PROCESS SAFETY AND ENVIRONMENTAL PROTECTION xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Estimation of the impact probability in domino effects due to the projection of fragments

Roberto Lisi[a], *Giancarlo Consolo*[b], *Giuseppe Maschio*[c], *Maria Francesca Milazzo*[a,*]

[a] *Department of Electronic Engineering, Industrial Chemistry and, University of Messina, Viale F.S. D'Alcontres 31, 98166, Messina, Italy*
[b] *Department of Mathematics and Computer Science, University of Messina, Viale F.S. D'Alcontres 31, 98166 Messina, Italy*
[c] *Department of Industrial Engineering, University of Padova, via F. Marzolo, 35131 Padova, Italy*

ABSTRACT

Despite the remarkable severity of domino effects in activities at major hazard, a complete methodology analysing such events has not been developed and integrated within Quantitative Risk Analysis (QRA). Such a deficiency appears to be particularly remarkable for domino effects triggered by the projection of fragments. The aim of the present work is therefore to propose a systematic procedure for the quantification of domino effects due to fragments projection within QRA. To achieve this objective, the deterministic approach for the estimation of the realistic trajectory of fragments is entirely reviewed. In order to incorporate such a reviewed approach within the standard QRA, a probabilistic model for the impact probability of the fragments is developed by applying a Monte-Carlo method to the trajectory equations. The validation of the proposed framework is carried out by using the data related to an accident occurred in 1993 in the oil refinery of Milazzo (Italy).

Keywords: Domino effect; Probabilistic analysis; Fragments projection; Tank explosion; Monte Carlo simulation; Quantitative Risk Analysis

1. Introduction

The *domino effect* is the propagation of a primary accident leading to secondary events. The latter is a major one and extends the damages due to the primary accident (Delvosalle, 1996). The literature shows that such events have a high destructive potential (Kletz, 1985; Pietersen, 1986, 1990), some examples are the accidents of Mexico City (1984), Buncefield in the United Kingdom (2005), Vishakhapatnam in India (1997) and Feyzin in France (1966).

A statistical investigation on accidents, occurred in the oil industry, was performed by Fabiano and Currò (2012) identifying failure causes; a complete inventory of domino effects was given by Abdolhamidzadeh et al. (2011). *Domino effects* could be triggered by overpressures, thermal radiations and projections of *fragments* (named *missiles*) (Kadria et al., 2013). In analyzing the potential for domino effects due to fires, the evaluation of the flame extent and temperature are of utmost importance: these items have been amply explored in the scientific literature and recently a novel analytical approach has been developed (Palazzi and Fabiano, 2012). In contrast, the problem of the fragments actually has not been completely treated.

According to the Council Directive 96/82/EC and subsequent laws, the analysis of *domino effects* due to explosions and fires is carried out using simplified methods based on *damage thresholds*. This estimation is based upon technical assessments, which are not probabilistic methods and, therefore, do not take into account uncertainty factors, as suggested by Milazzo and Aven (2012). Concerning Quantitative Risk Analysis (QRA), the literature gives many attempts to develop methods for the quantification of *domino effects* due to fires and

---

[*] Corresponding author. Tel.: +39 090 6765605; fax: +39 090 391518.
E-mail addresses: mfmilazzo@unime.it, francymilazzo@katamail.com (M.F. Milazzo).

http://dx.doi.org/10.1016/j.psep.2014.05.003

Please cite this article in press as: Lisi, R., et al., Estimation of the impact probability in domino effects due to the projection of fragments. Process Safety and Environmental Protection (2014), http://dx.doi.org/10.1016/j.psep.2014.05.003

Nomenclature

a	lower extreme of the range of the uniform density probability function
a_g	sound velocity in the gas
a_o	sound velocity
A	area of the detached portion of the vessel (area of the closed side)
A_D	drag area
A_L	lift area
A_M	coefficient including the effects of the mass of the fragment in the Moore's method
b	upper extreme of the range of the uniform density probability function
C_D	drag coefficient
C_L	lift coefficient
$E_{\text{expansion}}$	fluid expansion energy
E_f	energy stored in the vessel per unit of mass of fluid
$f_u(x)$	Gaussian probability density function
F	dimensionless parameter including the effects of the mass of the fragment in the Baum's method
F_D	drag force
F_L	lift force
g	gravity acceleration
k	coefficient including the effects of the air resistance in the two-dimensional motion equation
k_A	coefficient including the effects of the air resistance in the two-dimensional motion equation
k_D	coefficient including the effects of the air resistance in the two-dimensional motion equation
K	factor for unequal fragments
L	length of the cylinder
m_i	mass of the fragment (average mass of fragments)
$\dot{m}$	mass of the vessel per unit of area
m_f	mass of fluid
m_v	mass of vessel
n	number of fragments
p	absolute pressure of the gas inside the vessel
$\bar{P}$	scaled overpressure
p_d	design pressure
p_o	pressure ambient
QRA	Quantitative Risk Analysis
r	distance of the target from the centre of explosion
R	radius of the vessel
u	fragment velocity
u_i	initial velocity of the ith fragment
u_o	initial velocity of the fragment
$\bar{u}_0$	dimensionless initial velocity
V	volume of the vessel
V_g	volume of gas-filled part of the vessel
x	horizontal component of the trajectory
x_o	expectation value of the normal distribution
y	vertical component of the trajectory
y_A	ascending component of the trajectory
y_D	descending component of the trajectory
t	time
t^*	time at which the ascending of the trajectory reaches the maximum height
α	angle of attack
α_A	coefficient included in the two-dimensional motion equation
α_D	coefficient included in the two-dimensional motion equation
β	coefficient included in the two-dimensional motion equation
ε	fraction of the energy of the explosion
γ	ratio of the gas specific heats
θ	departure angle of the fragment
ρ	fluid (air) density
σ	standard deviation
w_A	coefficient included in the two-dimensional motion equation

explosions (Bagster and Pitblado, 1991; Cozzani et al., 2005; Khan and Abbasi, 1998; Bernechea et al., 2013).

The deterministic estimation of the *domino effects* due to the projection of fragments was proposed by the Centre for Chemical Process Safety (CCPS, 2000). This is a multi-step approach which requires, in sequence, the computation of: (i) explosion energy; (ii) number and size of *missiles* produced by the vessel collapse; (iii) initial velocity and angle of departure of each fragment; (iv) distance of fallout. The estimation of *domino effects* is made by analyzing the plant layout in order to identify facilities located in the range of potential fallout and, therefore, which of them could generate the secondary event. To include the quantification of this type of *domino effects* into the QRA, the consequence and the frequency of the scenario must be estimated. The critical point is the frequency estimation; the frequency of a domino effect is the product of the frequency of the primary event and the probability of the following sequence of events (given the occurrence of the primary event) (Gubinelli et al., 2004). The latter probability is obtained by multiplying the probabilities of the fragmentation, of impact on a target and of damage (given the impact occurrence). (Holden and Reeves, 1985) developed models for the estimation of the fragmentation probability of pressurized tanks. An approach estimating the impact probability based upon the analysis of the initial direction of fragment flight is due to Gubinelli et al. (2004); another method uses Monte Carlo simulations to derive the impact probability as a function of the target distance, this was proposed by Hauptmanns (2001). Finally, correlations for the probability of damage, due to the fragment penetration into the target, are reported by Lees (1996 – vol. 2, section 17/224–227).

The literature above cited shows that a completely consolidated methodology for the analysis of domino effects trigged by the projection of fragments has not been yet developed. This work is an attempt to achieve this goal in the context of the previously mentioned CCPS approach: the aim is to illustrate the entire procedure for the estimation of domino effects due to fragments originating from a BLEVE (Boiling Liquid Expanding Vapour Explosion). In detail, the proposed procedure accounts for Baum's model (Baum, 1995) to compute the initial velocity of fragments. Then, the analytical solution of the set of ordinary differential equations describing their flight is reviewed. The explicit expression for the fragment trajectory is provided with some comments about the differences with respect to other solutions given in the literature. The parameter values appearing in the model have been set-up by

Please cite this article in press as: Lisi, R., et al., Estimation of the impact probability in domino effects due to the projection of fragments. Process Safety and Environmental Protection (2014), http://dx.doi.org/10.1016/j.psep.2014.05.003