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Investigation on the approach of intercepting fragments generated by vessel explosion using barrier net

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ABSTRACT

The barrier net was put between accident source and objective vessel to reduce the probability of target damage due to fragments generated by vessel explosion, and to offset the requirement of safety distance. The fragment trajectory, impact probability of fragment, ruptured probability of the impacted target, and domino effect risk were respectively calculated using Monte-Carlo simulations under the barrier net. The effects of the height of barrier net on the probability of fragments impact were mainly investigated to obtain the reasonable height of barrier net. The results showed that the domino effect risk was decreased by nearly an order of magnitude, due to the significant reduction of impact probability of fragments. The relative differences demonstrated that 70%–90% reduction in the domino effect risk was performed by the barrier net. The impact probability of fragments decreased, but the intercepting probability of the barrier net increased linearly with the height of barrier net. To save cost and leave space for emergency escape and rescue, the barrier net should be installed on an initial height level. Under the same height of barrier net, the intercepting probability will be increased much more than that under the barrier net directly installed on the ground.

1. Introduction

A large number of dangerous chemicals are used or produced in chemical industrial parks, where massive complexes of chemical process equipment are concentrated in a relatively small area. When BLEVE (boiling liquid expanding vapor explosion) occurred in a vessel containing LPG (liquefied petroleum gas), fragments are generated due to tank fragmentation. These fragments have high velocity, high kinetic energy, and large penetrating power and can be projected over long distances, damaging other equipment and facilities and causing severe consequences in a domino effect (Antonioni et al., 2009; Cozzani et al., 2006; Nguyen et al., 2009). Fragment projection is an important cause of large numbers of casualties, property damage, equipment breakage, and domino effects in industrial accidents (Pietersen, 1988).

Each cycle of the domino effect caused by fragments includes three considerations: the source, the fragment trajectory, and the target:

- The source: fragment generation from the original explosion;
- Fragment trajectory: fragment projection;
- The target: impact of fragments on a target vessel, which may penetrate or perforate the vessel creating secondary incident(s).

Significant prior researches have been undertaken to investigate these three considerations, and the dominant effects are summarized in the following paragraph.

The behavior of ruptured tank cars involved in accidents was summarized by Westin (1971). The pressure wave and fragment effects of exploding propellant tanks and gas storage vessels were predicted by Baker et al. (1977). The behavior of projectiles generated by pressure component failure and its application to gas-cooled nuclear plant design were assessed by Tulacz and Smith (1980). Empirical equations for perforation of mild steel plates

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were developed by Neilson (1985). Incident experience relevant to major plant hazards, in particular the fragment hazards from failures of pressurized liquefied gas vessels, were reviewed and evaluated by Holden and Reeves (1985) and Holden (1986, 1988). Baum (1988, 1995, 1998, 1999a, 1999b, 2001) developed preliminary design guidelines for fragment velocity and the extent of the hazard zone for disruptive failure of pressure vessels; the velocity of a detached end-cap following rupture of a gas-pressurized cylindrical vessel; the behavior of rocket-like projectiles in failure cases of high-pressure liquid storage vessels, gas-pressurized vessels containing particulate material, and horizontal pressure vessels containing high-temperature liquid; and the velocity of large projectiles resulting from axial rupture of gas-pressurized cylindrical vessels. Impacts on stainless-steel plates subjected to rigid projectiles at low velocity were studied using experimental and numerical approaches by Lepareux et al. (1989). A methodology for predicting domino effects from pressure vessel fragmentation was proposed by Scilly and Crowther (1992). Guidelines for evaluating the characteristics of vapor cloud explosions, flash fires, and BLEVEs were developed by CCPS (Center for Chemical Process Safety) (1994), and a model for penetration of a metal barrier by a rod projectile was established by Bukharev and Zhukov (1995). Hazard identification, assessment, and control for loss prevention in the process industries were derived by Lees (1996). Methods for calculating physical effects were summarized by Van den Bosch and Weterings (1997). The flight of projectiles from cylindrical vessel explosions and tank explosions was analyzed by Hauptmanns (2001a, 2001b). Stawczyk (2003) evaluated LPG tank explosion hazards using an experimental approach. A simplified model for assessing the impact probability of fragments was developed by Gubinelli et al. (2004). The mechanism, consequence assessment, and management of the BLEVE were explored by Abbasi and Abbasi (2007). Blast-wave overpressure and fragment initial velocities for a BLEVE event were obtained using empirical correlations derived from a simplified model of released energy by Genova et al. (2008). The reference fragmentation patterns of the vessels were identified, and the fragment numbers and drag factors were assessed by Gubinelli and Cozzani (2009a, 2009b). Mébarki et al. (2009a, 2009b, 2007, 2008) and Nguyen et al. (2009) developed probabilistic distributions of the source terms. The trajectory equations and the ground distributions of the fragments were proposed and evaluated. Subsequently, probabilistic models of fragment impact were developed in the target term, the impact probability was calculated, and the effects of various factors on the impact probability were evaluated. A simplified plastic model to assess rupture probability with high reliability was proposed, and its influence on penetration depth was investigated. Fragment projectiles from a spherical tank BLEVE were analyzed using Monte Carlo simulations by Qian et al. (2009). The probability of domino effect impacts was investigated by Zhang and Chen (2009). A method for assessing the domino effect risk in the chemical process industry was proposed and applied by Bahman et al. (2010). The projectile fragments from a cylindrical tank BLEVE accident were analyzed using Monte Carlo simulations by Liu et al. (2010). Probabilistic models of the domino effect caused by fragments from a chemical vessel explosion and the consequences of storage-tank gap and volume on the domino effect were developed and evaluated by Chen et al. (2011). The roots, triggers, and other aspects of a domino accident were investigated by Abdolhamidzadeh et al. (2012). Risk impacts of new-plant construction in an existing chemical plant complex have been assessed using a multi-plant quantitative risk assessment procedure developed by Shahabaldin et al. (2012) and Baesi et al. (2012). Sun et al. (2012) developed 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. They proposed a more reasonable probability density function for the number of fragments from a spherical vessel explosion. Algorithms for the effects of fragment motion, fragment rotation, wind, and number of simulation runs on fragment trajectories and targets (ground distributions of fragments, probability of impact between the fragments and the target, and rupture probability of the impacted target), and the influence of calculation parameters (objective volume, degree of filling of the source vessel, and type of explosion) on the target terms (probability of fragment impact and rupture probability of the target) were explored using Monte Carlo simulations. Domino effects related to explosions were discussed by Salzano et al. (2013) in the framework of land-use planning.

The preceding discussions have revealed that the mechanisms of fragment generation, projection, impact, and equipment damage have been explored by many researchers. The dominant effects may be roughly summarized as follows (four stages):

- Probabilistic models have been developed for fragment generation, including the number of fragments, their shape and size, mass, initial velocity at departure, initial (horizontal and vertical) departure angles, aerodynamic lift and drag coefficients, and the degree of filling of the source vessel.
- Trajectory equations of the fragments, probabilistic models of fragment impact, and a simplified plastic model for assessing rupture probability with high reliability have been proposed, and the ground distributions of fragments, their impacts, and their damage probabilities have been assessed. The effects of various other factors have also been evaluated.
- Specific probabilistic models of the number of fragments from horizontal cylindrical and spherical vessel explosions have been derived. The effects of various parameters on the ground distributions of fragments, the probability of impact onto the target, and the rupture probability of the impacted target have been explored.
- The mechanisms of the domino effect caused by fragments have been explored and various explanatory models were developed.

On the basis of the previous achievements, the approach of intercepting the fragments generated by vessel explosion has seldom been investigated. Based on the former research, the barrier net put between the source and the objective was considered to analyze the reduction effects on the domino effect. Thus, in order to effectively mitigate and control the domino effect risk triggered by fragments generated by tank blast, practical actions should be adopted to offset the safety protection distance, if required safety distance can not be meet for the plant put into operation or planning land. The barrier net was put between the accident source and objective vessel to reduce the probability of the target damage by fragments. The actual fragment trajectory, the impact probability of fragments, the ruptured probability of the impacted target, and the domino effect risk were respectively calculated using Monte-Carlo simulations under the barrier net. The present results were compared with those without the barrier net. Moreover, the effects of the height of barrier net on the probability of fragments impact were mainly investigated to obtain the reasonable height of barrier net. Therefore, the guide that the block net was set from a height level in order to leave space for emergency escape and save the interception cost in the actual layout of plant was proposed.

2. Trajectory of the fragments and random variables

2.1. Movement approach of fragment

The equations of fragment trajectory established and adopted by