/ijeep.8103
5. Budiyanto M.A., Riadi A., Sumanta Buana I.G.N., Kurnita G. Study on the LNG distribution to mobile power plants utilizing small-scale LNG carriers. *Heliyon*, 2020, vol. 6, no. 7, pp. e04538. https://doi.org/10.1016/j.heliyon.2020.e04538
6. Strantzali E., Aravossis K., Livanos G.A., Nikoloudis Ch. "A decision support approach for evaluating liquefied natural gas supply options: Implementation on Greek case study". *Journal of Cleaner Production*, 2019, vol. 222, pp. 414–423. https://doi.org/10.1016/j.jclepro.2019.03.031
7. Kalajdžić M., Bobić D. Unconventional inland LNG carrier design for the river Danube. *Proc. of the 23th Symposium on Theory and Practice of Shipbuilding SORTA*, 2018, pp. 426–443.
8. Huerta F., Vesovic V. A realistic vapour phase heat transfer model for the weathering of LNG stored in large tanks. *Energy*, 2019, vol. 174, pp. 280–291. https://doi.org/10.1016/j.energy.2019.02.174
9. Wang Y., Yun Y., Chen M., Lim Y. Numerical prediction research on the evaporation rate of liquid cargo tank for LNG Filling Vessel Based on Ansys. *Proc. of the 5th International Conference on Measurement, Instrumentation and Automation (ICMIA 2016)*, 2016. https://doi.org/10.2991/icmia-16.2016.96
10. Lee D.-H., Cha S.-J., Kim J.-D., Kim J.-H., Kim S.-K., Lee J.-M. Practical prediction of the boil-off rate of independent-type storage tanks. *Journal of Marine Science and Engineering*, 2021, vol. 9, no. 1, pp. 36. https://doi.org/10.3390/jmse9010036
11. Ferrín J.L., Pérez-Pérez L.J. Numerical simulation of natural convection and boil-off in a small size pressurized LNG storage tank. *Computers and Chemical Engineering*, 2020, vol. 138, pp. 106840. https://doi.org/10.1016/j.compchemeng.2020.106840
12. Jo Y., Shin K., Hwang S. Development of dynamic simulation model of LNG tank and its operational strategy. *Energy*, 2021, vol. 223, pp. 120060. https://doi.org/10.1016/j.energy.2021.120060
13. Ivanov L.V., Baranov A.Yu., Malysheva T.A., Andreev A.M. Selection of cryogenic tanks for modernization of small-scale LNG carriers. *Journal of International Academy of Refrigeration*, 2021, no. 1, pp. 40–45. (in Russian). https://doi.org/10.17586/1606-4313-2021-20-1-40-45
14. Salarkia M., Golabi S., Amirsalari B. Optimum design of liquified natural gas Bi-lobe tanks using finite element, genetic algorithm and neural network. *Journal of Applied and Computational Mechanics*, 2020, vol. 6, no. 4, pp. 862–877. https://doi.org/10.22055/JACM.2019.14801
15. Sparks L.L. *Thermal conductivity of polyurethane foam from 95 to 340 K*. National Bureau of Standards, Boulder, Colorado, USA, 1982. Available at: https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir82-1664.pdf (accessed: 10.12.2021).

Литература

1. Lee S., Seo Y., Lee J., Chang D. Economic evaluation of pressurized LNG supply chain // Journal of Natural Gas Science and Engineering. 2016. V. 33. P. 405–418. https://doi.org/10.1016/j.jngse.2016.05.039
2. Knizhnikov A.Yu., Klimentiev A.Yu. Perspective and opportunities of usage of LNG in arctic regions of Russia // Conference WWF View Russia, Feb. 2018, Moscow.
3. Иванов Л.Е., Баранов А.Ю. Анализ технических и логистических решений, применяемых при транспорте спг малотоннажными газовозами // Газовая промышленность. 2021. № 4(815). С. 80–86.
4. Budiyanto M.A., Pamitran A.S., Yusman T. Optimization of the route of distribution of LNG using small scale LNG carrier: a case study of a gas power plant in the Sumatra region, Indonesia // International Journal of Energy Economics and Policy. 2019. V. 9. N 6. P. 179–187. https://doi.org/10.32479/ijeep.8103
5. Budiyanto M.A., Riadi A., Sumanta Buana I.G.N., Kurnita G. Study on the LNG distribution to mobile power plants utilizing small-scale LNG carriers // Heliyon. 2020. V. 6. N 7. P. e04538. https://doi.org/10.1016/j.heliyon.2020.e04538
6. Strantzali E., Aravossis K., Livanos G.A., Nikoloudis Ch. "A decision support approach for evaluating liquefied natural gas supply options: Implementation on Greek case study" // Journal of Cleaner Production. 2019. V. 222. P. 414–423. https://doi.org/10.1016/j.jclepro.2019.03.031
7. Kalajdžić M., Bobić D. Unconventional inland LNG carrier design for the river Danube // Proc. of the 23th Symposium on Theory and Practice of Shipbuilding SORTA. 2018. P. 426–443.
8. Huerta F., Vesovic V. A realistic vapour phase heat transfer model for the weathering of LNG stored in large tanks // Energy. 2019. V. 174. P. 280–291. https://doi.org/10.1016/j.energy.2019.02.174
9. Wang Y., Yun Y., Chen M., Lim Y. Numerical prediction research on the evaporation rate of liquid cargo tank for LNG Filling Vessel Based on Ansys // Proc. of the 5th International Conference on Measurement, Instrumentation and Automation (ICMIA 2016). 2016. https://doi.org/10.2991/icmia-16.2016.96
10. Lee D.-H., Cha S.-J., Kim J.-D., Kim J.-H., Kim S.-K., Lee J.-M. Practical prediction of the boil-off rate of independent-type storage tanks // Journal of Marine Science and Engineering. 2021. V. 9. N 1. P. 36. https://doi.org/10.3390/jmse9010036
11. Ferrín J.L., Pérez-Pérez L.J. Numerical simulation of natural convection and boil-off in a small size pressurized LNG storage tank // Computers and Chemical Engineering. 2020. V. 138. P. 106840. https://doi.org/10.1016/j.compchemeng.2020.106840
12. Jo Y., Shin K., Hwang S. Development of dynamic simulation model of LNG tank and its operational strategy // Energy. 2021. V. 223. P. 120060. https://doi.org/10.1016/j.energy.2021.120060
13. Иванов Л.В., Баранов А.Ю., Малышева Т.А., Андреев А.М. Методика подбора криогенных резервуаров для модернизации проектов малотоннажных судов // Вестник Международной академии холода. 2021. № 1. С. 40–45. https://doi.org/10.17586/1606-4313-2021-20-1-40-45
14. Salarkia M., Golabi S., Amirsalari B. Optimum design of liquified natural gas Bi-lobe tanks using finite element, genetic algorithm and neural network // Journal of Applied and Computational Mechanics. 2020. V. 6. N 4. P. 862–877. https://doi.org/10.22055/JACM.2019.14801
15. Sparks L.L. Thermal conductivity of polyurethane foam from 95 to 340 K. National Bureau of Standards, Boulder, Colorado, USA, 1982 [Электронный ресурс]. URL: https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir82-1664.pdf (дата обращения: 10.12.2021).

16. Arkharov A.M., Arkharov I.A., Belyakov V.P. et. al. *Cryogenic Systems. In 2 vol. V. 2. Fundamentals of Designing Devices, Installations and Systems*. Moscow, Mashinostroenie Publ., 1999, 720 p. (in Russian)

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16. Архаров А.М., Архаров И.А., Беляков В.П. и др. Криогенные системы. В 2 т. Т. 2. Основы проектирования аппаратов, установок и систем: учебное пособие. М.: Машиностроение, 1999. 720 с.

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