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Parametric approach of the domino effect for structural fragments

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ABSTRACT

More specific and accurate probabilistic models of the numbers of fragments generated respectively by Boiling Liquid Expanding Vapor Explosions (BLEVEs), Mechanical Explosions (MEs), Confined Explosions (CEs), and Runaway Reactions (RRs) of a horizontal cylindrical vessel were developed using the maximum entropy principle based on historical accident data. The theoretical results from the four probability density functions were compared to the observed data, and the numbers of fragments followed discrete exponential distributions in the interval [1, 9]. Beside the summary of the probabilistic distributions of the other random variables in the process of fragment projection, the effects on the fragment trajectory and target terms were investigated using a parametric approach. The results showed that using the complete model, wind shear, turbulence, and absence of fragment rotation caused the fragments to impact within shorter distances; fragment rotation and lack of wind decreased the probability of impact within a given distance, but the rupture probability of the target was not affected by fragment rotation or wind. The probabilistic confidence intervals of fragment range, impact, and target penetration became narrower with the number of simulation runs, but the accuracy of the results increased. The probability of fragment impact increased with the volume of the target vessel and the degree of filling of the explosion vessel, but did not depend on the kind of explosion. The probability of target rupture increased slowly with the degree of filling of the explosion vessel, but was little influenced by the volume of the target vessel or the kind of explosion.

1. Introduction

In chemical process industries, the domino effect is a well-known cause of major accidents (Antonioni, Spadoni, & Cozzani, 2009; Cozzani, Antonioni, & Spadoni, 2006; Nguyen, Mébarki, Ami Saada, Mercier, & Reimeringer, 2009). An accidental event which starts at one unit may damage another through heat radiation, blast waves, or projectiles. In reality, a sudden explosion can generate many fragments which can be projected over long distances, threaten other sites located in the vicinity, and lead to more severe consequences due to the nature of the domino effect. Fragment projection in an explosive accident is one important cause of the domino effect on chemical process equipment (Pietersen, 1988). The overall domino effect caused by fragments is composed of a set of elementary cycles, and each cycle includes three detailed steps: the source term (explosion and generation of the fragments), the fragment trajectory term (angles, velocities, and displacements from the source), and the target term (impact of and interaction between the fragments and the target).

2. Analysis of previous work

Some research on the three components described above has been performed in previous work (Abbasi & Abbasi, 2007; Bahman, Abbasi, Rashtchian, & Abbasi, 2010; Baum, 1988, 1995, 1998, 1999a, 1999b, 2001; Bukharev & Zhukov, 1995; CCPS, 1994; Genova, Silvestrini, & Leon Trujillo, 2008; Gubinelli & Cozzani, 2009a, 2009b; Gubinelli, Zanelli, & Cozzani, 2004; Hauptmanns, 2001a, 2001b; Holden, 1988; Holden & Reeves, 1985; Lees, 1996; Lepareux et al., 1989; Mébarki, Mercier, Nguyen, & Ami Saada, 2009; Mébarki, Nguyen, Mercier, 2009; Mébarki et al., 2007; Mébarki, Nguyen, Mercier, Ami Saada, & Reimeringer, 2008; Neilson, 1985; Nguyen et al., 2009; Qian, Xu, & Liu, 2009; Scilly & Crowther, 1992; Stawczyk, 2003; Tulacz & Smith, 1980; Van den

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Bosch & Weterings, 1997; Zhang & Chen, 2009). In recent work (Mébarki, Mercier, et al., 2009; Mébarki, Nguyen, et al., 2009; Mébarki et al., 2007, 2008; Nguyen et al., 2009), the mechanical and kinetic features of the source terms (random variables such as number of fragments, shape, and mass) were investigated, and the corresponding probabilistic distributions were developed using the maximum entropy principle for the source terms. In the fragment trajectory term, trajectory equations for the fragments were proposed, and the ground distributions of the fragments were assessed. In the target term, probabilistic models of fragment impact were developed, a calculation of the impact probability was carried out, and its effects on the probability of impact were evaluated. As for target damage, a simplified plastic model for evaluating the probability of rupture with high reliability was proposed, and its influence on penetration depth was investigated. However, in the analysis described above (Mébarki, Mercier, et al., 2009; Mébarki, Nguyen, et al., 2009; Mébarki et al., 2007, 2008; Nguyen et al., 2009), for the source terms, i.e. the development of a probabilistic model for the number of fragments from a horizontal cylindrical vessel explosion, available accident data were scarce, and only BLEVEs (Boiling Liquid Expanding Vapor Explosions) resulting in fragment projection had been considered; for a spherical vessel explosion, a uniform distribution of the number of fragments within the interval from 1 to 19 was assumed. Furthermore, the characteristics of fragment flight, impact, and penetration into nearby facilities, i.e., the fragment trajectory and target terms, still need to be improved. Generally speaking, the accuracy of quantitative risk analysis for industrial sites relies intimately on the hypotheses and the adequacy of the models developed for the whole domino-effect sequence. On the basis of these findings (Mébarki, Mercier, et al., 2009; Mébarki, Nguyen, et al., 2009; Mébarki et al., 2007, 2008; Nguyen et al., 2009), improvements was made to define more specific and accurate probabilistic models of the number of fragments from a horizontal cylindrical vessel explosion by collecting and analyzing data from past accidents leading to fragment projection. The objectives were to recommend a more reasonable probability density function for the number of fragments from a spherical vessel explosion, to reach more specific conclusions after reviewing the reference works on the source terms, and then to explore the effects of the algorithms (movement approach, fragment rotation, wind, and number of simulation runs) on the fragment trajectory and target terms (the ground distributions of fragments, the probability of impact between the fragments and the target, and the rupture probability of the impacted target) and the influence of the calculation parameters (the objective volume, the degree of filling of the source vessel, and the kind of explosion) on the target term (the probability of fragment impact and the rupture probability of the target) using Monte-Carlo simulations including the improved source terms, the kinematics of projectiles, and probabilistic models of fragment impact, penetration, and damage.

3. Source terms

An industrial explosion may generate many fragments with various features, which can be considered as random variables: number of fragments (N), shape and size (f_P), mass (m), initial velocity at departure (v_O), initial departure angles (horizontal and vertical angles, θ and φ), aerodynamic coefficients (lift and drag coefficients, C_L and C_D), and degree of filling of the source vessel (f).

3.1. Number of fragments, N

3.1.1. Case of horizontal cylindrical vessel explosion

In recent work (Mébarki, Mercier, et al., 2009; Mébarki, Nguyen, et al., 2009; Mébarki et al., 2007, 2008; Nguyen et al., 2009), the maximum entropy principle was used to establish the probability density function (p.d.f.) of the number of fragments. However, few experimental or accident data were used, and only the BLEVEs generating the fragments were investigated. In fact, for a horizontal cylindrical vessel, many other accidental scenarios (e.g., a Mechanical Explosion (ME), Confined Explosion (CE), or Runaway Reaction (RR)) can also cause fragment projection. Therefore, more data on the number of fragments generated by various experimental and accident scenarios should be collected so that more specific models of the number of fragments can be developed. Based on the work of Gubinelli and Cozzani (2009a, 2009b), the primary scenarios for a horizontal cylindrical vessel are BLEVE, ME, CE and RR, based on research on data sources of past accidents leading to fragment projection. The relations between the number of fragments from the vessel explosion, the tank shape, the type of primary scenario, and the fracture patterns and mechanics were discussed in detail. Moreover, the number of fragments was determined with high reliability for each type of primary scenario for the tank. The data from Gubinelli and Cozzani (2009a, 2009b) were collected for horizontal cylindrical vessels and are shown in Table 1. Simultaneously, the data from previous authors (Abbasi & Abbasi, 2007; Baker et al., 1977; Hauptmanns, 2001a; Holden & Reeves, 1985; Mébarki, Mercier, et al., 2009; Nguyen et al., 2009) for horizontal cylindrical vessels were comprehensively collected and are shown in Table 2. The data for each type of primary scenario in Tables 1 and 2 are incorporated in Table 3. The number of BLEVEs is larger than in previous work. Generally speaking, the reliability of the results depends on the amount of data used in the probability analysis. The number of events with respect to the observed probabilities of the number of fragments for different accidental events can be obtained by statistics and is shown in Table 3. For CEs and RRs, the number in the interval [5–9] is considered as a random variable following a uniform distribution. Therefore, each value in [5–9] has the same observed frequency. In

Table 1
Accident data for horizontal tank from Gubinelli and Cozzani.

Source: Gubinelli and Cozzani (2009a,b)	Number of fragments				
	1	2	3	4	[5–9]
Explosion category					
BLEVE					
Number of events	5	56	35	3	0
ME					
Number of events	0	6	1	1	0
CE					
Number of events	0	9	0	0	1
RR					
Number of events	2	3	1	0	1

Table 2
Accident data for BLEVE of horizontal tank from Hauptmanns, Holden, and Mébarki.

Explosion category	Number of fragments								
BLEVE	1	2	3	4	5	6	7	8	9
Source	Number of events								
Hauptmanns (Baker et al., 1977; Hauptmanns, 2001a; Holden & Reeves, 1985)	9	17	11	5	2	1	1	–	–
Holden and Reeves (Abbasi & Abbasi, 2007)	8	7	9	3	–	–	–	–	–
Holden and Reeves (Holden & Reeves, 1985; Nguyen et al., 2009)	11	8	11	6	–	–	1	–	–
Mébarki et al. (Mébarki, Mercier, et al., 2009)	17	10	12	7	1	1	1	0	1