Evaluation of Explosive Safety Parameters for Stationary Roofs of Vertical Steel Tanks

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Abstract. The article is devoted to a current problem of the need to increase the explosive safety of tanks. The paper analyzes the causes of explosions in tanks. Constructive solutions of existing stationary tank roofs are analyzed, including with an easily removable sheathing. The required areas of loss of containment of the tank roof are calculated depending on the type of flammable liquid. The dependence of the level of filling the oil product in the tank on the excess pressure during the explosion has been determined. Criteria and requirements have been developed for fixed roofs with easily removable sheathing.

1. Introduction

The central place in tank farms is occupied by metal tanks, among which the most common are vertical steel tanks [1, 2, 3]. At these facilities, all the necessary rules for maintaining safety are observed, but nevertheless, sometimes it is simply impossible to avoid a disaster.

The number of accidents associated with tanks is growing every year due to the depletion of their design resources. The depreciation rate of existing vertical steel tanks reaches 60-80%.

Of the total number of fires and accidents, 93.3% occurred at ground storage tanks. If we consider the causes of fires by types of stored products, then:

- 32.4% - vertical steel tank (VST) for storing crude oil;
- 53.8% - vertical steel tank for storing gasoline;
- 13.8% - vertical steel tank with other types of petroleum products (kerosene, diesel fuel, etc.) [4].

Sources of fires can be hot work, ignition of pyrophoric sediments, sparks from electrical installations, static electricity discharges, etc. In different industries, the share of fires from the listed sources is different.
The existing methods for fire safety of tanks and tank farms are not able to completely prevent the occurrence of accidents. This fact suggests that the problem exists and new or improved methods and designs are needed to maintain fire safety.

An urgent problem is also to maintain the stability of an already burning tank to prevent the transfer of combustion to nearby objects, because this could lead to even greater disaster.

In the event of a fire, an explosion of the tank may follow, which may lead to the complete or partial destruction of the exploded tank due to the impact of the shock wave, as well as the destruction of tanks and nearby structures in the event of the scattering of structural elements of the emergency tank.

2. Design characteristics of the device

One way to protect tanks explosions can be prevented by the use of a roof with an easily removable flooring. According to [5], safe (without destruction of the tank shell) discharge of excess internal overpressure, including in the event of a fire in neighboring tanks, is possible by creating a “weak node” connecting the fixed roof sheathing with the tank wall.

The “weak knot” of the roof sheathing-to-wall connection should allow partial or complete separation of the roof sheathing from the external support assembly and rapid release of excess pressure.

In [5,6], the requirements are given that the diameter of the tank should be at least 15 m, while the angle of inclination of the radial beams should not exceed 9.46°. However, there is also a requirement that for frameless conical roofs, the angle of inclination should be in the range from 15 to 30°. The radius of curvature of the roof should vary from 0.7D to 1.2D. That is, the radius of curvature of the roof varies in the range of 24.6° ≤ αc ≤ 45.58°, regardless of the tank diameter. This means that frameless conical and domed roofs cannot be fitted with an easy drop sheathing. The same applies to frame domed roofs, where the radius of curvature of the roof is 0.7D ≤ R ≤ 1.5D and minimum αc = 19.47°, regardless of the diameter of the tank. Then only the frame conical roofs remain, recommended for tanks with a diameter of 10 ≤ D ≤ 30 m, which can be equipped with an easily drop sheathing, since the angle of inclination of the roof generatrix to the horizontal surface is not specified for them.

This design of the tank roof makes it possible to limit the magnitude of the explosion pressure in the tank due to the release of the combustible mixture and explosion products through the constructed openings in the roof. This prevents the destruction of the main supporting structures and technological equipment [8,9,10].

3. Calculation of the areas of the safe loss of containment window

3.1. Measurements

To design parameters roofs with easy release sheathing calculations were made the required safe area for loss of containment of the tank according to [7].

The calculation makes it possible to establish the dependence of the loss of containment area on the volume of the structure or equipment and the maximum pressure in it, the temperature and pressure of the process medium, the parameters of the flammable combustible mixture, the outflow conditions, and the degree of turbulence.

Let us consider the dependence of the loss of containment area on the oil product using the example of the vertical steel tank RVS-10000 (diameter 28.5 m).

The calculation of the safe area for loss of containment of technological equipment with gas-steam mixtures is performed according to the given dimensionless criterion ratios [7]:

\[
W \geq \frac{\chi(E, -1)}{\sqrt{E_{(\tau^*_c - 1)}}}
\]  

(1)
For vessels designed for the maximum relative explosion pressure $I < \pi < 2$ (if the condition $p_m \geq 2p$) the denominator of the formula is the factor $(\pi_m - 1)$ missing, and:

$$W \geq 0.9 \cdot \frac{\chi(\pi_m - \pi_m)}{\sqrt{E_i}} \quad (2)$$

For vessels withstanding explosion pressure in the range of relative values: $2 < \pi_m \leq \pi_e$.

The relative maximum allowable pressure in the vessel, which does not lead to its deformation and (or) destruction according to the formula:

$$\pi_m = \frac{p_m}{P_i} \quad (3)$$

Where $R_m$ - absolute maximum allowable pressure inside the vessel, which does not lead to its deformation and (or) destruction, Pa (according to the technical specifications for RVS-10000 tanks: $R_m = 0.1034 \text{ MPa}$);

$P_i$ - absolute initial pressure of the combustible mixture in the apparatus at which combustion is initiated, Pa (pressure of one atmosphere: $P_i = 0.101 \text{ MPa}$);

$E_i$ - coefficient of expansion of combustion products of the mixture (for gasoline [7]; $E_i = 7.99$);

$\chi$ - the turbulence factor, which, in accordance with the Gui-Michelson principle: the ratio of the actual surface of the flame front in the apparatus to the surface of the sphere, into which the combustion products that are inside the vessel at a given time can be collected (for gasoline [6]; $\chi = 8$).

Similarity complex $W$ is, up to a constant factor, the product of two ratios - the effective loss of containment area to the inner surface of a spherical vessel of equal volume and the speed of sound in the initial mixture to the initial normal flame velocity:

$$W = \frac{1}{(36\pi_0)^{0.333} \cdot V^{0.667} \cdot \left( \frac{RT_{u_i}}{M_i} \right)^{0.5} \cdot \frac{1}{S_{u_i}}} \quad (4)$$

where $\mu$ - the flow coefficient for the outflow of a fresh mixture and (or) combustion products through an explosion-discharging device (safety membrane, valve, depressurizer, etc.), (for gasoline [6]; $\mu = 0.4$);

$F$ - loss of containment area (discharge section);

$V$ - maximum internal volume of the vessel in which the formation of a combustible gas-vapor mixture is possible ($V = 11406.36 \text{ m}^3$);

$R$ - universal gas constant equal to 8314 (J/kmolK);

$T_{u_i}$ - the temperature of the combustible mixture;

$M_i$ - the molecular weight of the combustible mixture;

$S_{u_i}$ - normal speed of flame propagation at the initial pressure and temperature of the combustible mixture, (for gasoline [7]; $S_{u_i} = 0.36 \text{ m/s}$).

Calculation of the areas of the safe loss of containment window:

$$V = \pi \cdot R^2 \cdot H \quad (5)$$

$$W = \frac{1}{(36\pi_0)^{0.333} \cdot V^{0.667} \cdot \left( \frac{RT_{u_i}}{M_i} \right)^{0.5} \cdot \frac{1}{S_{u_i}}} \quad (6)$$

If the normal speed data at process-specific pressures $P$ and temperature $T$ are absent, then in a limited range of extrapolation, you can use the formula for estimation:
Where $S_{uo}$ - known value of normal speed at pressure $P_0$ and temperature $T_0$, $n$ and $m$ - pressure and temperature indicators respectively.

Below is an example of calculating the loss of containment area for gasoline.

Flame propagation speed:

$$S = S_n \left( \frac{P}{P_0} \right)^n \left( \frac{T}{T_0} \right)^m,$$

(7)

The obtained data is presented in Table 1.

**Table 1. Calculation of the loss of containment area.**

| Type of HIL    | VST roof area $F_o$, m$^2$ | Area of a safe loss of containment window $F$, m$^2$ | Percentage window area of total roof area, % | Density HIL $p_{HIL}$, kg/m$^3$ |
|---------------|---------------------------|-----------------------------------|--------------------------------------|--------------------------|
| Gasoline      | 637.94                    | 521.41                            | 82%                                  | 710                      |
| Diesel fuel   | 637.94                    | 538.35                            | 84%                                  | 830                      |
| Oil           | 637.94                    | 550.92                            | 86%                                  | 860                      |
| AMT-300 oil   | 637.94                    | 561.63                            | 88%                                  | 930                      |

Figure 1 shows the results of calculations of the areas of safe loss of containment windows for tanks of various volumes.

![Figure 1. Dependence of the area of safe loss of containment windows on the area of the roof. The type of HIL is gasoline.](image)

**3.2 Analysis of measurement results**

From the received data the following conclusions can be drawn:
1) for tanks up to 34.2 m in diameter, it is advisable to develop roofs with a weak knot along the chimney seam of the roof, due to the small difference between the area of safe loss of containment and the area of the roof (less than 25%);

2) for tanks with a diameter of 34.2 m and more, it is advisable to develop roofs with a folding sheathing along the border of the window area for safe loss of containment, since P The percentage of window area from the total roof area is more than 40%;

3) the density of the product affects the area of the safe loss of containment window: with an increase in the density of the stored product, the area of safe loss of containment window also increases.

4. Calculations to reveal the dependence of excess pressure on the nature and level of the stored liquid

4.1 Measurements

Calculations were made to reveal the dependence of excess pressure on the nature and level of the stored liquid [7].

If a source of ignition enters a tank containing highly inflammable liquid, the contents of the tank may heat up to a temperature significantly higher than the normal boiling point, with a corresponding increase in pressure. Due to the heating of the non-wetted walls of the vessel, the strength characteristics of the material are reduced, as a result of which, under certain conditions, it is possible to rupture the tank with the occurrence of compression waves.

Overpressure calculations were made for a VST-10000 tank (diameter 28.5 m), product type is gasoline.

Overpressure $\Delta P$ and momentum $I^*$ in the pressure wave, formed during the explosion of a tank with an overheated HIL in the fire center, are determined by the formulas:

$$\Delta P = P_0 \cdot \left(0.8 \cdot \frac{m_{red}}{r} + 3 \cdot \frac{m_{red}^{0.66}}{r} + 5 \cdot \frac{m_{red}}{r}\right)$$

$$I^* = 123 \cdot \frac{m_{red}^{0.66}}{r}$$

Where $P_0$ is atmospheric pressure, kPa (it is allowed to be taken equal to 101 kPa);

$r$ is the distance from the center of the tank to the object exposed to compression waves, ($r = 14.25m$);

$m_{red}$ is reduced weight, kg.

$$m_{red} = \frac{E_{eff}}{4.52} \cdot 10^{-6}$$

where $E_{eff}$ - effective explosion energy, J.

$$E_{eff} = k \cdot c_p \cdot m(T - T_b)$$

Where $k$ - the fraction of the pressure wave energy (it is allowed to be taken equal to 0.5);

$m$ is the mass of HIL contained in the tank, ($m = 7,435,416$ kg for a tank with a volume of 10,000 m$^3$);

$T_b$ - normal boiling point, ($T_b = 353K$).

If there is a safety device (valve or diaphragm) in the tank, the value $T$ determined by the formula:

$$T = \frac{B}{A - \lg P_{val}} - C_{\Delta} + 273.15,$$

where $P_{val}$ - pressure of the safety device;
A, B, C - constants of the equation of the dependence of the pressure of saturated vapors of a liquid on temperature (Antoine’s constants), determined from the reference literature. Units $P_{val}$ (kPa, mm Hg, atm) should correspond to the used Antoine constants, $(A = 5.61391, B = 902.275, C = 178.099)$.

$$T = \frac{902.275}{5.61391 - \log_{10}1500} - 178,099 + 273.15 = 465,167K.$$  

$$E_{eff} = 0.5 \cdot 2000 \cdot 7435416 \cdot (465,167 - 353) = 2.17 \cdot 10^{11}.$$  

$$m_{red} = \left(\frac{2.09 \cdot 10^{11}}{4.52}\right) \cdot 10^{-6} = 48050.68kg.$$  

$$I^* = 123 \cdot \frac{46128,67^{0.66}}{17,1} = 10617,25kg / m \cdot s$$  

$$\Delta P = P_0 \cdot \left(0.8 \cdot \frac{46128,67^{0.33}}{17,1} + 3 \cdot \frac{46128,67^{0.66}}{17,1} + 5 \cdot \frac{46128,67}{17,1}\right) = 10,42MPa.$$  

4.2 Analysis of measurement results  
The calculation for other types of HIL was performed in a similar way. The data obtained are shown in the graph of the dependence of excess pressure on the height of the filling level in a tank with a volume of 10,000 m$^3$ (Figure 2).

![Figure 2. Dependence of excess pressure on the height of the filling level.](image)

5. Conclusions  
Based on the results of the calculations of the dependence of the excess pressure on the nature and level of the height of the stored liquid, it can be concluded that with an increase in the filling height of the highly inflammable liquids, the excess pressure, which can arise when the tank ignites, also increases. The density of the HIL also has an effect: with an increase in density, the area of loss of containment also increases.

According to the calculations given above, for the development of a roof structure with an easily removable sheathing, the areas of a safe loss of containment window were obtained. The roof area outside the safe loss of containment window ranges from 30.9% to 54.1% of the entire tank area. On this area, the equipment of the tank is located, which, in the event of an explosive situation and when the flooring is torn off inside the safe loss of containment window, will remain in place.
6. References

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