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Assessment of the hazard due to fragment projection: A case study

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A B S T R A C T

Fragment projection following vessel burst is a possible cause of domino effects in industrial accidents. The projection of fragments from stationary equipment usually follows the catastrophic rupture of process equipment due to internal pressure exceeding design values. In recent years, a detailed model was developed to assess fragment impact probability. The model, based on the use of fragmentation patterns and of a simplified analysis of fragment trajectory, allows the calculation of impact probabilities considering different scenarios leading to vessel burst and fragment projection. In the present study a case-study was analyzed to assess model performance and to test the credibility of the model predictions for fragment number, shape and impact probability. The cumulative probability of fragment impact was found to be in good agreement with the actual distribution of the landing points experienced for the fragments formed in the accident. The maximum projection distance predicted by the model resulted comparable to the maximum landing distance experienced in the accident. The model tested thus seems to yield significant results, well in the range of those experienced in the case-study analyzed.

1. Introduction

Catastrophic failures of process vessels may result in fragment projection up to relevant distances. Fragments generated and projected in the catastrophic failure of static equipment are a possible cause of damage to workers, of asset damage, and, mostly, a potential cause of escalation events (domino effect) (Bagster & Pitblado, 1991; CCPS, 2000; Khan & Abbasi, 1998; Mannan, 2005; Pettitt, Schumacher, & Seeley, 1993). The relevant projection distances of fragments that were experienced (up to 1 km) hinder the application of safety distance criteria and of preventive actions to avoid domino effect (Gledhill & Lines, 1998). In this framework, the assessment of the hazard due to missile projection in domino scenarios caused by equipment fragmentation may be an important integrative tool for the management of risk due to major accidents. In recent years, a detailed model suitable for application in quantitative risk assessment (QRA) was proposed (Gubinelli & Cozzani, 2009a, 2009b; Gubinelli, Zanelli, & Cozzani, 2004).

Missiles are generated in scenarios involving an equipment failure which is able to project fragments at significant distances (CCPS, 2000; Mannan, 2005). An extended analysis of past accidents leading to fragment projection was performed in previous studies (Gubinelli & Cozzani, 2009a) and allowed the identification of the main categories of process equipment and primary scenarios that were responsible of fragment projection in process plants. Table 1 lists the scenarios that more frequently resulted in vessel burst followed by fragment projection.

Several models were proposed in the literature for the analysis of fragment projection scenarios. Procedures based on a direct statistic analysis of post-accident data were proposed for the estimation of fragment impact probability, as well as for the assessment of the maximum distance reached by a fragments (Holden & Reeves, 1985; Scilly & Crowther, 1992). More recently, comprehensive ballistic methodologies for the calculation of the impact probabilities of a fragment were developed (Gubinelli et al., 2004; Hauptmanns, 2001a, 2001b; Pula, Khan, Veitch, & Amyotte, 2007), mainly derived from the fundamental approach to fragment trajectory analysis proposed by Baker, Cox, Westine, Kulesz, and Strehlow (1983). A comprehensive review is given by Mannan (2005). Recently, Gubinelli and Cozzani (2009a, 2009b)

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Table 1
Scenarios leading to missile projection as for the analysis of past accidents (Gubinelli & Cozzani, 2009a).

Primary scenario	Description
Fired BLEVE	Catastrophic failure of a vessel containing a liquid at temperature above its boiling temperature at atmospheric pressure, due to an external fire.
Unfired BLEVE	Sudden loss of containment of a vessel containing a liquid at temperature above its boiling temperature at atmospheric pressure, not due to an external fire (e.g. due to corrosion, erosion, fatigue, external impact).
Physical explosion	Catastrophic failure of a vessels containing a compressed gas phase and/or a non-boiling liquid, due to an internal pressure increase not caused by fire or chemical reactions. Possible causes: overfilling, corrosion, etc.
Confined explosion	Catastrophic vessel failure due to an internal pressure increase caused by the unwanted combustion of gases, vapours, or dust inside the vessel.
Runaway reaction	Catastrophic vessel failure due to an internal pressure increase caused by the loss of control of a chemical reaction.

proposed a detailed approach for the analysis of fragment impact probability, based on the probabilistic assessment of fragment number, shape and drag factor. The approach was based on the development of a previous study by Zanelli and coworkers (Gubinelli et al., 2004), that carried out a simplified analysis of the fragment trajectory given a set of initial projection parameters.

In the present study the approach of Gubinelli and Cozzani (Gubinelli et al., 2004; Gubinelli & Cozzani, 2009a, 2009b) was applied to the analysis of a case-study. A past accident in which a vessel burst caused fragment projection was considered. Detailed data were available for the accident causes, the burst vessel geometry, the number, weight and shape of fragments generated. A map with the landing position of the fragments was also available. In the following, first a short outline of the model applied is given. The accident is then described, and the model results are compared to the actual data from the accident.

2. Model

The methodology tested for the assessment of fragment impact probability, derived from that proposed by Gubinelli et al. (2004), is summarized in the following. The first step of the methodology is the identification of the credible fragmentation patterns for the vessel that originates the fragments. The second step is the calculation of the fragment initial velocity. The third and last step is the calculation of fragment impact probability based on a simplified analysis of fragment trajectory.

Predicting the number, shape and size of fragments generated in the failure of process equipment is the starting point in the assessment of fragment projection. While case-specific issues (e.g. defects in the construction material, design features, stress concentration points, location of the fracture) may define the characteristics of the actual fragments, generalized patterns of fragmentation can be identified for standard vessels. A fragmentation pattern is a failure scheme which defines the expected position and number of the main fracture lines originated in the burst of a vessel. The concept of fragmentation pattern was originally introduced by Holden, Westin and Reeves (Holden, 1986; Holden & Reeves, 1985; Westin, 1973). Gubinelli and Cozzani (2009a) proposed a set of reference fragmentation patterns for different vessel categories and linked them to the primary accident scenarios. Table 2 summarizes the fragmentation patterns identified for the burst of cylindrical storage vessels following a physical explosion. Further sets of fragmentation patterns for different primary scenarios and a more detailed discussion on the origin of fragmentation patterns are reported elsewhere (Gubinelli & Cozzani, 2009a).

The identification of the possible reference fragmentation patters allows for the assessment of the expected shape and number of fragments formed in vessel burst. Hence fragment mass and drag factors for each possible fragment F may be calculated (Gubinelli & Cozzani, 2009b).

Several models are proposed in the literature for the evaluation of the initial velocity of fragments. The underlying concept of any of the proposed model is to evaluate the fraction of the internal energy (pressure energy) which is transferred to the fragments as kinetic energy during vessel failure. A first set of methods simply defines an efficiency in the conversion of expansion energy to kinetic energy of the fragments:

$$u^2 = \alpha \cdot \left(\frac{2E_v}{M_v}\right) \tag{1}$$

where u is the initial velocity of the fragments, E_v is the liberated explosion energy (see e.g. CCPS (1994), Mannan (2005) and Van Den Bosh and Weterings (1997) for calculation), M_v is the mass of the vessel, and α is the fraction converted to kinetic energy (Fingas, 2002).

Other methods based on theoretical considerations define the initial velocity of fragments based on energy and momentum balances. Available solutions are usually limited to specific vessel geometries and fragmentation patterns or to vessels filled with ideal gas (Baker et al., 1983; Gel'fand, Frolov, & Bartenev, 1989; Grodzovskii & Kukanov, 1965). Empirical correlations for the initial velocity were instead proposed by Moore (Moore, 1967) and Baum (Baum, 1984, 1987).

The most suitable model for initial velocity should be selected on a case-by-case basis considering the applicability to the analyzed failure scenario. In the case of vessel burst from physical explosions, the use of the Baker method (Baker et al., 1983; Brode, 1959; Holden, 1986) is suggested by TNO's Yellow Book (Van Den Bosh & Weterings, 1997). This method correlates a scaled initial velocity (u/a, ratio of actual initial velocity and sound speed in the gas) with a scaled overpressure parameter (P_s):

$$P_s = \frac{(p_1 - p_{\text{atm}}) \cdot V_g}{M_V \cdot a^2} \tag{2}$$

where p_1 is the pressure in the vessel at failure, p_a is the ambient pressure, V_g is the volume of the gas-filled part of the vessel, M_V is the mass of the vessel and a is the sound speed in the gas at failure. Correlation tables are available for the calculation of the initial velocity of fragments for different vessel geometries (Baker et al., 1983; Brode, 1959; Holden, 1986).

The evaluation of the overall probability of a given target to be impacted by a fragment (P_{imp}) is based on the combination of several factors representing the contribution of all the single fragments from the possible fragmentation pattern of concern in the vessel burst scenario. The main equations used in the quantitative evaluation of such probability are reported in Table 3 and briefly discussed in the following; a more detailed account of the procedure can be found elsewhere (Gubinelli et al., 2004; Gubinelli & Cozzani, 2009a, 2009b).

The probability of impact for each individual fragment F on a target ($P_{\text{imp,F}}$) is evaluated as for eq. A in Table 2, considering the probabilities associated to the following sequence of events: i) generation of a fragment of defined mass, size and shape during the primary event, and ii) projection of the fragment on a trajectory that will impact the target of concern.

The probability of the fragment F to be generated ($P_{\text{gen,F}}$) can be expressed, in turn, as the combination of three factors (eq. B in