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NATURAL VENTILATION OF GAS SPACE IN RESERVOIR WITH INTERNAL FLOATING ROOF

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The article deals with safe operation issues of vertical steel reservoirs with an internal floating roof when storing volatile oil products. The purpose of the work is to study the influence of ventilation openings area and wind speed on the duration of explosive state of vertical reservoirs with an internal floating roof. The influence of ventilation pipes' dimensions and the wind speed on the duration of explosive state of the reservoir has been studied. Method for calculating this time is proposed. It is shown that natural ventilation of the reservoir gas space is caused by the effect of two forces, which are formed due to: 1) the density difference between the vapor-air mixture in the reservoir and outside air; 2) wind pressure occurring on the roof of the reservoir. An algorithm for calculating the duration of reservoir being in an explosive state with wind pressure and no wind is obtained. The greater the difference in geodetic marks of the central and peripheral nozzles, the more efficient the ventilation. This distance will be greatest if the lower ventilation pipes are located on the upper belt of the reservoir or the reservoir is equipped with an air drain. Increase in wind speed of more than 10 m/s does not significantly affect the duration of the reservoir being in an explosive state. Increasing the diameter of the central nozzle from 200 to 500 mm can significantly reduce the duration of the reservoir degassing in windless weather.

***Kew words*:** vertical steel reservoir with internal floating roof; explosive state of the reservoir; ventilation pipes; natural ventilation time

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Introduction. The vapor concentration of the oil product (combustible gases) in the gas space of the reservoir above the floating roof, which is highly efficient in reducing the loss of oil products from evaporation, is usually less than the lower concentration limit of flame propagation. According to the literature [1], the lower explosive limit for vapors of stock oil and gasoline ranges from 1 to 2 % by volume. According to the test conducted on the RVSP 10000 reservoir with the «Alpon» floating roof at «Ryazan» LPDS in July 2000, the concentration of oil vapor at two measurements was 0.88 and 0.76 % by mass. Similar results on reservoirs with a floating roof were obtained earlier [2, 8]. These reservoirs were equipped with ventilation pipes.

The feasibility of equipping reservoirs with floating roof by ventilation openings (nozzles) was shown in the Russian literature relatively long time ago [3]. The need for forced ventilation of reservoirs before repair work is considered in [4, 6, 7].

We first carried out measurements of oil vapors concentration on reservoirs with a floating roof equipped with ventilation openings at «Starolikeevo» LPDS in December 2002. Gas samples for analysis were taken one by one from the windward and leeward sides, two samples from the middle surface of the reservoir. The concentration of oil vapor was: the windward side – 420 mg/m^3, the leeward side – 500 mg/m^3, the median plane – from 450 to 500 mg/m^3. This is significantly less than the lower concentration limit of explosiveness. Analogous measurements of oil vapor concentration were also carried out in reservoir N 2 with a floating roof ZHBR 10000 at the «Sheskharis» oil depot of «Transneft». The reservoir was equipped with 18 nozzles around the perimeter and two – at the zenith of the dome. The experiment was carried out in December at an oil temperature of 13 °C and an air temperature of 9 °C. The oil vapor concentration was 116-690 mg/m^3. All these measurements were carried out on reservoirs with brand new technically working floating roofs in the usual technological mode of operation, without landing the roof on the support struts.

An explosive concentration of combustible vapors in a reservor with a floating roof can form when an empty oil reservoir is filled with oil products (oil, gasoline), which was operated with the residue before, as well as during long-term storage of hydrocarbons in summer conditions. The reasons for the formation of explosive concentrations in reservoirs with floating roof and ventilated above-roof space are described in more detail in the literature [5].

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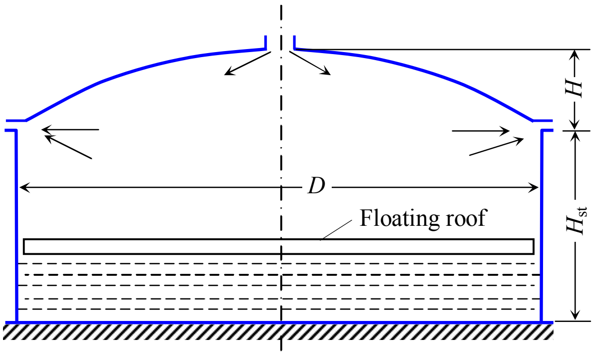

Fig.1. Gas space ventilation scheme of reservoir with internal floating roof

To confirm this, consider an example. Reservoir RVSP 10000, $D = 34.2$ m; saturated oil vapor pressure (GOST 1756-2000) $P_S = 350$ mm Hg., the temperature in the reservoir is 20 °C. At this temperature, saturated oil vapor pressure will be 275 mm Hg. The reservoir stood with the residue of the gasoline with a height of no more than 300 mm, the floating roof was at 2 m, the roof valve was open. The volume of gas space above the roof is 10500 m^3. Under the floating roof there will be a saturated air-vapor mixture of 1600 m^3. This volume will contain 460 m^3 of oil product vapor. The concentration of oil product vapors under the floating roof is at least 29 %. The environment is flammable, but not explosive. Upon the subsequent filling of this reservoir, the vapors of the oil product will be transferred to the above-roof space and the concentration of the oil product vapors above the roof will be at least 4.4 %. This is an explosive concentration, the gas space must be ventilated.

According to GOST 12.1.044-89, one of the ways to prevent explosive hazards in the reservoir is to eliminate the possibility of the combustible medium formation. For the lower concentration limit, this condition

$$\varphi_{\text{g.bez}} \leq 0{,}9(\varphi_n - 0{,}7R), \tag{1}$$

where φ_n – lower concentration limit of flame propagation through a mixture of combustible gas with air; R – reproducibility of the method for determining the fire hazard index with a confidence level of 95 %. For the lower limit, this value should not exceed 0.3 % by volume.

GOST 31385-16 provides for mandatory ventilation of the gas space of the reservoir with a floating roof through the nozzles. The total cross-sectional area of the pipes must be greater than or equal to 0.06 D (in squared meters), where D is the diameter of the reservoir. Nozzles should be located evenly around the perimeter at a distance of no more than 10 m from each other and one in the center (Fig. 1).

These requirements are borrowed from the US standard API Std 650-13, and the calculations were not experimentally verified in the conditions of Russia. In API Standard Std 650-13, the area of the central hole is 0.032 m^2, which corresponds to a circular hole 200 mm in diameter. In GOST 31385-16 there is no requirement for a central hole. A small cross section area of the central nozzle indicates that the API Std 650-13 standard does not take into account ventilation due to the difference in density between the air-vapor mixture and air (due to gravity). GOST 31385-16 also does not attach any importance to this. In the absence of wind, the only source of ventilation is the difference in the density of the vapor-air mixture and air.

The purpose of the work is to study the influence of ventilation openings area and wind speed on the duration of explosive state of vertical reservoirs with an internal floating roof.

To achieve this goal, the following tasks were set and solved:

– analysis of the existing system of natural ventilation of reservoirs with floating roof gas space, adopted by GOST 31385-16;

– estimation by calculation methods of the explosive periods duration in the reservoirs with floating roof gas space in the process of natural ventilation, which occurs under the action of the density difference between the vapor-air mixture and air and under the action of wind pressure on the roof of the reservoir.

Mathematical model of the ventilation process of reservoirs with floating roof gas space. Figure 1 shows the ventilation scheme due to the difference in the density of the vapor-air mixture and air. Heavier vapor-air mixture exits through the lower nozzles, air enters through the upper.

As the air enters the reservoir, the concentration of combustible gas decreases and may be below lower concentration limit of flame propagation. Therefore, to maintain the explosion-proof concentration, the gas exchange rate should be as large as possible. Gas exchange in the reservoir

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occurs (here the filling and emptying of the reservoir are not considered) due to the difference in density of the vapor-air mixture and air and due to wind pressure, as well as during thermal expansion and compression of gas (lesser breathing).

The flow of gases from the reservoir through the nozzles during ventilation due to the difference in density of the vapor-air mixture and air is determined by the formula

$$q_o = \mu S_c \sqrt{2gH \frac{C(\rho_o - \rho_a)}{\rho_o C + (1-C)\rho_a}}, \qquad (2)$$

where μ – flow coefficient, $\mu = 0,62$; S_c – cross-sectional area of the central nozzle, m^2; ρ_o, ρ_a – vapor density of oil and air, kg/m^3; H – nozzle height difference, m; C – oil product vapor concentration, units.

Under the effect of wind on the reservoir on the windward side of the roof, the greatest negative wind pressure (vacuum) is observed, the smallest – on the leeward side. Gas will be coming out from the windward side. Depending on the ratio of wind pressures on the windward and leeward sides, gas can flow out or air can enter through the central nozzle.

Gas flow due to wind pressure occurring on the dome roof of the reservoir is determined by the formula

$$q_w = \mu S_{noz} \sqrt{2gH_w}, \qquad (3)$$

where H_w – pressure head from wind pressure, m; $H_w = P/\gamma_a$; P – wind pressure, N/m^2; γ_a – air specific weight, N/m^3; S_{noz} – the total cross-sectional area of the peripheral nozzles through which gas is released or air enters (they are equal in size, since the reservoir is «atmospheric»), m^2.

The total area of peripheral nozzles is an order of magnitude larger than the central one; therefore, the consumption of the vapor-air mixture under the action of wind pressure through the central nozzle is practically absent. Perhaps for this reason, in API 650-13, the area of the central hole is so small.

Wind pressure is determined according to SP 43.13330-10

$$P = P_0 k(z) c, \qquad (4)$$

where P_0 – standard wind pressure, N/m^2; $k(z)$ – coefficient taking into account the change in wind pressure in height, for reservoirs with a height of 20 m can be taken equal to 0.85; c – aerodynamic coefficient; for reservoirs at $f/D = 0,2$; where D – diameter, f – dome height. Following values of c are received: windward side $c = -0,95$; leeward side $c = -0,3$; along the middle plane of the reservoir, perpendicular to the wind direction, including in the center of the roof $c = -0,75$.

These data show that negative wind pressure forms on the entire surface of the dome roof. At first glance, gas should flow out through all nozzles. This is contrary to the principle: how much gas is released, the same amount of air must enter as the reservoir is «atmospheric». This means that air will enter through some nozzles. Such are the nozzles located in the zone of lower absolute pressure. With this in mind, the wind pressure for the calculation of ventilation

$$H_w = (P_{ww} - P_{lw}) / \gamma_a, \qquad (5)$$

where P_{ww}, P_{lw} – wind pressure on the windward and leeward side of the dome roof of the reservoir, N/m^2.

During ventilation, due to the difference in density of the vapor-air mixture and air, air enters through the central nozzle, its area is specified. However, under the action of wind pressure, the total area of the pipes through which air enters (the vapor-air mixture goes out) depends on the wind pressure on the entire roof area. Since the exact distribution of wind pressure over the entire roof is very difficult to determine, in the first approximation it can be assumed that the cross-sectional area of the pipes through which air enters is equal to the area through which the vapor-air mixture goes out.

Consider the volume of the gas mixture in the reservoir with a concentration of combustible gases $C_0 = V$. Gas exits through the vent pipe with the flow rate Q and the concentration of combustible gases C (variable, varies from C_0 to zero).

During time period $d\tau$, amount of air $Qd\tau$ enters the reservoir, and $QCd\tau$ of vapor or combustible gases is displaced. At the same time, the vapors of the oil product exit through the leaks of the gate into the over-floating roof space. The volume of such vapors can be determined by the equation

$$\frac{dV_o}{d\tau} = kL(C_S - C)(P_a/\gamma_o), \tag{6}$$

where k – coefficient taking into account the sealing degree of the gate, m/h; L – the length of the sealing gate, m; P_a – atmospheric pressure, N/m^2; γ_o – specific weight of oil product vapors, N/m^3; C_S – vapor concentration at saturation level, units; C – vapor concentration in gas space, units.

According to American data for external floating roofs, $k = (0.6 – 1.0)\ 10^{-5}$ m/h.

According to SP 43.13330-10 and SNiP 2.09.03-85, $k = 1 \cdot 10^{-5}$ m/h.

For modern internal floating roofs' gates there are no experimental data on this coefficient; therefore, in the calculations data for floating roofs are used. For the reservoir RVSP 20000 (L = = 125 m) at $C_S = 0.4$; $C = 0.01$, using formula (6), $V = 1.8$ m^3, or about 5 kg of vapors per hour. This value is small compared with the volume of vapors located in the above-floating roof space, therefore it can be neglected.

The change in the volume of combustible gas in the reservoir in the process of natural ventilation will be

$$\frac{VdC}{\lambda} = Qd\tau - QCd\tau - kL(C_S - C)\frac{P_a}{\gamma_o}d\tau, \tag{7}$$

where $Q = q_o + q_w$ – total gas flow through the nozzles.

The air entering the reservoir mixes with the gas not instantaneously, but gradually, therefore, the coefficient λ is introduced: it takes into account the uneven mixing of gases with the incoming air. With instantaneous mixing, $\lambda = 1$, which is not possible in practice, therefore, this coefficient is usually less than one.

From (7) a differential equation with separable variables is obtained:

$$d\tau = \frac{VdC}{\lambda\left[Q(1-C) - kL(C_S - C)\frac{P_a}{\gamma_o}\right]}. \tag{8}$$

Since $Q = q_o + q_w$, a differential equation describing the course of a change in the concentration of combustible gases (vapors) in the gas space of the reservoir during the ventilation process is obtained:

$$d\tau = \frac{VdC}{\lambda\mu\left[S_c\sqrt{2gH\frac{C(\rho_o - \rho_a)}{\rho_o C + \rho_a(1-C)}} + S_{noz}\sqrt{2gH_w}\right](1-C) - kL(C_S - C)\frac{P_a}{\gamma_o}}. \tag{9}$$

Integrating this equation in time from 0 to τ, concentration from C_0 to C, the value of the time length during which the concentration of combustible gases decreases from C to the lower concentration limit of flame propagation is obtained, for example, $C_0 = 0.01$ (1 %):

$$\tau = \int_{C_0}^{C} \frac{VdC}{\lambda\mu\left[S_c\sqrt{2gH\frac{C(\rho_o - \rho_a)}{\rho_o C + \rho_a(1-C)}} + S_{noz}\sqrt{2\,gH_w}\right](1-C) - kL(C_S - C)\frac{P_a}{\gamma_o}}. \tag{10}$$

Results and discussion. The results of calculations by the formula (10) are shown in Fig.2. Figure 2, *a* presents calculation results of the vertical steel reservoir RVSP 20000 m^3 degassing time,

D = 39.9 m with the following parameters: $\lambda = 0.3$; $\mu = 0.62$; $C_S = 0.4$; $L = 125$ m; $\rho_o = 2.75$ kg/m^3; $\rho_a = 1.25$ kg/m^3; $P_a = 10^5$ N/m^2; $g = 9.81$ m/s^2; $C = 0.08$; $C_0 = 0.01$; S_c=0,283 m^2 (diameter 500 mm). It is seen that when the diameter of the central nozzle is 200 mm (according to GOST 31385-16) and the height difference between the nozzles is up to 10 m, the time the reservoir is in an explosive state is not less than 60 h.

Increasing the diameter of the central nozzle from 200 to 500 mm reduces the time the reservoir is in an explosive state, in the absence of wind in our example, to 9.8 h (more than 6 times).

The duration of the reservoir degassing with the same parameters at wind speed of up to 15 m/s and different cross-section areas of the lower nozzles (Fig.2, *b*) was considered. It has been established that the presence of wind significantly reduces the duration of the reservoir degassing. So, with a total cross-section area of the lower pipes equal to 0.036 D and a wind speed of 10 m/s, the duration of reservoir being in an explosive state in our example does not exceed 1.08 h, and at a wind speed of 15 m/s – 0.88 h (curve 1). An increase in the total cross-sectional area of the lower nozzles to 0.06 D (curve 2) and a wind speed of 10 m/s, the duration of a reservoir in an explosive state does not exceed 0.63 h, and at v = 15 m/s – 0.51 h.

An air drain with a width of 50 mm in the area of the connection between the dome and the reservoir wall makes it possible to shorten the duration of a reservoir being in an explosive state up to 0.19 h (curve 3).

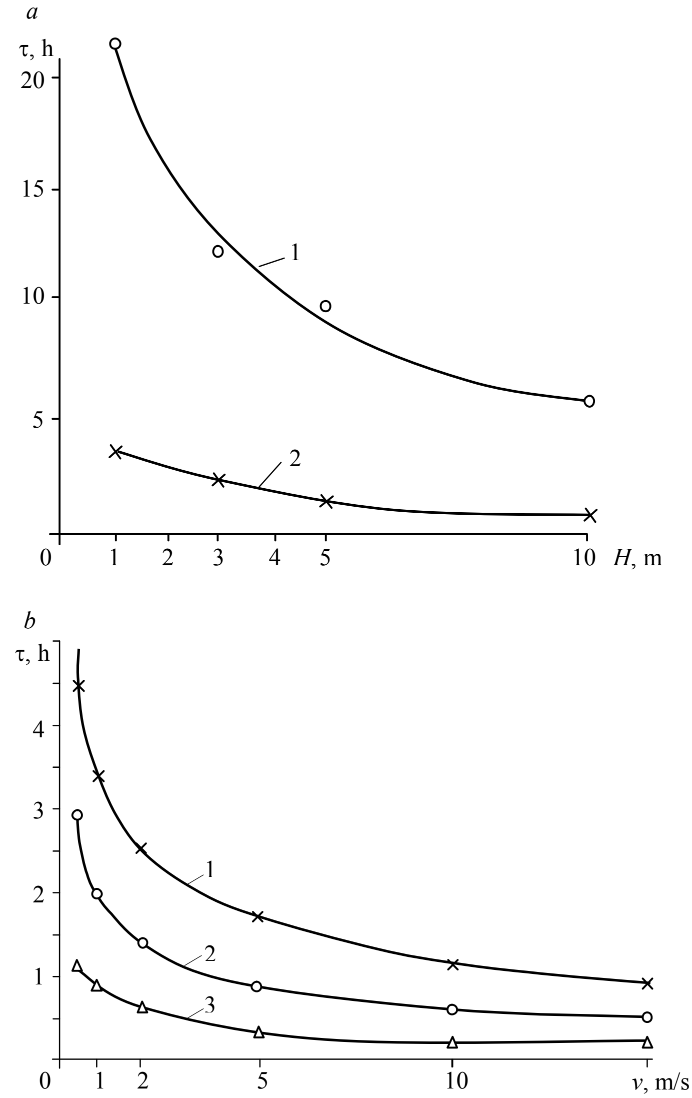

Fig.2. The dependence of the time the reservoir being in an explosive state: *a* – on the diameter of the central nozzle and the difference in the heights of the vent nozzles at a wind speed equal to zero (1 – S = 0.032 m^2 (d = 200 mm); 2 – S = 0.196 m^2 (d = 500 mm)); *b* – on wind speed and cross section area of ventilation pipes (1 – S_1 = 0.196 m^2 (d = 500 mm); 2 – S_2 = 0.283 m^2 (d = 600 mm); 3 – air drain with a width of 50 mm)

Since 2000, more than 60 vertical steel reservoirs with an internal floating roof and a dome roof of aluminum alloys, equipped with air drains from 50 to 100 mm wide, have been built in Russia. The experience of operating such reservoirs showed their high fire safety. In addition, the removal of the ventilation pipes from the surface of the dome roof of the reservoir significantly reduces the snow retention effect.

Conclusion

1. Natural ventilation of the reservoir gas space is caused by the action of two forces generated due to:

– the difference in density of the vapor-air mixture in the reservoir and the outside air;

– wind pressure occurring on the roof of the reservoir.

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2. An algorithm has been obtained for calculating the duration of a reservoir being in an explosive state at wind pressure, as well as in the absence of wind.

3. The greater the difference in geodetic marks of the central and peripheral nozzles, the more efficient the ventilation. This distance will be greatest if the lower ventilation pipes are located on the upper belt of the reservoir or the reservoir is equipped with an air drain.

4. An increase in wind speed (more than 10 m/s) does not significantly affect the duration of a reservoir being in an explosive state.

5. Increasing the diameter of the central nozzle from 200 to 500 mm can significantly reduce the duration of tank degassing in windless weather.

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