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Domino Effects Due to the Projection of Fragments: Estimation of the Impact Probability Using a Monte Carlo Simulation

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Although the remarkable severity of accidental scenarios arising from the propagation of moderate primary accidents, a complete methodology has not been developed for the prediction and prevention of such events, in particular for domino effects trigged by the projection of fragments. This contribution, illustrates the application of a well known methodology for the estimation of potential impacts of tank explosions producing fragments given by CCPS (Centre for Chemical Process Safety). In order to incorporate the procedure into the standard QRA (Quantitative Risk Analysis), a probabilistic model for the impact probability of the fragments is developed by applying a Monte-Carlo method on the analytical solution of the set of equations describing the motion of the fragment.

1. Introduction

Domino effects are propagations of primary accidents leading to secondary events, which are more severe scenarios and extend the damages due the primary accidents. Notwithstanding the widespread application of inherent safety criteria also to consolidated processes (e.g. Fabiano et al., 2013), still large quantities of HazMats are produced, stored and handled in industrial plants. Domino effects have a high destructive potential (Kletz, 1985; Pietersen, 1986). A statistical investigation on accidental events occurred in the oil industry was performed by Fabiano and Currò (2012), it includes a large number of such events, but a complete inventory of them was realized by Abdolhamidzadeh et al. in 2011.

Domino effects could be triggered by overpressures, thermal radiations and projections of fragments. Analyzing those due to fires, the evaluation of the flame extent and temperature is essential (Palazzi and Fabiano, 2012). Other factors, mainly related to the equipment type, geometry, mechanical resistance and the eventual presence of mitigation/protection barriers must be accounted for (Badri et al., 2013). The problem of the projection of fragments is relevant to the domino escalation, but actually it is not completely faced. A deterministic approach to the estimation of domino effects triggered by fragments was proposed by the Centre for Chemical Process Safety (CCPS, 2000). This is a multi-step approach which requires the computation of: (i) explosion energy; (ii) number and size of fragments produced by the collapse of the vessel; (iii) initial velocity and angle of departure of each vessel's portion; (iv) distance of fall of the fragments. Then, by analyzing the plant layout, facilities located in the range of potential fallout could be identified and, thus, it is possible to define which of them could generate the secondary event.

In order to integrate the CCPS approach in the classic QRA (Quantitative Risk Assessment), the consequence and the frequency of the domino effect must be estimated. In this framework, the critical step is the frequency estimation; Gubinelli et al. (2004) showed that this frequency is the product between the frequency of the primary event and the probability of the following sequence of events (given the

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occurrence of the primary event). The probability of the sequence of events is the product of the probabilities of the fragmentation, of impact on a certain target and of damage given the impact occurrence. Holden and Reeves (see Lees 1996) developed models for the estimation of the fragmentation probability. Approaches to the modelling of the impact probability based upon the analysis of the initial direction of fragment flight are due to Hauptmanns (2001) and Gubinelli et al. (2004). An application of this last method was recently published by Tugnoli at al. (2013). Finally, correlations for the calculation of the probability of damage are reported in Lees (1996).

By means of a literature analysis, Lisi et al. (2013) recently reviewed the analytical solution of the set of ordinary differential equations describing the flight of a fragment and, then, they validated the reviewed approach by using the accident occurred in the Italian refinery of Milazzo (Maschio et al., 2004). The objective of this work is to extend the approach proposed by Lisi et al. (2013), which has been developed only for cylindrical vessels, in order to be applied also to spherical tanks. In the first part of this paper the implementation of the method is described, while in the second part an application to a case study is given, which is the accident occurred in the refinery of Feyzin (France).

2. Methodology

The literature points out that a completely consolidated methodology for the prediction and prevention of domino effects triggered by the projection of fragments does not exist. This work is an attempt to achieve this goal in the context of the previously mentioned CCPS approach. As mentioned above, the CCPS approach is deterministic and does not take into account uncertainty factors, as suggested by Milazzo and Aven (2012). Its probabilistic implementation is necessary to integrate domino effect due to fragments projection within the QRA and extend study such as Baesi et al. (2013) and Milazzo et al. (2002).

Lisi et al. (2013) reviewed the analytical solution of the set of ordinary differential equations describing the flight of a fragment in the air. To obtain a probabilistic model for the impact probability of fragments due to BLEVE, the authors applied a Monte Carlo method to the solution of the system. In this work this approach has been extended to spherical tanks.

2.1 Flight of a fragment

The equation of the fragment's trajectory was obtained by solving the equation of motion in two spatial dimensions and taking into account the air resistance, expressed through the contributions of the drag and lift forces (respectively F_D and F_L). The equations of motion in the form of a system of second-order ordinary differential equations are:

$$\begin{cases} \ddot{x} + k\,\dot{x}^2 = 0 \\ \ddot{y}_A + k_A\,\dot{y}_A^2 + g = 0 \\ \ddot{y}_D - k_D\,\dot{y}_D^2 + g = 0 \end{cases} \tag{1}$$

The dot notation indicates the time derivative of the indicated variable, x and y_i ($i=A,D$) are, respectively, the horizontal and vertical components of the trajectory and g is the gravitational constant. The first equation describes the time evolution of the horizontal component of the trajectory, the last ones account, respectively, for the ascending and descending vertical branches. The set of initial conditions is:

$$\begin{cases} x(0) = 0 \\ \dot{x}(0) = u_o \cos q \\ y_A(0) = 0 \\ \dot{y}_A(0) = u_o \cos \\ \dot{y}_D(t^*) = \max(y_A(t)) \\ \dot{y}_D(t^*) = 0 \end{cases} \tag{2}$$

where: t^* = time at which the ascending of the trajectory reaches the maximum height.

The effects of air viscosity are included through the coefficients:

$$k = \frac{r C_D A_D}{2m_i} \tag{3}$$

$$k_A = \frac{r\left(C_D A_D - C_L A_L\right)}{2m_i} \tag{4}$$

$$k_D = \frac{r\left(C_D A_D + C_L A_L\right)}{2m_i} \tag{5}$$

where: ρ = air density; m_i = mass of the fragment; C_D = drag coefficient; C_L = lift coefficient; A_D= drag area; A_L = lift area; u_o = initial velocity of the fragment; θ = departure angle; t =time.
Drag coefficients for various shapes of fragments can be found in Baker et al. (1983). As suggested by Daugherty et al. (1989), the lift contribution is to be assumed to act only when fragments are launched with an angle of attack between 0° and 10°. The areas A_D and A_L are, respectively, the projection of the object on a plane perpendicular to the direction of motion and that on a plane parallel to the direction of motion. The analytical solution has been derived by Lisi et al. (2013).

2.2 Probabilistic model

In the model proposed, the initial velocity and the departure angle, which are the variables mostly affected by uncertainties, are assumed to be stochastic variables. Besides the commonly used assumption to consider the projection to be equally probable in all the directions (i.e. uniformly distributed), the possibility that the stochastic variables obey a Gaussian (normal) probability density function has also accounted. Results were then compared to each other in order to investigate the sensitivity of the resulting behaviour.

3. Case-study

The methodology described above has been applied to a case-study in order to extend the approach to the analysis of potential domino effect caused by the explosion of spherical tanks. In order to achieve these objectives, the accident occurred in the refinery of Feyzin (France) in 1966 has been analysed.
The Feyzin refinery, located near Lyon, was built in the 1964 for the treatment of 1.7 million barrels per year of petroleum. It has a storage area of liquefied petroleum gas (LPG) under pressure with a capacity of about 13,100 m^3. The LPG storage area comprises 10 tanks (8 spheres and 2 cigars), it also includes storage tanks for the heating oil, gasoline and premium gasoline.

3.1 The accident of Feyzin

The accident occurred on the 4th January 1966 and was caused by the uncontrolled release of propane from a storage sphere (T61 443), due to the misbehaviour of the operators involved in the purge operation. These did not execute the correct instructions for the blockage of the two safety valves (located at the base of the sphere) and caused a leakage of propane.
The flow of propane generated a cloud with a thickness of about 1 m, the ignition triggered in a very short time a vapour cloud explosion (VCE). The emergency crews immediately began to cool down the spheres surrounding the T61 443, but in a short time the metal lost its strength and exploded. After the BLEVE a fireball and the projection of fragments occurred. After 15 minutes also the nearest sphere (T61 442) exploded and a third one completely released its contents due to a broken pipe.
Three other spheres were broken during the accident, without generation of fragments. The accident caused a total of 18 dead and 81 injured. The characteristics of the tanks are given in Table 1.

Table 1: Characteristics of the tanks (source Ministère chargé de l'environnement, 2006)

Tank	Type of steel	Volume (m^3)	Dimension (m)	Pressure (bar)	Thickness (mm)	Empty weight (t)
Sphere of propane	BH 36 KT (carbon steel)	1218	diameter: 13.27	18.7÷28.05	42 ÷ 43	220
Sphere of butane	BH 36 K (carbon steel)	2038	diameter: 15.74	7.97÷11.95	24.5 ÷ 25.4	186
Cylinders of propane / butane	BH 36 KT (carbon steel)	161	diameter: 3.04 length: 20.80	28.05	mantle: 11 end-cup: 20	not known

3.2 Consequences of the incident

After the explosion of two spheres (T61 442 and T61 443), many fragments were projected within an area having a radius of 800 m. Larger fragments, some of which weighed more than 80 tons, were projected up to about 270 m from their original location. Table 3 shows their sizes, masses and distances, whereas Figure 1 shows the location of 69 fragments produced by the explosion of the spheres.

Table 2: Characteristics of the main fragments (source Ministère chargé de l'environnement, 2006)

Tank	Fragment ID	Dimension (m x m)	Mass (t)	Fallout distance (m)
T61 442	A1	19 x 21.5	88.2	138
T61 442	A2	10.5 x 18.3	47.7	325
T61 442	A3	12.6 x 14.5	53.1	222
T61 443	B1	10.5 x 15	48	85
T61 443	B2	4 x 3	2.8	82
T61 443	B3	4.2 x 11.5	18	228
T61 443	B4	16.8 x 18.2	79	248
T61 443	B5	10.5 x 17.5	37	270

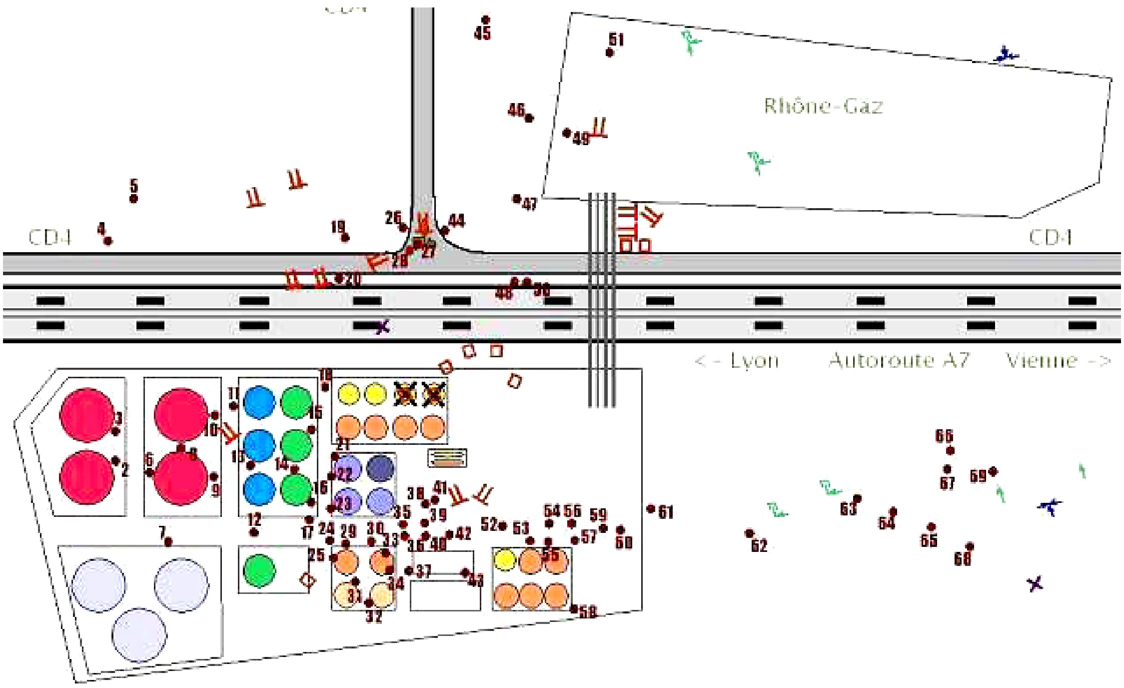

Figure 1: Localization of the fragments (source Ministère chargé de l'environnement, 2006)

3.3 Deterministic analysis

The initial velocities have been calculated by using the model proposed by Baum (Van den Bosch and Weterings, 2005) because, as a result of the preliminary analysis made by Lisi et al. (2013), it is the most suitable for BLEVE. The authors calculated the fragments' velocities by using several methods and, also the related trajectory, then they validated results by comparing with case-studies. The subsequent step of the investigation consists of setting-up the numerical values of the parameters involved in the phenomenon (extracted from the survey after the accident) with the aim to verify whether, once inserted them into the equation of motion, they realistically reproduce the experimental data (the fallout distance have been calculated and compared with real data). The numerical integration of the previous equations of motion provided the values of the departure angles (θ) for the fragments given the knowledge of the fallout distance reported in Table 2. Figure 2 shows the results of the deterministic estimation of the value of θ of each fragment.

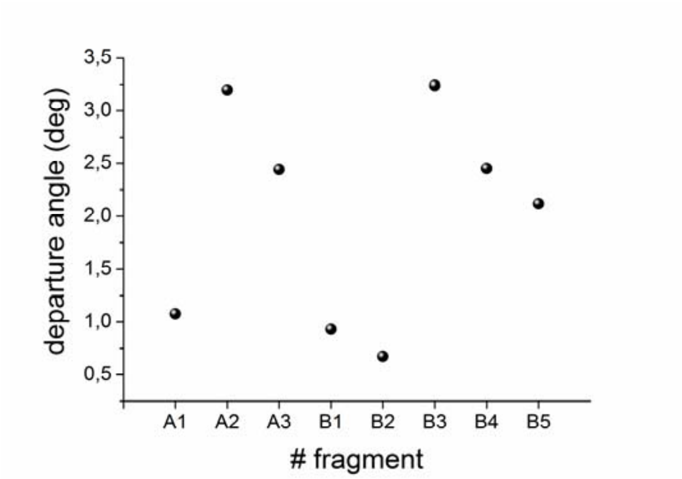

Figure 2: Deterministic estimation of the departure angles (θ)

3.4 Probabilistic analysis

A computational algorithm, based upon a Monte Carlo method, has been developed to estimate the probability that a fragment originated from a vessel could hit a specific target placed at a distance r. To simplify the analysis and considering that the work focuses on the evaluation of a domino effect probability, the target has been considered to be another vessel with radius of 2 m and height of 4 m.

Within the Monte Carlo procedure, two quantities are assumed to vary randomly: the departure angle θ and the initial velocity u_o. The probability density functions associated to these quantities are those described in Section 2.2. Figure 3 shows that fragments, given their characteristics, depart almost parallel to the floor, so that the range 0°< θ <5° is considered. Concerning the initial velocities, based upon the realistic estimations arising from the previous estimations, vary in the interval 140 m/s < u_o < 200 m/s.

The numerical solutions of the previous set of equation of motion, expressed in such a way to obtain the whole fragment trajectory, are iterated 75.000 times. This value is chosen to ensure, at the same time, a high accuracy and the stochastic convergence of the algorithm.

4. Results and discussion

The impact probability is evaluated as a function of the spatial position of the target. Results are shown in Figure 3 and lead to the same considerations made by Lisi et al. (2013). The impact probability for fragments of type A (portions of T61 442) and B (portions of T61 443), which depart almost parallel to the floor, exhibits a monotonically decreasing dependence on the target distance. Appreciable differences can not be observed by comparing the results obtained by both the type of fragments. In particular, in all cases, the probability is about 0.4 at 120 m, using a uniform distribution function, and 150 m, in case of a Gaussian one; then it smoothly decreases down to 10^{-3} at 450 m.

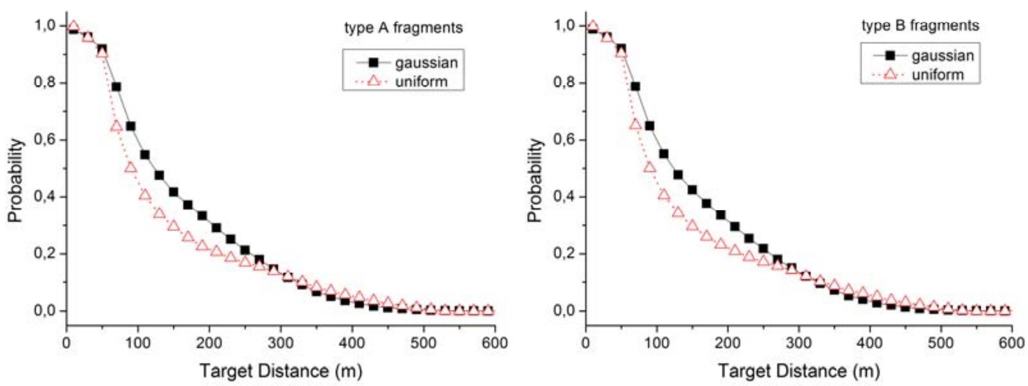

Figure 4: Impact probability for fragments of type A (portions of T61 442) and B (portions of T61 443)

5. Conclusions

In this paper a methodology for the estimation of the impact probability of fragments, originated by tank explosions (BLEVE), has been extended to the study of spherical tanks. The set-up of the model has been made by using the data of the incident occurred in the refinery of Feyzin. The probabilistic model for the estimation of the impact probability of the fragments has been developed by applying a Monte-Carlo simulation to the analytical solution of the trajectory of fragments, where the departure angle and the velocity are assumed to be stochastic variables obeying either a uniform or a Gaussian distribution. The trend of the impact probability with respect to the target distance has shown a monotonically decrease.
The proposed approach allows the integration of the domino projection of fragments in the QRA. In fact, once potential domino scenarios have been identified, the proposed framework allows estimating the impact probability of a given fragment on each selected target.

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