MODELING OF THERMAL AND MASS TRANSFER PROCESSES IN STORAGE OF LIQUEFIED NATURAL GAS IN THE CLOSED VOLUME

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We need to study the phenomenon of «rollover» for secure storage in the tanks of liquefied natural gas. This phenomenon occurs during the mixing and vaporization of the product layers. To study this phenomenon in an article the mathematical model of heat and mass transfer between the layers of liquefied natural gas.

Keywords: liquefied natural gas, storage, reservoir, equipment, stratification, rollover, heat and mass transfer processes, temperature, pressure, density

Introduction

Modern experience in the operation of engineering facilities intended for the storage of liquefied natural gas (LNG) presents special requirements for existing technical and technological storage complexes (TTCS), which includes both fixed tanks installed on specially prepared bases and equipment intended for storage of liquefied natural gas Their filling and shipping, as well as equipment ensuring the safety of storage of LNG.

It should be noted that one of the main technological problems in the operation of such storage facilities is the occurrence in them of the phenomenon of fluid stratification, which can lead to damage to the tank farm, the cost of which is about 50% of the cost of all TTCs [1, 2]. This situation is explained by the fact that the storage of LNG in the tank is characterized by the following features:

- the presence in the storage of the product in the liquid and gaseous phases;

- the dependence of the mass ratio of the product in the gaseous and liquid phases on the temperatures and, respectively, the gaseous and liquid phases, and the pressure of the gaseous phase;

- the invariability of the total mass of the stored product in the form of components from the gaseous and liquid phases that do not enter into a chemical reaction with each other;

- multicomponent nature of LNG with different physicochemical characteristics (see table 1).

Table 1 Multicomponent composition of liquefied natural gas.

Gas	Formula	Molar mass,G / mol	$T_{boiling}$, °C	Volumetric shares In LNG
Methane	CH_4	16,04	-161,58	0,92
Ethane	C_2H_6	30,07	-88,6	0,04
Propane	C_3H_8	44,1	-42,09	0,025
Nitrogen	N_2	14,01	-195,8	0,015

The operation of engineering facilities in the oil and gas industry places special demands on the observance of thermal regimes when storing liquefied natural gas (LNG) in tanks. Thus, the safe operation of stationary tanks during storage of LNG has a significant impact [1, 2]:

1) the composition and temperature stabilization of the product during its filling, storage and emptying;

2) technical and technological characteristics and design features of storage facilities;

3) compliance with special requirements in the case of long-term storage of the product, as well as when filling a new lot in the tank, the physical parameters of which differ from those already available in the LNG storage.

In the process of loading a new batch of LNG, which, as a rule, has a higher density, a lower layer is formed in the tank, and a top layer is formed from the stored product with a lower density. In this case, these LNG layers are not mixed, that is, the phenomenon of stratification occurs. Such a state of LNG in a non-isolated closed reservoir is represented as the following complex technical system "reservoir - liquid phase (lower layer) - liquid phase (upper layer) - gaseous phase" (see Figure 1).
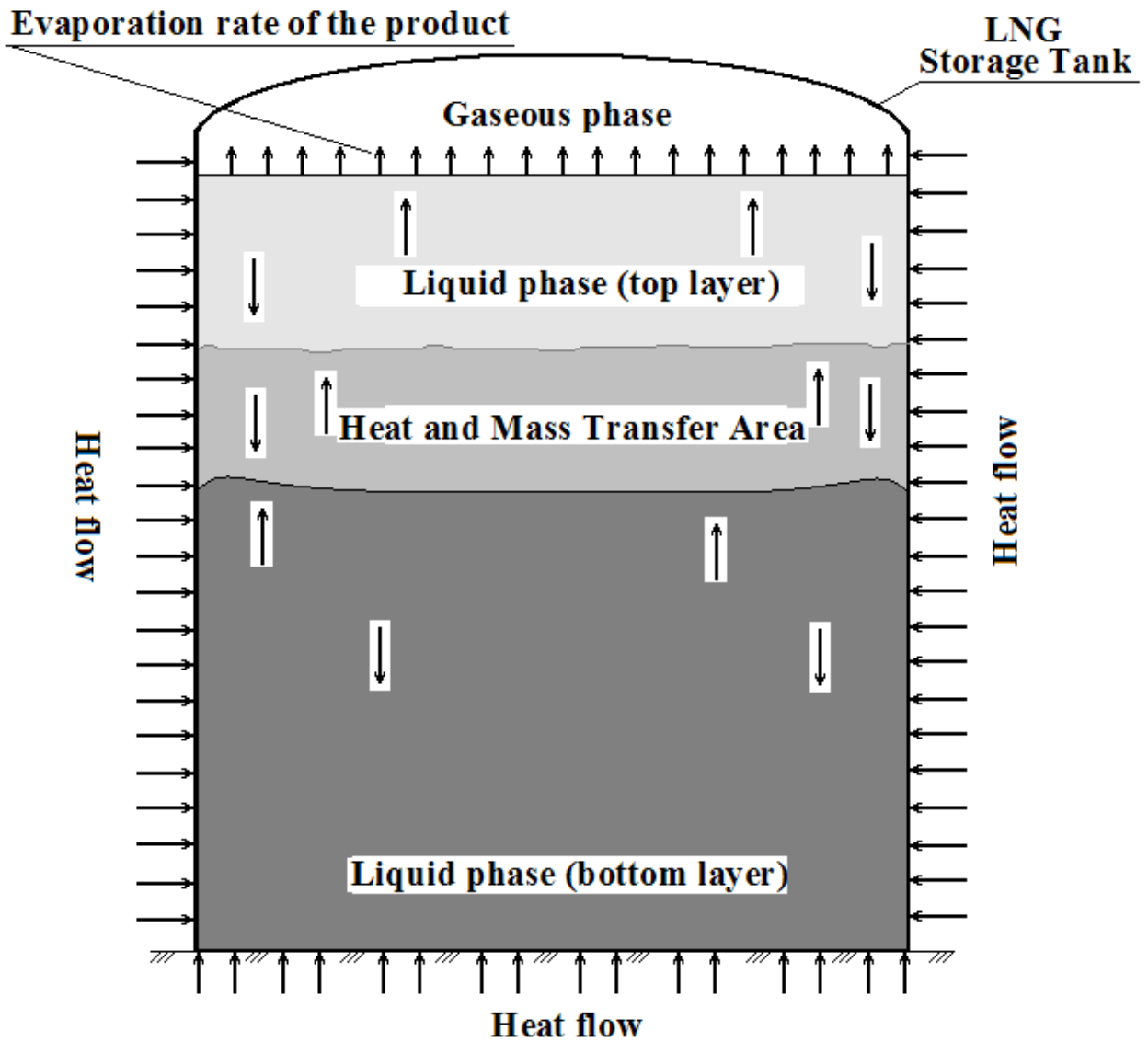
Figure 1 Closed non-isolated system "reservoir - liquid phase of natural gas - gaseous phase of natural gas"

As a result of the transfer of heat from the external environment through the walls and bottom of the tank, the two liquid and gaseous phases of the product stored in it are unevenly heated. At the same time, as a result of heat and mass transfer, mixing of the layers is accompanied by intensive evaporation of the product with a significant increase in the pressure in the reservoir, which can lead to its damage. This phenomenon was called the "rollover" and has not been studied sufficiently to date. Taking

into account the foregoing, it should be noted that for various input parameters for modeling a complex technical system, "reservoir-liquid phase (lower layer)-liquid phase (upper layer) -gas phase", it is possible to predict the time of "rollover" and possible vaporization to prevent damage to the storage, As well as to identify technological and constructive ways to solve this problem [3].

To model these processes, we will create a system of equations that form:

includes the equations of continuity, balance of forces and conservation of energy, taking into account the temporary storage factor for LNG [4, 5, 6].

Accounting for the continuity factor of the stored product

The system of equations of continuity (conservation of mass) for a product consisting of N components that do not enter into a chemical reaction with each other is suggested to be written in the

$$
\begin{cases}
\dfrac{\partial M_{A,1}}{\partial t} + \dfrac{\partial M_{L,1}}{\partial t} = 0 \\[2mm]
\dfrac{\partial M_{A,2}}{\partial t} + \dfrac{\partial M_{L,2}}{\partial t} = 0 \\[2mm]
\ldots\ldots \\[2mm]
\dfrac{\partial M_{A,i}}{\partial t} + \dfrac{\partial M_{L,i}}{\partial t} = 0 \quad , \\[2mm]
\ldots\ldots \\[2mm]
\dfrac{\partial M_{A,N}}{\partial t} + \dfrac{\partial M_{L,N}}{\partial t} = 0
\end{cases}
\tag{1}
$$

where $M_{A,i}$ is the mass of the gaseous phase of the i-th component of the stored product;

$M_{L,i}$ – mass of the liquid phase of the i-th component of the stored product;

i - component number, varying from 1 to;

N - the number of components included in the LNG;

t – time.

And the mass M of the entire stored product will be equal to

$$
M = \sum_{i=1}^{N} M_{A,i}(t) + \sum_{i=1}^{N} M_{L,i}(t).
\tag{2}
$$

The mass $M_{ph,i}$ of the phase of the i-th component of the stored product can be calculated as

$$M_{ph,i}(t) = \int\limits_{(V_{ph})} m_{ph,i}(t)\,dV_{ph} = \int\limits_{(V_{ph})} r_{ph,i}(t)\,dV_{ph,i}\,dV_{ph} \,, \tag{3}$$

where $m_{ph,i}$ is the local mass of the phase of the i-th component;

$r_{ph,i}$ - local phase density of the i-th component;

V_{ph} - the volume occupied by the phase of the stored product.

$dV_{ph,i}$ - the elementary volume occupied by the phase of the i-th component of the stored product and determined by the formula:

$$dV_{ph,i} = C_{ph,i} \times dV_{ph} \,, \tag{4}$$

where $C_{ph,i}$ is the volume concentration of the phase of the i-th component of the stored product;

dV_{ph} - the elementary volume occupied by the phase of the stored product.

To describe the C in the concentration of the stored product component (diffusion processes) it is proposed to use the second Fick law for an inhomogeneous medium and the diffusion coefficient $D = f(x,y,z)$, which is a function of the coordinate:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial C}{\partial z}\right) = div(D \times grad C) \tag{5}$$

At that

$$\sum_{i=1}^{N} C_{ph,i} = 1 \tag{6}$$

and

$$V_{ph} = \sum dV_{ph} \,. \tag{7}$$

The change in the local density of the gaseous phase of the *i*-th component of the stored product in a given volume over time will be determined by the equation:

$$\frac{\partial r_{A,i}}{\partial t} = \frac{\partial r_{A,i}(p_A, T_A)}{\partial t} + \frac{\partial r_{A,i}(u_A)}{\partial t} + \frac{\partial r_{A,i}(L \hat{U} A)}{\partial t}, \tag{8}$$

where $\dfrac{\partial r_{A,i}(p_A, T_A)}{\partial t}$ - change in the local density $r_{A,i}$ of the gaseous phase of the i-th component of the stored product in a given volume over time due to changes in its temperature T and pressure p;

$\dfrac{\partial r_{A,i}(u_A)}{\partial t}$ - Change in the local density $r_{A,i}$ of the gaseous phase of the i-th component of the stored product in a given volume over time due to mechanical transfer of the substance;

$\dfrac{\partial r_{A,i}(L \hat{U} A)}{\partial t}$ - Change in the local density $r_{A,i}$ of the gaseous phase of the i-th component of the stored product in a given volume over time due to the "liquid-gas" phase transition;

To describe the behavior of a real gas, it is proposed to use the equation:

$$p_A = Z(\overline{p}, \overline{T}) r_A R T_A, \tag{9}$$

where p_A is the gas pressure;

r_A - density of gas;

R - gas constant of real gas;

T_A - gas temperature;

$Z(\overline{p}, \overline{T})$ - compressibility factor.

In turn, the gas constant of a real R gas is:

$$R = \frac{R_0}{m}, \tag{10}$$

where R_0 is the universal gas constant;

$\overline{T}$ - is the molar mass of the gas.

The compressibility factor $\overline{p}$ is proposed to be calculated by the approximation formula [6]:

$$\overline{p} = \frac{p}{p_{Kp}}, \tag{12}$$

where p_{Kp} is the critical pressure.

The temperature $\bar{T}$ is calculated by the formula:

$$\bar{T} = \frac{T}{T_{Kp}},\tag{13}$$

where T_{Kp} is the critical temperature.

The molar mass m and critical parameters p_{Kp} and T_{Kp} of the gas mixture are calculated from the following additive formulas:

$$\left|\begin{array}{l} m = \sum\limits_{i=1}^{N} C_{A,i} \times m_i \\[2mm] p_{Kp} = \sum\limits_{i=1}^{N} C_{Ai} \times p_{Kp,i} , \\[2mm] T_{Kp} = \sum\limits_{i=1}^{N} C_{A,i} \times T_{Kp,i} \end{array}\right.\tag{14}$$

where $C_{A,i}$ are the volumetric concentrations of the components constituting the gas mixture.

The dependence of the density of a real gas r_A on its temperature T_A and on its pressure P_A will have the form:

$$r_A = \frac{p_A}{Z(\bar{p},\bar{T})RT_A}.\tag{15}$$

To describe the effect of mechanical transfer of matter on its density ρ, it is proposed to use the dependence:

$$-\frac{\partial r}{\partial t} = r \times div\left(\vec{u}\right) + \vec{u} \times grad\left(r\right),\tag{16}$$

where $\vec{u}$ is the velocity vector of the substance.

To describe the phase transition of a substance, it is proposed to use the Clapeyron-Clausius equation [7]:

$$\frac{dp}{dT} = \frac{l\left(T\right)}{T\left(v_{ph2} - v_{ph1}\right)},\tag{17}$$

where v_{ph1} and v_{ph2} are the specific volumes of the initial and resulting phases, respectively;

$\lambda(T)$ - specific heat of phase transition;

T - temperature of the substance;

p - pressure.

In turn, the specific volume of the phase v_{ph} is calculated by the formula:

$$v_{ph} = \frac{1}{\rho_{ph}},\qquad(18)$$

where ρ_{ph} is the phase density.

We transform equation (17) with allowance for (18) with respect to the density ρ_{ph2} of the resulting phase, we have

$$\rho_{ph2} = \frac{\rho_{ph1}Tdp}{Tdp + \rho_{ph1}\lambda(T)dT}.\qquad(19)$$

Thus, taking into account equations (15), (16) and (19), equation (8) will have the following form:

$$\frac{\partial \rho_{A,i}}{\partial t} = \frac{\partial}{\partial t}\left(\frac{p_A}{Z(\bar{p},\bar{T})R_iT_A}\right) - \left(\rho_{A,i}\times div(\vec{u}_A) + \vec{u}_A \times grad(\rho_{A,i})\right) +$$
$$+ \frac{\partial}{\partial t}\left(\frac{\rho_{L,i}T_Adp_A}{T_Adp_A + \rho_{L,i}\lambda_i(T_A)dT_A}\right)\qquad(20)$$

The change in the local density $\rho_{L,i}$ of the liquid phase of the i-th component of the stored product in a given volume over time will be determined by the partial differential equation:

$$\frac{\partial \rho_{L,i}}{\partial t} = \frac{\partial \rho_{L,i}(u_L)}{\partial t} + \frac{\partial \rho_{L,i}(A\hat{U} L)}{\partial t},\qquad(21)$$

where $\dfrac{\P r_{L,i}(u_L)}{\P t}$ - change in the local density $r_{L,i}$ of the liquid phase of the i-th component of the stored product in a given volume over time due to mechanical transfer of the substance;

$\dfrac{\P r_{L,i}(A \hat{U} L)}{\P t}$ - change in the local density $r_{L,i}$ of the liquid phase of the i-th component of the stored product in a given volume over time due to the "gas-liquid" phase transition;

Taking into account equations (16) and (19), equation (21), which reflects the dependence of the change in the local density $r_{L,i}$ of the liquid phase of the i-th component of the stored product in a given volume over time will have the following form:

$$\frac{\P r_{L,i}}{\P t} = -\left(r_{L,i} \times div(\vec{u}_L) + \vec{u}_L \times grad(r_{L,i})\right) + \frac{\P}{\P t}\left(\frac{r_{A,i} T_L dp_L}{T_L dp_L + r_{A,i} l_i(T_L) dT_L}\right) \tag{22}$$

The distribution of the pressure $r_{L,x}$ of the liquid phase (see Figure 1) according to the depth x of the stored product, taking into account the location of the reference point of the coordinate system at the phase interface, is determined by the dependence:

$$p_{L,x} = p_{A,0} + \int_0^x r_L(x)g\,dx. \tag{23}$$

Accounting for the balance of forces for the liquid phases of matter in the system

For the formation of ideas about the motion of the layers of liquid phases of stored fuel, we use the Navier-Stokes equation to describe a viscous Newtonian fluid.

In vector form for an incompressible fluid, it has the form [8]:

$$\begin{cases} \dfrac{\P \vec{u}}{\P t} = -(\vec{u} \times \tilde{N})\vec{u} + n\Delta\vec{u} - \dfrac{1}{r}\tilde{N}p + \vec{f} \\ \tilde{N} \times \vec{u} = 0 \end{cases}, \tag{24}$$

where $\vec{u}$ is the velocity vector of the substance;

$\vec{f}$ - vector of mass forces;

n - is the coefficient of kinematic viscosity.

Thus, the equation of balance of forces along the OX axis for the liquid phase of the stored product can be written as:

$$r_L \frac{\P^2 x}{\P t^2} = r_L g - \frac{\P p_L}{\P x} + h_L \left(\frac{\P^2 u_{L,x}}{\P x^2} + \frac{\P^2 u_{L,x}}{\P y^2} + \frac{\P^2 u_{L,x}}{\P z^2} \right), \tag{25}$$

where r_L is the local density of the liquid phase of the product;

g – acceleration of gravity;

p_L – local static pressure of the liquid phase of the product;

h_L –coefficient of dynamic viscosity of the liquid phase;

$u_{L,x}$ – projection of the velocity vector of the liquid phase onto the OX axis.

The equation of balance of forces along the OY axis for the liquid phase of the stored product has the following form:

$$r_L \frac{\P^2 y}{\P t^2} = - \frac{\P p_L}{\P y} + h_L \left(\frac{\P^2 u_{L,y}}{\P x^2} + \frac{\P^2 u_{L,y}}{\P y^2} + \frac{\P^2 u_{L,y}}{\P z^2} \right). \tag{26}$$

The equation of balance of forces along the OZ axis for the liquid phase of the stored product has the following form:

$$r_L \frac{\P^2 z}{\P t^2} = - \frac{\P p_L}{\P z} + h_L \left(\frac{\P^2 u_{L,z}}{\P x^2} + \frac{\P^2 u_{L,z}}{\P y^2} + \frac{\P^2 u_{L,z}}{\P z^2} \right). \tag{27}$$

The local density of the product phase r_{ph} is:

$$r_{ph} = \sum_{i=1}^{N} r_{ph,i}. \tag{28}$$

In the case of a compressible medium in the form of a gaseous phase of the stored product (see Figure 1), the Navier-Stokes equation will have the following form (projection onto the OX axis):

$$\rho_A \frac{\partial^2 x}{\partial t^2} = \rho_A g - \frac{\partial p_A}{\partial x} + \frac{\partial}{\partial x}\left(2\eta_A \frac{\partial u_{A,x}}{\partial x} - \frac{2}{3}\eta_A \nabla \cdot \vec{u}_A\right) +$$

$$+ \frac{\partial}{\partial y}\left[\eta_A\left(\frac{\partial u_{A,x}}{\partial y} + \frac{\partial u_{A,y}}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\eta_A\left(\frac{\partial u_{A,x}}{\partial z} + \frac{\partial u_{A,z}}{\partial x}\right)\right], \tag{29}$$

where ρ_A is the local density of the gaseous phase of the product;

g - acceleration of gravity;

p_A - local pressure of the gaseous phase of the product;

η_A - coefficient of dynamic viscosity of the gaseous phase;

$u_{A,x}$, $u_{A,y}$, $u_{A,z}$ – respectively, the projection of the velocity vector of the gaseous phase onto the axis OX, OY and OZ.

The equation of the balance of forces along the OY axis for the gaseous phase has the following form:

$$\rho_A \frac{\partial^2 y}{\partial t^2} = - \frac{\partial p_A}{\partial y} + \frac{\partial}{\partial y}\left(2\eta_A \frac{\partial u_{A,y}}{\partial y} - \frac{2}{3}\eta_A \nabla \cdot \vec{u}_A\right) +$$

$$+ \frac{\partial}{\partial z}\left[\eta_A\left(\frac{\partial u_{A,y}}{\partial z} + \frac{\partial u_{A,z}}{\partial y}\right)\right] + \frac{\partial}{\partial x}\left[\eta_A\left(\frac{\partial u_{A,y}}{\partial x} + \frac{\partial u_{A,x}}{\partial y}\right)\right]. \tag{30}$$

The equation of the balance of forces along the OZ axis for the gaseous phase has the following form:

$$\rho_A \frac{\partial^2 z}{\partial t^2} = - \frac{\partial p_A}{\partial z} + \frac{\partial}{\partial z}\left(2\eta_A \frac{\partial u_{A,z}}{\partial z} - \frac{2}{3}\eta_A \nabla \cdot \vec{u}_A\right) +$$

$$+ \frac{\partial}{\partial x}\left[\eta_A\left(\frac{\partial u_{A,z}}{\partial x} + \frac{\partial u_{A,x}}{\partial z}\right)\right] + \frac{\partial}{\partial y}\left[\eta_A\left(\frac{\partial u_{A,z}}{\partial y} + \frac{\partial u_{A,y}}{\partial z}\right)\right]. \tag{31}$$

Accounting for energy conservation in the system

Due to the fact that the medium under study is near the phase transition point and its heat capacity can vary significantly, the energy conservation equation must be resolved through the enthalpy of the phases of the stored LNG. By the nature of interaction with the environment, the reservoir in the process of storing LNG in the general case is a closed, non-isolated system that exchanges only energy with the external environment. In accordance with the first law of thermodynamics, the energy dQ coming from the external environment into a closed system consisting of two phases is spent on changing the enthalpy dH_L of

the liquid phase and the enthalpy dH_A of the gaseous phase:

$$dQ = dH_L + dH_A.\tag{32}$$

For the case of stratification of the stored LNG into two horizontal layers, the change in the enthalpy of the liquid phase is proposed to be written in the form [5, 9]:

$$dH_L = \frac{\lambda\tilde{N}^2 T + div\left[(H_{L1} - H_{L2})\rho D\left(\tilde{N}m + k_T\dfrac{\tilde{N}T}{T} + k_p\dfrac{\tilde{N}p}{p}\right)\right]}{\rho}dt,\tag{33}$$

where λ is the coefficient of thermal conductivity;

T - temperature;

p - pressure;

H_{L1}, H_{L2} – the enthalpy of the lower and upper horizontal LNG layer, respectively;

ρ – average density of stored LNG;

D – the coefficient of mutual diffusion;

m – mass of stored LNG;

k_T - Thermodiffusion ratio;

k_p – Barodiffusion ratio.

The change in the enthalpy dH_A of the gaseous phase is proposed to be written in the form [9]:

$$dH_A = C_p(T)dT + V_A dp_A,\tag{34}$$

where $C_p(T)$ is the heat capacity of the gaseous phase at constant pressure.

The system of equations for the mathematical model of heat and mass transfer, taking into account the continuity factor of the stored product, the balance of forces for the liquid phases of the substance and the conservation of energy in a closed uninsulated system, "liquefied natural gas (LNG) - natural gas," made it possible to perform a preliminary assessment of the degree of influence of the thermal insulation resistance of the storage facility, Its shape and geometric dimensions, as well as the physical characteristics of the stored product for the time of onset of the rollover phenomenon.

In addition, the proposed mathematical model as a result of changes in the input parameters will

allow us to quantify the spatial distribution of temperature, both directly in the design of the reservoir, and in the surrounding ground space of its base. Preliminary data obtained during the solution of the test problem, confirmed the correctness of the proposed approach in describing the processes of heat and mass transfer when storing liquefied natural gas in a closed volume.

Figure 2 presents the results of numerical simulation of the effect of constant heat input through the side surface and bottom of the reservoir on the processes of heat and mass transfer in a closed uninsulated system "liquefied natural gas (LNG) - natural gas" containing a stratified liquid phase.
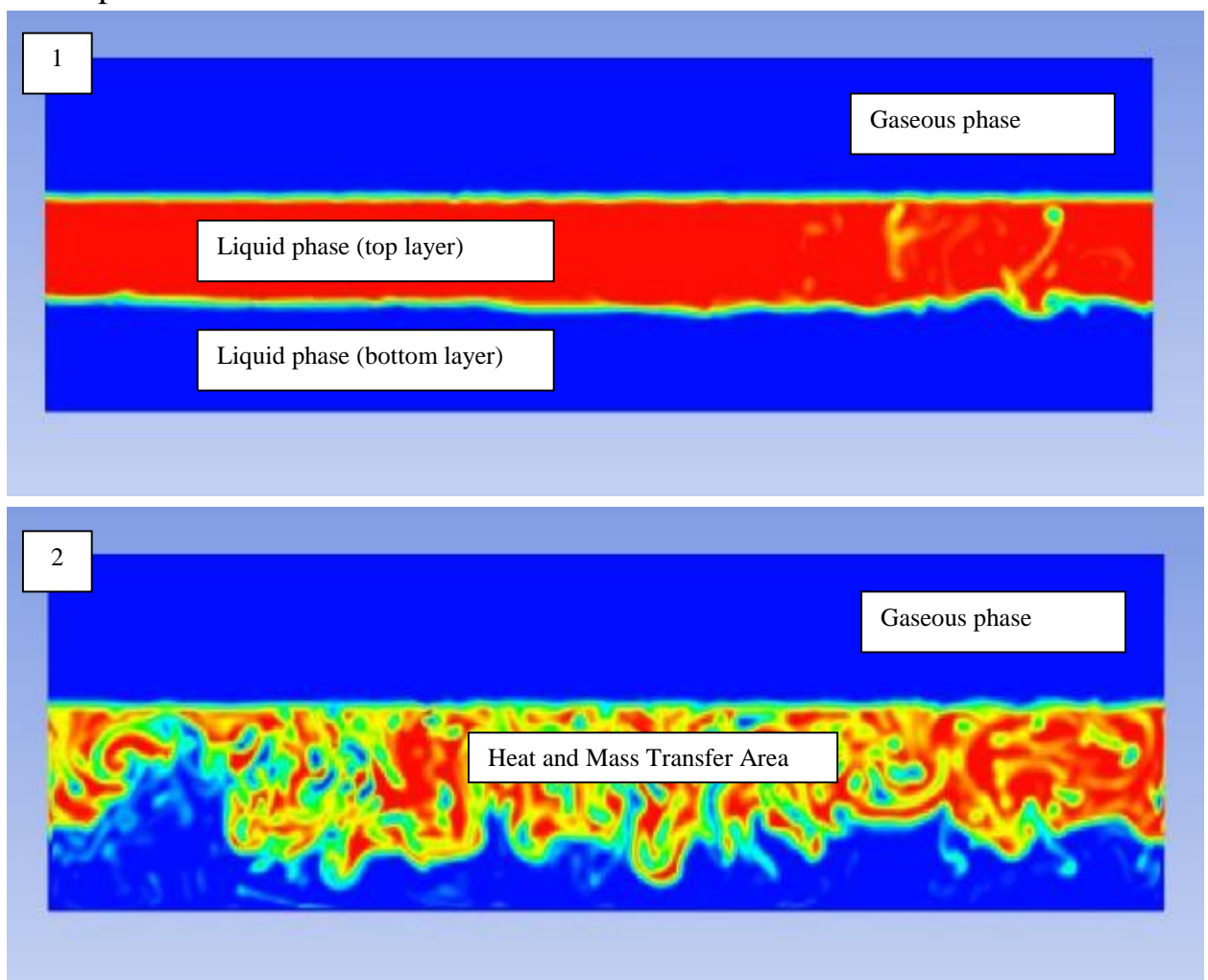

Figure 2 Simulation model of heat and mass transfer in the stratified liquid phase: 1 - initial phase of the process; 2-development of the heat and mass transfer process over time

The aim of the presented mathematical model of the closed non-isolated system "liquefied natural gas (LNG) - natural gas", describing heat and mass transfer during storage of liquefied natural gas, is the assessment of technical and technological parameters and characteristics of the product storage process and operation of engineering structures in the oil and gas industry.

To determine the degree of influence of the thermal resistance of the storage insulation, its shape and geometric dimensions, as well as the physical characteristics of the stored product at the time of the appearance of the rollover phenomenon, the dependence of the pressure distribution $r_{L,x}$ of the liquid phase on the depth of the stored product was established.

It is expected that rational choice of technological measures and design parameters of isothermal reservoirs based on numerical simulation data will allow to exclude both the risk of occurrence of the "rollover" phenomenon in LNG storage facilities and the probability of occurrence and development of critical stresses in their structures and loss of stability of the ground base.

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Түйін

Резервуарларда сұйытылған табиғи газдарды қауіпсіз сақтау үшін «ролловер» құбылысан зерттеу қажет. Бұл құбылыс өнім қабаттарының араласуы мен булану үрдісінде пайда болады. Мақалада сұйытылған табиғи газ жылу қабаттары және массаларының араласуының математикалық моделі құрылған.

Резюме

В закрытых резервуарах при нарушении теплового режима хранения сжиженного природного газа при интенсивном перемешивании слоёв продукта и его парообразовании возникает явление «ролловера». Для изучения особенностей этого явления и обеспечения безопасности инженерных объектов разработана математическая модель тепло- и массопереноса между слоями хранящегося сжиженного природного газа.