Reliability of cylindrical tank exposed to fire

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Abstract. The paper presents a methodology for assessment the reliability of tank due to typical accidents. The aim of the research is to identify fracture lines and shapes of fragments generated by tank explosions. Accident scenarios and their probabilities are defined with Event Tree Analysis (ETA). Static structural analysis of the tank is realized by the software package ANSYS 15. The probabilistic mass method (PMM) was used to assessment the shape of the fragments. The assessment of the reliability of the tank affected by the fire was carried out according to Fault Tree Analysis (FTA). Verification of the results obtained was made according to available accidents. It has been found that the construction of the tank and especially the type of end caps affects the fragmentation pattern, i.e. the shape of fragments created by explosion. The results of the research are practically usable during the design of the tank because they provide information that is not contained in EN 13445-3.

1. Introduction

Explosion of process equipment is one of the most common causes of chemical accidents [1]. Explosion of process equipment is an inevitable event in the accident chain - a domino effect [2]. Every rapid pressure build up in a confined space (thus a tank) causes an explosion [3]. Releasing of flammable substances is the most common cause of fire in chemical processing facilities, while fires in the vicinity of process equipment cause the appearance of hot BLEVE (Boiling Liquid Expanding Vapour Explosion) [4]. The primary accidents scenarios that accompany the explosion of process equipment include fire BLEVE, unfire BLEVE, mechanical explosion (ME), confined explosion (CE) and runaway reaction (RR) [5]. The root causes of rapid pressure increase within the process equipment can be due to evaporation of the liquid (BLEVE), overpressure (ME), combustion of gases, vapours and dust (CE) and uncontrolled chemical reactions (RR). The thermal influence results in a reduction in the critical pressure that causes the explosion of process equipment [6]. Explosion of pressurized vessels is accompanied by the effects of fragmentation, blast wave and thermal radiation. The fragmentation effect of the tank is characterized by every explosion, regardless of the type of dangerous substance [7]. The fragmentation effect is much more pronounced than the blast effect and thermal radiation (fireballs) and can manifest at distances over 1.2 km [8]. A fragmentation risk analysis can be used to assess the reliability of process equipment. In this paper, the assessment of the probability of fault of the tank is carried out through fragmentation probabilities using PMM [9]. The starting hypothesis of this study is based on the attitude that a greater number of generated fragments is an indicator of greater reliability of the pressure vessel. The research in this paper should show that the prevention of the hot BLEVE effect directly affects the higher reliability of the process equipment.
2. Case study: Horizontal cylindrical tank

The tank reliability assessment procedure is presented through a case study of the cylindrical storage tank (Figure 1) for LPG (liquid petroleum gas). The study is based on the following assumptions:

1) The probability of fault (unreliability) of the tank is conditioned by the effect of fragmentation,
2) The influence of secondary fragments is negligible compared to primary fragments,
3) The tank is designed according to EN 13445-3 and
4) The tank is directly exposed to fire.

![Figure 1. Dimensions and constructional type of tank with static structural analysis.](image)

2.1. Critical zones of the tank

Cylindrical tanks are characterized by three critical cross sections: A-A, B-B and C-C. A critical cross-section depends to a large extent on the type of the end caps. Typical forms of end caps for horizontal cylindrical tank are spherical, ellipsoidal and torispherical. Spherical tanks contain a critical zone in the cross-section C-C, while the ellipsoidal end cap is characterized by a critical cross-section B-B. Critical zone A-A occurs only in tanks with torispherical end caps. In the given case study, a tank with ellipsoidal end caps according to DIN 28013 is considered, whose stress state can be represented by:

\[
\sigma_x = \left[1 + \frac{3}{2} \frac{1}{\sqrt{3(1-v^2)}} \left(\frac{D}{2h}\right)^2 e^{-\lambda x} \sin(\lambda x)\right]\left(\frac{Dp}{4\delta}\right)_{x=\frac{\pi}{4\lambda}} = 46.5 \text{ p}
\]  

\[
\sigma_\theta = \left[1 + \frac{1}{4} \frac{3v \sin(\lambda x) - \cos(\lambda x)}{\sqrt{3(1-v^2)}} \left(\frac{D}{2h}\right)^2 e^{-\lambda x}\right]\left(\frac{Dp}{2\delta}\right)_{x=\frac{\pi}{4\lambda}} = 92.5 \text{ p}
\]  

\[
\sigma_{\text{max}} = \sqrt{\sigma_x^2 + \sigma_\theta^2 - \sigma_x \sigma_\theta + \frac{3}{2} (\sigma_x - \sigma_\theta)^2} = 98 \text{ p}
\]
Where is the tank diameter $(D = 2600 \text{ mm})$, the height of the end cap $(h = 650 \text{ mm})$, wall thickness of the tank $(\delta = 14 \text{ mm})$, the Poisson's ratio $(\nu = 0.3)$, the coefficient $\lambda = [12(1-\nu^2)/(D\delta)^2]^{1/4} = 9.53 \text{ m}^{-1}$ and the tank pressure $(p)$. The maximum stress of the tank with an ellipsoidal end cap is in cross-section B-B. The position of this cross-section is defined with $x = \pi/4\lambda$ measured from the beginning of the cylinder. For the given parameters is $x \approx 82 \text{ mm}$, which means that the critical cross-section is close to the zone of the joint of the cylinder and the end caps. The maximum operating pressure of the tank is determined on the basis of the allowable stress $(f)$ for the tank material (S235J2G3) which according to EN 13445-3 amounts $f = R_m/2.4 = 195.8 \text{ MPa}$ (the tensile strength of the material is $R_m = 470 \text{ MPa}$). The operating pressure inside the storage tank of the LPG is from 16.4 to 16.9 bar (average 16.7 bar). Equivalent (von Mises) stress according to (3) for the average pressure is $\sigma_{\text{theory}} = 98p = 163.7 \text{ MPa}$. This stress according to EN 13445-3 is $\sigma_{\text{EN13445-3}} = pD_m/(2ze_a) = 154.2 \text{ MPa}$, where the mean diameter of the tank $D_m = (D-e_a) = 2586 \text{ mm}$, wall thickness $e_a = \delta = 14 \text{ mm}$ and coefficient of welded seam $z = 1$ (full control of welded seams). Equivalent stress in accordance with the FEM model (ANSYS 15) is 150.2 MPa. Comparative analysis shows that the mathematical model and EN 13445-3 give several percent higher equivalent stress than the FEM model. Theoretical analysis and EN 13445-3 consider the cylinder of the tank without the influence of other structural elements (supports, lifting lugs, etc.).

### 2.2. Mechanism of explosion of the tank

The explosion is caused by a rapid increase in pressure inside the tank and always manifested by the fragmentation effect. Explosion of the tank is a result of extremely dynamic pressure changes. The intensity of the fragmentation effect is conditioned by the rate of pressure change. Fracture of the tank under the influence of quasi-static pressure is not accompanied by a fragmentation effect or poorly expressed. Explosion of the tank follows the detonation process whose velocity of the spherical longitudinal wave is up to several $\text{km/s}$. The velocity of the wave propagation $(c)$ through the wall of the steel tank is $c = (E/\rho)^{0.5} = 163.6 \text{ m/s}$. This velocity is most common in the whole order of magnitude (10 times) less than the detonation velocity. The detonation velocity depends on the type of combustible substance within the pressure vessel and for the LPG is about $v = 1800 \text{ m/s}$. The time required to propagate the wave through the wall of the tank is $t = \delta/c = 8.55 \times 10^{-5} \text{ s}$. The impact wave due to detonation for the same time crosses the path $s = vt = 154 \text{ mm}$. This means that during the explosion of the tank in which the LPG is located at time $t$, radial deformation will be achieved $\varepsilon_\theta = \Delta D/D = 11.8\%$. This situation is not even theoretically possible, since the fracture of the tank occurs at a much less radial deformation $\varepsilon_{\text{failure}} = [(2-v)/(392)] \cdot (R_m/E) \cdot (D/\delta) = 0.18\%$. Numerical illustration has the role to explain the mechanism of the explosion of the tank. The tank fracture due to the quasi-static pressure always runs along the high stress zone and starts at the stress concentration points. The quasi-static pressure change allows the stress lines to find a critical zone of the tank from which the cracks spread. Due to the dynamic change in pressure, the stress lines do not have enough time to localize in the external critical zone of the tank. In this case, the crack propagation starts from internal sources of stress concentration. The expansion of the pressurized vessels takes place at a velocity of $v$, which affects the interruption of the stress lines transmitted by the velocity of $c$. Then the ductile materials of the tank behave like brittle and generate a larger number of fragments. Therefore, a higher detonation velocity causes a greater number of generated fragments. The previously described explosion mechanism is illustrated in Figure 2.

![Figure 2](image-url). Mechanism of explosion of the tank depending on the detonation velocity.
3. Fracture lines and fragmentation patterns

The assessment of fracture lines and fragmentation patterns was performed on the basis of structural analysis and Monte Carlo simulation. Critical zones of the tank are defined by structural analysis, while the Monte Carlo simulation estimates the most probable masses of fragments (Figure 3). The fragmentation analysis of the tank is limited to two fragments, which is a typical in the BLEVE effect.

![Figure 3. Potential fracture lines and mass distribution for the first two fragments.](image)

The most likely fragmentation patterns due to the BLEVE effect are shown in Table 1. The masses of the fragments are expressed through a percentage share in the tank mass, according to the histogram of Figure 3. The mass of the tank is 12300 kg. The maximum probability of generating two fragments (≈17%) occurs if the aggregate mass of the fragments is between 1300 kg and 2225 kg.

**Table 1. Characteristic forms of fragments due to tank explosion.**

| ONE FRAGMENT | TWO FRAGMENTS |
|--------------|---------------|
| Fragment mass: 1350 kg | Fragment mass: 820 kg and 480 kg |
| Fracture zone: II+III+VI | Fracture zone: II+III and IV+V |
| Generation probability: 9.10% | Generation probability: 17.04% |

| Fragment mass: 2050 kg | Fragment mass: 205 kg and 2050 kg |
| Fracture zone: II+III+IV+V+VI | Fracture zone: VII+VIII and II...VI |
| Generation probability: 10.00% | Generation probability: 17.06% |

| Fragment mass: 1590 kg and 2050 kg |
| Fracture zone: II...VII and VIII+IX |
| Generation probability: 14.85% |

| Fragment mass: 1365 kg and 3545 kg |
| Fracture zone: XIII...XV and II...IX |
| Generation probability: 13.00% |
4. Accident scenarios due to tank explosion

Explosion of the tank caused by critical pressure includes more accidents scenario, which are caused by the fracture of the segments of the tank. The division of the tank into segments was performed for easier assessment of fragmentation probabilities [9-10]. The first segment of the tank (S1) belongs to the cylinder in the length L (S1) according to Figure 1. The remaining part of the tank belongs to the segments S2 and S3. Propagation of fracture lines can be carried out individually or combined along segments S1, S2 and S3. The Event Tree Analysis (ETA) provides a total of 6 potential scenarios for the explosion of the tank (Figure 4).

![Figure 4. The definition of accident scenarios using Event Tree Analysis – ETA.](image)

Accident scenarios Sc1 and Sc2 include a fracture of the tank in at least two segments S1 and S2/S3. Accident scenarios Sc3, Sc4 and Sc5 include a fracture only in one of the segments S1, S2 and S3. The last outcome (Sc6) is not an accident, as there is no fracture of any segment of the tank. The fragmentation probabilities of the segments were obtained by the implementation of PMM [9]. The limit fragmentation probabilities by segments and generated fragments are given in Table 2. The maximum values for S1 correspond to the minimum values for S2 and S3.

| Segment | Probability | Number of fragments |
|---------|-------------|---------------------|
|         | % | 1 | 2 | 3 | 4 | 5 | 6 | 7 | ≥ 8 |
| S1      | max | 35.500 | 25.000 | 9.375 | 2.500 | 0.500 | 0.094 | 0.013 | 0.019 |
|         | min | 27.500 | 18.333 | 6.875 | 1.833 | 0.367 | 0.069 | 0.009 | 0.014 |
| S2 or S3| max | 11.250 | 11.791 | 5.165 | 1.467 | 0.299 | 0.056 | 0.007 | 0.011 |
|         | min | 6.250 | 6.120 | 2.810 | 0.811 | 0.166 | 0.031 | 0.004 | 0.006 |

5. Assessment of tank reliability

Assessment of tank reliability includes qualitative and quantitative analysis using Fault Tree Analysis – FTA. The loss of the operating function of the tank is conditioned by the fragmentation effect and represents the top event. Realizing this event involves generating a number of fragments (1,2, ...). Basic events include accident scenarios (Sc1 ... Sc5) whose probability of realization can be determined on the basis of Table 2. The minimum fragmentation probability corresponds to the thermal influence due to the BLEVE effect (the temperature of the tank wall is about 500°C). Maximum reliability values are achieved when the tank is not exposed to fire. The failure tree and the limit values of the tank reliability are given in Figure 5. The probability of tank failure is defined by $T = P(Sc1) + ... + P(Sc5)$. Tanks of reduced reliability are characterized by a smaller number of fragments.
6. Conclusion
The reliability assessment in this paper was carried out according to real exploitation conditions. A qualitative assessment of reliability (Table 3) can be made on the basis of available accidents for a known type of tank. A quantitative assessment requires the implementation of PMM [9] with ETA and FTA. It was concluded that the thermal influence adversely affects the reliability of the tank. A larger number of generated fragments is a reflection of higher tank reliability. The reliability analysis proves the starting assumption of the paper. Preventive action from the emergence of the BLEVE effect implies the simultaneous increase in the reliability of the tank.

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References
[1] Hemmatian B, Abdolhamidzadeh B, Dabra R M and Casal J 2014 The significance of domino effect in chemical accidents, Journal of Loss Prevention in the Process Industries 29 30-38
[2] Abdolhamidzadeh B, Abbasi T, Rashtchian D and Abbasi S A 2011 Domino effect in process-industry accidents – An inventory of past events and identification of some patterns, Journal of Loss Prevention in the Process Industries 24 575-593
[3] Tognoli A, Gubinelli G, Landucci G and Cozzani V 2014 Assessment of fragment projection hazard: Probability distributions for the initial direction of fragments, Journal of Hazardous Materials 279 418-427 (https://doi.org/10.1016/j.jhazmat.2014.07.034)
[4] Eckhoff R K 2014 Boiling liquid expanding vapor explosions (BLEVEs): A brief review, Journal of Loss Prevention in the Process Industries 32 30-43
[5] Gubinelli G and Cozzani V 2009 Assessment of missile hazards: Identification of reference fragmentation patterns. Journal of Hazardous Materials 163(2-3) 1008-1018
[6] Plans E, Pastor E, Casal J and Bonilla J M 2015 Analysis of the boiling expanding vapor explosion (BLEVE) of a liquefied natural gas road tanker: The Zarzalico accident, Journal of Loss Prevention in the Process Industries 34 127-138
[7] Mébarki A, Mercier F, Nguyen Q B and Saada R A 2009 Structural fragments and explosions in industrial facilities. Part I: Probabilistic description of the source terms, Journal of Loss Prevention in the Process Industries 22 408-416 (https://doi.org/10.1016/j.jlp.2009.02.006)
[8] Mébarki A, Nguyen Q B and Mercier F 2009 Structural fragments and explosions in industrial facilities. Part II: Projectile trajectory and probability of impact, Journal of Loss Prevention in the Process Industries 22 417-425 (https://doi.org/10.1016/j.jlp.2009.02.005)
[9] Djelosevic M and Tepic G 2019 Identification of fragmentation mechanism and risk analysis due to explosion of cylindrical tank, Journal of Hazardous Materials 362 17-35
[10] Djelosevic M and Tepic G 2019 Probabilistic simulation model of fragmentation risk, Journal of Loss Prevention in the Process Industries 60 53-75