Journal of Loss Prevention in the Process Industries 31 (2014) 16–25

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

New correlation for vapor cloud explosion overpressure calculation at congested configurations

Jingde Li [a], Madhat Abdel-jawad [b,*], Guowei Ma [a]

[a] School of Civil and Resource Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
[b] GexCon Australia, 8/64 Fitzgerald Street, Northbridge, WA 6003, Australia

ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form
27 May 2014
Accepted 29 May 2014
Available online 21 June 2014

Keywords:
Confinement
Congestion
Blockage ratio
Obstacle diameter
Flame path

ABSTRACT

In this study, we present a newly developed correlation for the estimation of boundary overpressures in and around congested regions subjected to vapor gas explosions. The GAME correlation, which is based on the MERGE, EMERGE experimental programs, shows rather moderate correlation with computational fluid dynamics (CFD) results in homogeneously congested configurations, however, a greater level of inaccuracy is found when it comes to the combination of a number of realistic scenarios. The newly developed model (confinement specific correlation), which consists parameters of volume blockage ration, the density of the gas, the flame path distance, the confinement ratio and the laminar flame speed of the flammable gas is proposed as a non-dimensional alternative and it shows a closer correlation with detailed CFD simulation in general particularly for realistic geometries. A linear least square method is used to achieve the best fitting parameters by applying the validated commercial software FLACS. About 400 CFD cases with homogenous congestions are modeled using FLACS for the purpose of testing both the GAME correlation and the confinement specific correlation (CSC). In addition to those 400 CFD homogenous cases, around 700 realistic cases in ten different module scenarios of a Liquefied Natural Gas (LNG) train along with three simplified models are simulated to validate the CSC; it is found that the CSC is applicable to both realistic modules with irregular obstacles and homogenous artificial modules.

1. Introduction

Explosions and fires in the process industry (Mannan, Aldeeb, & Rogers, 2002) can result in large financial and environmental damages in addition to potential injury and loss of life. Typical major industrial accidents include vapor cloud explosions (VCE), Boiling Liquid Expanding Vapor Explosions (BLEVEs) and dust explosions. The VCE is defined as “an explosion resulting from an ignition of a premixed cloud of flammable vapor, gas or spray with air, in which flames accelerate to sufficiently high velocities to produce significant overpressure” (Mercx & van den Berg, 2005). Although analytical methods for the calculation of overpressures arising from accidental inventory releases and subsequent delayed ignition of resulting gas clouds leading to explosions have long been in use, these methods hold significant uncertainty because they do not adequately account for several important parameters, particularly the role that congestion and confinement play in flame acceleration and hence the overpressures arising. In particular, methods such as the multi-energy method (MEM) can be in error by more than an order of magnitude because they do not take into account the geometry detail of most industrial layouts and also rely on estimates of explosion strength and congestion input by the engineer. Where such methods are applied conservatively, the estimated overpressure can be much higher than in a real event, leading to significant financial overspends. Conversely, where these estimates are under-conservative (which is a possibility with these methods even when thought to be applied conservatively), the results can be catastrophic.

Computational fluid dynamics (CFD) is by far the most detailed methodology for quantifying the risk posed by this class of catastrophic events. However, despite significant advances deployed in CFD, it remains computationally and labor intensive. There is, therefore, a need for the development of faster analytical models that can be applied with far less effort yet still capture the dominant mechanisms for gas dispersion and flame propagation and flame acceleration. Here we present a correlation that better accounts for important details of complex geometries, which enables this

---

* Corresponding author.
E-mail addresses: jaden_li@hotmail.com (J. Li), madhat@gexcon.com (M. Abdel-jawad), ma@civil.uwa.edu.au, guowei.ma@uwa.edu.au (G. Ma).

http://dx.doi.org/10.1016/j.jlp.2014.05.013
0950-4230/© 2014 Elsevier Ltd. All rights reserved.

correlation to be more accurate that existing analytical methods while offering greater implementation speed compared to existing CFD methods.

Simpler methods such as the TNT-equivalency method (Safety, 1994) and TNO Multi-Energy Method (MEM) (Alonso et al., 2006; Gugan, 1979; Lobato, Canizares, Rodrigo, Saez, & Linares, 2006; Vandenberg, 1985), are often adequate for the estimation of far field pressures where the explosion field displays little directionality. The TNT-equivalency method uses the blast generated by an equivalent amount of TNT to describe the strength of the vapor cloud explosion and the decay of the blast as a function of distance. However, it is inherently assumed that the overpressures generated are equal in all directions with no accounting for directional effects, and it is hard to achieve the correlation between the quantity of fuel involved in the explosion and the equivalent-charge weight of TNT required to model its blast effect (Gugan, 1979). Therefore, this method has limited applicability in scenarios where the layouts are directionally irregular. Further, it is difficult to set up a standard to convert the equivalent charge weight of TNT, in most cases, the effects of VCE in the near field can be either overestimated or underestimated.

The Multi-Energy Method (MEM), which is regarded as a more reasonable simple and practical method alternative (Mercx, van den Berg, Hayhurst, Robertson, & Moran, 2000), is also only reliable for the calculation of far field pressures. MEM uses overpressure results phenomenologically derived from several from simplified numerical solutions of idealized gas explosions (van Wingerden, Hansen, & Foisselon, 1999). MEM has shortcomings similar to those of TNT equivalence method in that they both assume the gas pressure fields are radial. MEM is also ultimately based on a selected severity from 1 to 10 entirely at the discretion of the engineer applying the method with no mathematical basis for the selection.

The shortcomings in MEM led to the development of a Guidance for the Application of the Multi-Energy method (GAME) (Eggen, 1995). GAME was designed to provide additional guidance and to extend its applicability to cases where MEM is designed to address. The phenomenological approach, which is effective for qualitative research projects (Alfred, 1976; Edmund, 1989; Gurwitsch & Garcia-Gomez, 2009), is used to derive the GAME correlation based on the experimental research programs performed during the MERGE and EMERGE projects (EMEG, 1997; Harris & Wickens, 1989; Mercx, Johnson, & Puttock, 1995; Schumann, Haas, & Schmittberger, 1993; Wingerdenv, 1988, 1989) at the Dutch research institute TNO.

As seen in the report (Eggen, 1995), satisfactory correlation with limited experiments were obtained by using GAME correlation, and the it is a safe approach in the determination of the overpressure in most situations characterized by artificially homogenous congestion and confinement.

To set up such experimental tests is a very expensive task and there is a significant limit on the quality of possible tests in that it is very difficult to create realistic fields of congestion and confinement at the appropriate scale. Further, the reliability and repeatability of the tests are often very difficult to achieve because some factors such as initial turbulence, the stability of the wind direction and speed as well as the flexibility of some structural components is very difficult to characterize or account for. Hence we have chosen to compare the results from our new correlation as well as results from the GAME correlation against the highly validated well-established CFD software FLACS. This allows us to examine hundreds of cases including those for realistic geometries at realistic scales which would be impossible to set up without tens of years of significant spend.

Our new correlation presented in this study is validated against widely-accepted CFD commercial software FLACS, which itself has been the validated over the last 40 years against numerous experiments and previous work (Bleyer, Taveau, Djebaili-Chaumeix, Paillard, & Bentaib, 2012; Hansen, Gavelli, Ichard, & Davis, 2010; Middha, Hansen, Grune, & Kotchourko, 2010; Middha, Hansen, & Storvik, 2009). The FLACS CFD solvers account for the parameters of the congestion (Bakke, van Wingerden, Hoorelbeke, & Brewerton, 2010; Davis & Hanen, 2010; Hansen, Hinze, Engel, & Davis, 2010; Huser, Foyn, & Skottene, 2009), the flame path distance and the laminar flame speed of the flammable gas (Chen, Qin, Xu, Ju, & Liu, 2007; Pfahl, Ross, Shepherd, Pasamehmetoglu, & Unal, 2000; Silvestrini, Genova, & Trujillo, 2008) which were derived by using the idealized experimental programs' data, the new correlation was deduced with a set of parameters by means of the linear least square method to describe the obstructed region and the fuel properties in the vapor cloud explosion.

By comparing the results from 1100 simulation cases carried out using FLACS, we are able to compare the estimate the overpressures from the new correlation and the GAME correlation for vapor cloud explosions in realistically congested areas, taking into account the complexity of the geometry; and the congestion and confinement with a well validated benchmark.

2. The GAME correlation and case studies

In this section, the GAME correlation is introduced and investigated by comparing its results with those of FLACS for both realistic and idealized configurations from CFD simulations.

As originally derived from experiments, two variants of the GAME correlation were given in the GAME project to determine the vapor cloud explosion overpressure (Eggen, 1995).

For low ignition energy and no confinement in 3D flame expansion conditions:

$$\Delta P_o = 0.84 \cdot \left(\frac{\mathrm{VBR} \cdot L_f}{D}\right)^{2.75} S_l^{2.7} \cdot D^{0.7} \tag{1}$$

For low ignition energy and confinement between parallel plates (2D expansion):

$$\Delta P_o = 3.38 \cdot \left(\frac{\mathrm{VBR} \cdot L_f}{D}\right)^{2.25} S_l^{2.7} \cdot D^{0.7} \tag{2}$$

where:

ΔP_o = the overpressure [barg],
VBR = the volume blockage ratio, which is defined as the ratio of the total volume of the obstacles inside an obstructed region,
L_f = the maximum distance of flame propagation obtained by assuming L_f equal to the radius of a hemisphere with a volume equal to the volume of the configuration [m],
D = the average obstacle diameter, which give a single average value for the whole obstructed region by assuming a homogenous distribution of obstacle types and obstacle diameters [m],
S_l = the laminar flame speed of the flammable gas by assuming a homogenous stoichiometric flammable cloud in all assessment [m/s].

2.1. Modules tested in CFD simulations

CFD simulations were carried out to validate the results from both the GAME correlation and the newly developed correlation. The overpressures arising from the CFD simulations were extracted for the purpose of comparison with results from both correlations.