TRANSPORT AND STORAGE OF LNG IN CONTAINER TANKS

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Abstract

The work presents issues with the structure and thermal calculations of mobile tank for transport and storage of LNG. A modern design of cryogenic tank container and stationery cryogenic tank is presented in the paper. Mobile cryogenics container tank has been designed for transportation of LNG as well as other liquefied cryogenic gases with the temperature down to –196°C. The analysis included two types of logistics solutions: one involving the transport full container, which is removable from the vehicle and left in the workplace, and the second solution with reloading from mobile tank into simplified container tank or other mobile tank located in the workplace. Simplified container tank and mobile tank have been designed to storage some cryogenics gases as well as mobile container but without transportation of them. Modern and effective insulation materials were applied in the tank structure. Therefore, the liquefied cryogenic gases can be stored for a long time periods. Presented are selected depending on the extent of heat exchange in cryogenic conditions, as well as a model for FEM calculations of thermal insulation inside the tank and supports. Simulation results show the long storage times obtained for a simplified container which are close to the times obtained by stationary tanks, however a lot easier to transport without charge. Presented solutions and results of simulations may indicate, that depending on the requirements and considering manufacturing costs and operational conditions, the proper variant of the tank can be chosen.

Keywords: *LNG, transport, container tank, stationery tank, cryogenic tank, simulation*

1. Introduction

In this paper a problem of mobile tank containers construction has been considered. The tanks are designed mainly for usage in the LNG supply stations. The tanks can be used for storing the liquefied natural gas for several weeks and then they are refuelled again. Storing of gas in liquefied form is an advantageous option, because it is strongly condensed and occupies volume approximately 660 times less than in gaseous form under the normal conditions. Nowadays, the LNG becomes more and more popular fuel in areas as:

- gas supplying of small villages and places which cannot be connected to the gas piping,
- satisfying short-term, culminating demands for gas, during 1 to 4 months of the year (i.e. the winter period),
- supplying of gas consumers temporarily cut off from the gas piping (i.e. due to repairs or maintenance of the piping),
- supplying final LNG consumers as an alternative for gas delivered by conventional piping. This is the method of gas delivery diversification which guarantees the energy independence,
- supplying the LNG car filling stations [7, 10].

The local LNG supply station consists of the cryogenic tank and the vaporising installation. The main cost of the local station is a cryogenic tank. The tank is usually built with two walls and the suitable layers of insulation with the purpose of obtaining the highest level of thermal insulation efficiency. Inner tank and piping are made of the stainless steel. Therefore, usage of the cryogenic tank has significant contribution in operating costs. Essentially, in local LNG supply stations two types of tanks can be used: stationary ones and mobile ones. Mobile tanks can have form of a standard ISO TC 104 container adapted for both road and rail transport with the load.

The second option is a free-style construction, which only fulfils requirements applied to limiting outline dimensions in road or rail transport. European regulations allow transporting containers which have transverse dimensions of 2438 mm x 2591 mm, while the tank transported as a common load can have transverse dimensions 3000 mm x 3000 mm. So, assuming the same length of a mobile tank, a larger capacity can be obtained. Therefore, construction of a mobile tank gives an opportunity to use wider range of tank dimensions, what can be used to obtain better operating parameters.

Keeping in mind foregoing considerations, four design versions of cryogenic tanks were developed and simulations of the variants were carried out. The types include various tank diameters and operating pressures 7 and 12 bar:

- type I – tank installed in a standard ISO TC 104 container frame (Fig. 1) with the parameters: outer tank diameter D=2350 mm, length L=5946 mm, volume V=19 m3 and operating pressure p=7 bar,
- type II – tank constructed as variant I, with decreased dimensions of inner supports for the sake of assumption, that only empty tank can be transported,
- type III – tank with the outer diameter D=3000 mm and length L=6058 mm, what gives the volume V=32 m3; operating pressure p=7 bar (Fig. 2),
- type IV – tank as in variant III, but operating pressure increased to 12.5 bar (Fig. 2).

2. The design of the tank type I and II

Tank models of variants I and II are shown in Fig. 1 Stainless steel tank 1, in which the cryogenic fluid is stored, is mounted by means of supports 2 of insulating material in the outer shielding tank 3, made of carbon steel. In the space between the tanks there is a multi-layer insulation material 4 with the radiation shields 5. The air has been removed from the space between the tanks 6 in order to obtain a medium-level vacuum. The tank with fittings is placed on external supports 7 in container frame 8. Container frame and the outer tank, together with other construction elements must have sufficient strength to meet the requirements of road rail and marine transportation in this case.

LNG storage container of type II has a structure similar to the mobile tank container I. However, some changes had to be made due to the possibility of omitting computational cases connected with the movement with the load. After carrying out the strength analysis, shapes of the supports have been modified. The supports have been narrowed in the middle part. Besides, the number of supports in the upper part of the tank has been reduced of half. The construction gives the possibility of transporting the empty tank using the container – transportation devices.

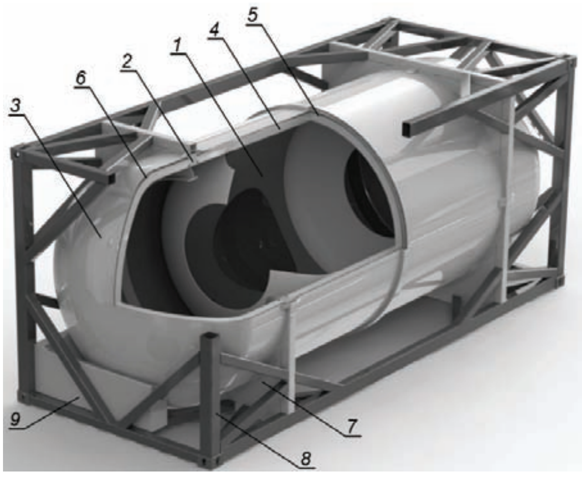

Fig. 1. Model of the LNG tank container for LNG transportation and storage, tank type I and II : 1 – inner tank, 2 – inner supports made of plastic materials, 3 – outer tank, , 4 – insulation, 5 – radiation shields, 6 – the vacuum, 7 – outer supports, 8 – container frame, 9 – fittings

3. The design of the mobile tank built for type III i IV

For this comparison, also included a mobile tank with a design similar to the tank container, but devoid of container frames and mountings. By omitting the limitations of container it was possible to increase the capacity of the tank. In the design process of the tank, the ability to road transport was taken into account. View of the mobile tank is shown in Fig. 2.

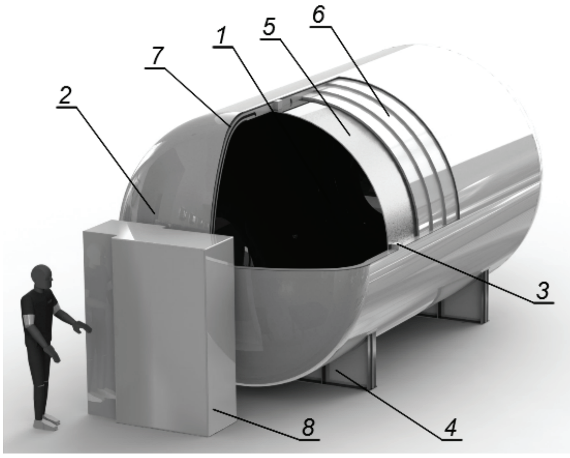

Fig. 2. Model of the mobile LNG, tank type III and IV: 1 – inner tank, 2 – outer tank, 3 – inner supports made of plastic materials, 4 – outer supports, 5 – insulation, 6 – radiation shields, 7 – the vacuum, 8 – fittings

4. Heat transfer to the tank

Due to the large temperature differences between the medium and the environment, the heat transfer to the tank may occur in three ways: by conduction, by convection and by radiation. Using the theory of heat transition can be determined by these methods.

4.1. Heat transfer by the conduction

The heat conduction in designed tank occurs through walls of tank, supports, pipe fittings and other elements connected with the tank. For LNG tanks, temperature difference between transported liquid and outer environment can be 200 K or even more, under particular conditions. In this case, the heat conduction process can be described as one-dimensional problem under steady-state conditions [2, 3, 9]. This process can be described by the Fourier equation:

$$q = -\lambda \cdot grad(T), \qquad (1)$$

where:
q - elementary heat flux [W/m^2],
λ - thermal conductivity [W/(m K)],
$grad(T) = \partial T / \partial n$ - derivative of temperature in direction n – perpendicular to isothermal surface.

Thermal conductivity under cryogenic conditions strongly depends upon the temperature. Therefore, this dependence must be taken into consideration during computations.

4.2. Heat transfer by the convection

Convection in LNG tank, under cryogenic conditions does not differ from convection in higher temperatures. Process of heat transmission from wall of tank to liquid gas can be computed on the base of the Newton's equation [2, 3, 9]:

$$Q = \alpha \cdot F \cdot (T_s - T_f), \qquad (2)$$

where:
α - heat transfer coefficient [W/(m^{2}K)],
F - area of solid body surface [m^2],
T_s - temperature of solid body surface [K],
T_f - – temperature of liquid [K].

Using of equation (2) requires value of heat transfer coefficient, which usually must be determined experimentally. Similarity numbers *Nu*, *Re*, *Pr* and other necessary for describing heat transfer by convection depend on thermal and transport properties of liquid. In particular, these properties are: thermal conductivity λ, viscosity μ, thermal capacity c, density ρ and others. Under cryogenic conditions, these properties strongly depend on the temperature. Therefore, the heat transfer coefficient α should also be a function of temperature

4.3. Heat transfer by the radiation

Heat radiation is a process which is present in every body with temperature higher than absolute zero. The heat flux transmitted by heat radiation between two bodies, which have temperatures T_1 and T_2 (assuming, that $T_1>T_2$) can be determined from the following equation [3, 9]:

$$q_r = \sigma \cdot \varepsilon' \cdot \left(T_1^4 - T_2^4\right), \tag{3}$$

where:
σ - a Stefan – Boltzmann constant ($\sigma = 5.67\ 10^{-8}$ W/m^{2}K^4),
ε' - a substitute emissivity of considered system,
T_1, T_2 - temperatures [K].

The heat radiation between two surfaces can be reduced by placing radiation shields between them. Shields will receive intermediate temperatures between T_1 and T_2. If radiation shield and surface of body which exchange the heat have the same emissivity, then amount of heat exchanged by radiation between surfaces with one shield is two times smaller than without the shield. Therefore, larger number of shields improves efficiency of radiation heat insulation. By the other hand, each radiation shield takes some place, so the number of shields must be limited. In the considered insulation of designed tank, three radiation shields have been applied.

4.4. Heat transfer by the residual gas

Obtaining a high-level vacuum (p << 0.1 Pa) is a time-consuming and expensive process for two-walled cryogenic tanks with fibrous insulation. Besides, the keeping of the vacuum on the high level can be difficult for the sake of outgassing materials of the tanks and insulation. The residual gas remaining at the space between tank walls conduct heat. In considered tanks, the heat transfer by radiation and by the residual gas conduction can be close to themselves, so this effect cannot be omitted.

In the first step of residual gas conduction modelling, a Knudsen number *Kn* was calculated. In considered construction $Kn \approx 1$, what indicates, that the residual gas cannot be modelled as a continuous medium. Therefore, the Corruccini formula has been used [9]:

$$q_{gr} = \frac{\gamma + 1}{\gamma - 1} a \left(\frac{R}{8\pi M T_p}\right)^{\frac{1}{2}} p(T_2 - T_1), \tag{4}$$

where:

$$\gamma = c_p / c_V, \tag{5}$$

$$a = \frac{a_1 a_2}{a_2 + a_1(1 - a_2) A_1 / A_2}, \tag{6}$$

where:

c_p - specific heat of air at constant pressure [J/(kg K)],
c_v - specific heat of air at constant volume [J/(kg K)],
α_1, α_2 - heat transfer coefficients for the surface of the inner tank and the outer tank,
A_1, A_2 - area of inner tank walls and outer tank walls [m^2],
R - gas constant [J/(mol K)],
M - molar mass of the residual gas [kg/mol],
T_p - temperature in the pressure measurement point (on the outer tank) [K],
p - pressure of the residual gas [Pa],
T_2, T_1 - temperature of outer wall of inner tank and outer shield of inner tank insulation [K].

5. Modelling of the heat insulation

With the purpose of estimation usability of insulation materials in LNG tank containers construction, several types of insulations have been selected for simulation research. The simulations consisted in determination of average heat fluxes to the LNG from the environment [1, 4, 5]. An insulation based on aerogel (trade name cryo-lite) has been chosen for analysis [5].

FEM calculations were carried out using the SolidWorks Simulation program. The following assumptions were made: the model is in the thermal equilibrium, heat resistance of the inner tank wall is omitted as negligible in comparison to insulation materials. Radiation shields were placed between layers of insulation. Heat transfer in the vacuum space was considered only by the radiation. Emissivity coefficients of the surfaces were assumed as dependent on type and temperature of the particular surface. Moreover, heat transfer between the outer surface of the tank and the environment proceeds only by convection with known, constant coefficient. The inner tank was placed inside the outer one using system of plastic supports. Thermal contact resistance was defined on the contact surfaces between supports and tanks. The coefficient values were assigned on the basis of the own tank model investigations [3, 12-14]. According to EN 12213 standard, a 50% filling ratio and +15°C degrees of ambient temperature were assigned. A solid model was used for FEM calculations in SolidWorks Simulation.

As a result of the analysis, distributions of temperature and heat flux were obtained. Fig. 3 and 4 show the distribution of heat flux on the external tank respectively for variant construction for tank types I and II and in Fig. 5 and 6 for the tank types III and IV. As it arise from the obtained results, the highest value of heat flux occurs at the site of the inner supports. Temperature distributions for tank type II on Fig. 7 and on Fig. 8 for type IV were shown.

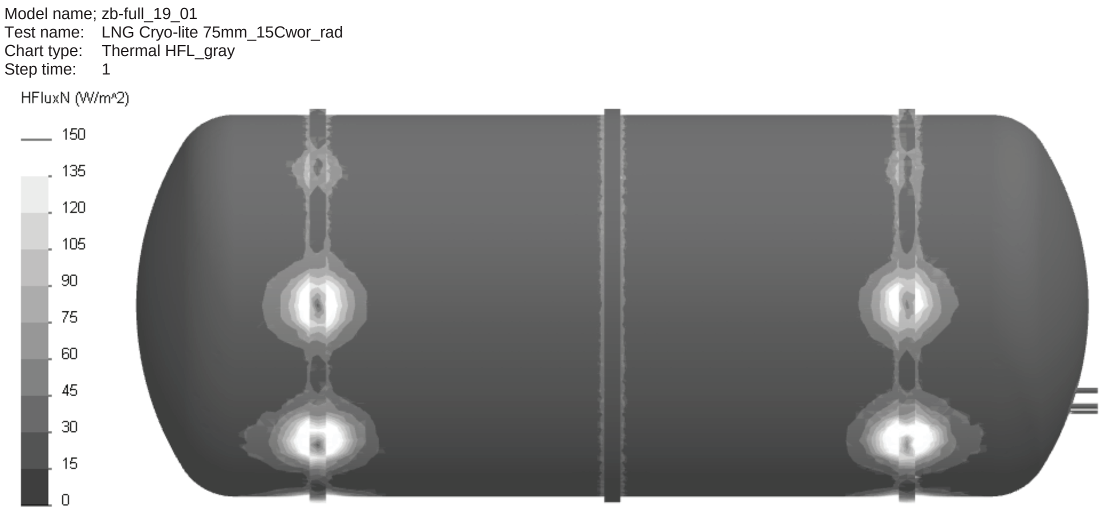

Fig. 3. Heat flux on outer surface of container tank type I

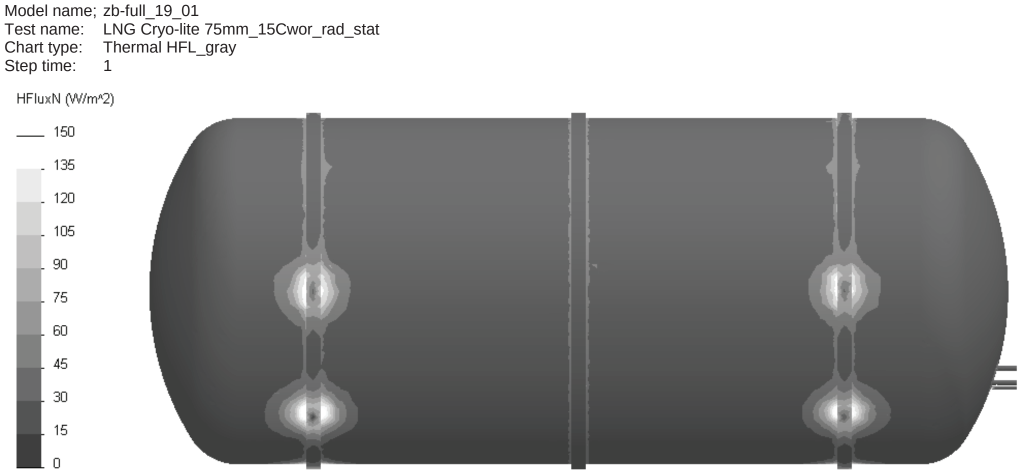

Fig. 4. Heat flux on outer surface of simplified container tank type II

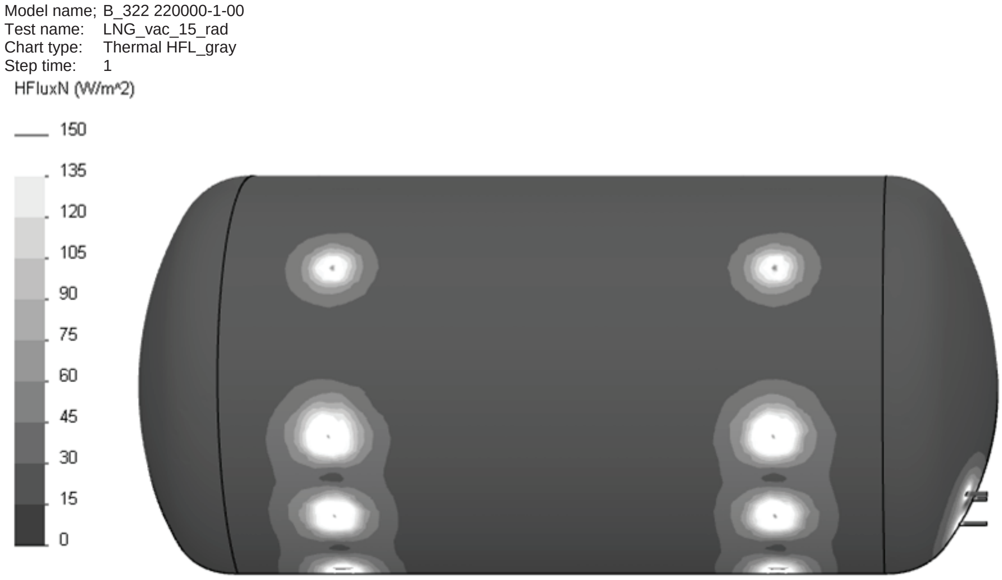

Fig. 5. Heat flux on outer surface of stationery tank type III

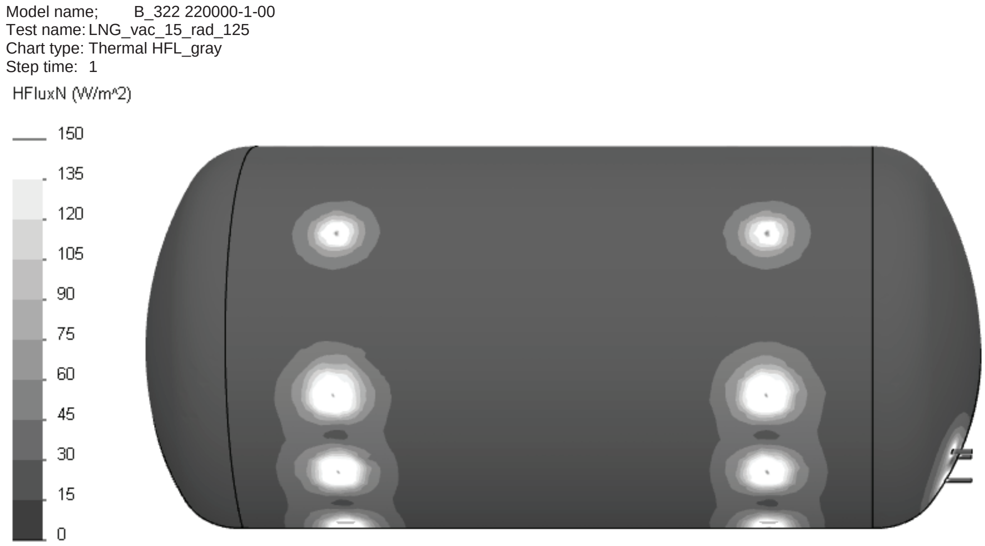

Fig. 6. Heat flux on outer surface of stationery tank type IV

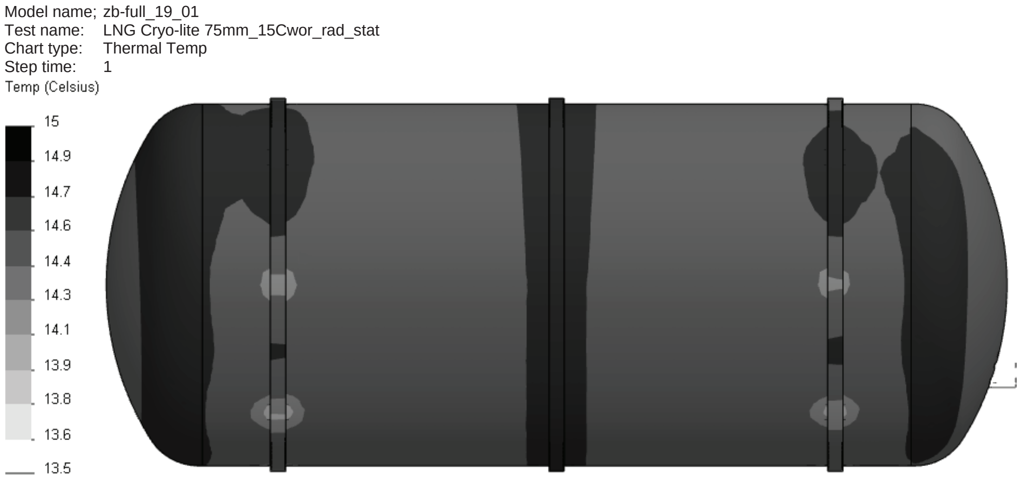

Fig. 7. Temperature distribution on outer surface of stationery tank type II

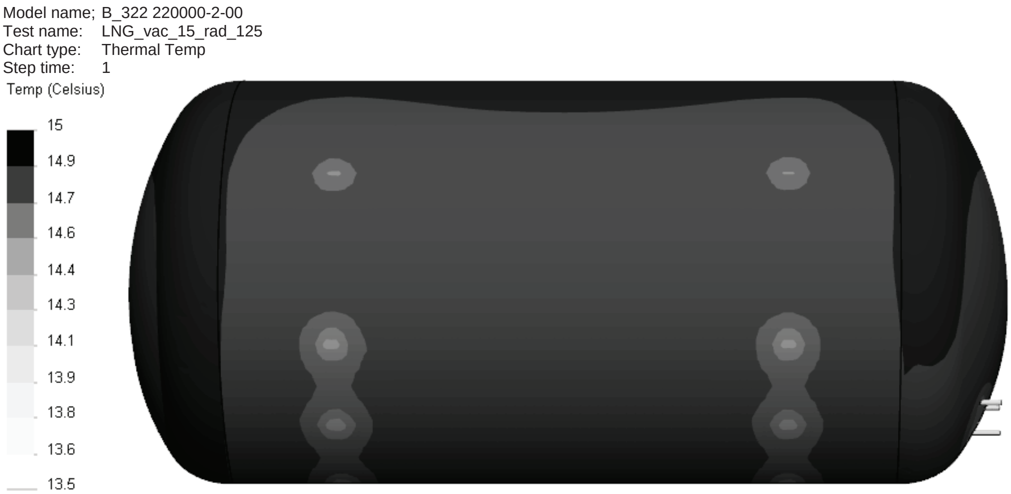

Fig. 8. Temperature distribution on outer surface of stationery tank type IV

Comparison of the results of investigations was made using the EN 12213 methodology. With the help of FEM models, an average heat flux on the outer surfaces of the tank was calculated. Using FEM models was obtained the average heat flux on the external surfaces of tanks. Comparison of the average heat fluxes on the outer surfaces of considered tanks is presented in Fig. 9.

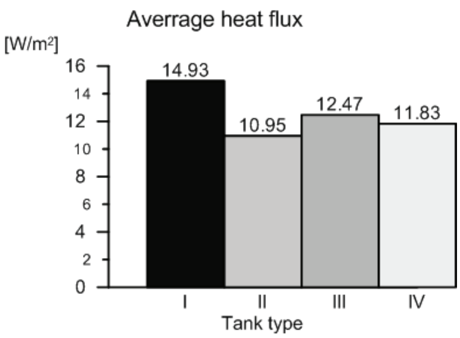

Fig. 9. Comparison of the average heat fluxes of the different tank types

The heat leakage was calculated using the formula [8]:

$$L = \frac{86400 \cdot Q_c \cdot A}{h \cdot F}, \tag{7}$$

where:
Q_c - average heat flux on outer surface of the tank [W/m^2],
A - area of outer surface of the tank [m^2],
h - latent heat of vaporization [J/kg],
F - total mass of LNG in the tank [kg].

On the basis of the percentage heat leakage, a number of the days to empty the tank were determined. Values of the percentage heat leakage and storage time in days of considered tank types are summarized in Fig. 10.

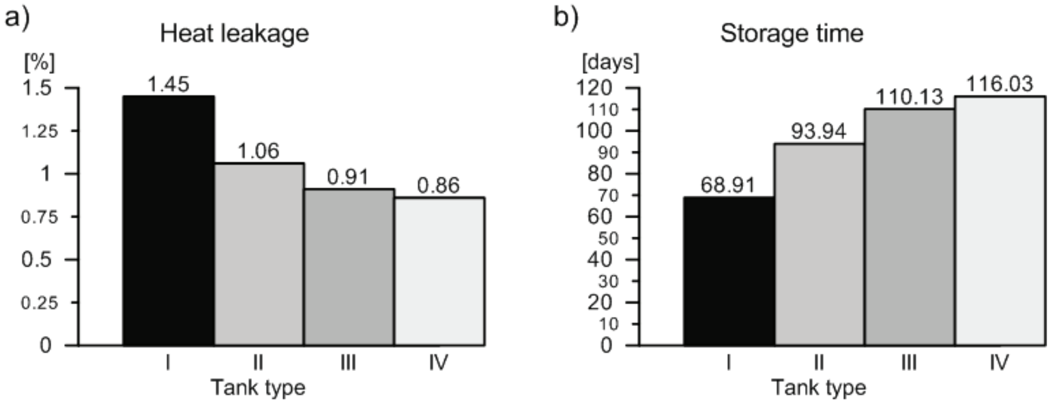

Fig. 10. Comparison of the heat leakages (a) and storage time in days (b) of considered tank versions

As it arises from Fig. 9, the lowest value of average heat flux was obtained for tank type II. The largest heat flux was obtained for LNG 1 tank container, what is obvious because the construction had to fulfil increased strength requirements.

Comparison of heat leakages and connected with it storing time leads to the slightly different conclusions. The longest storing times (Fig 10b) was obtained for tank variants III and IV. This comes from their larger capacity. The tank variant II obtained considerably longer storing time than tank container I, but shorter than variants III and IV.

6. Summary

In the paper is presented simulation research of four design variants of tank containers. The tanks are assigned for movable LNG supply stations. The first variant consisted in using the standard solution of a road and rail transportable container. This variant allows transporting the tank container filled up with the LNG. The remaining three versions of tanks can be transported only empty.

Presented solutions and results of simulations indicate, that depending on the requirements and considering building costs and operational conditions, the proper variant of the tank can be chosen. It arises from the analysis, that tank which is installed in the container frame and fulfils the requirements of both road and rail transport in the filled up state has considerably worse thermal properties than mobile tanks destined for transportation in the empty state only.

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