Journal of Loss Prevention in the Process Industries xxx (2017) 1–8

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Specific effects of a blast wave impact in vented premises

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ARTICLE INFO

Article history:
Received 17 July 2016
Received in revised form
26 March 2017
Accepted 26 March 2017
Available online xxx

Keywords:
Accident blast
Specific gasdynamic effects
Overpressure
Pressure force impulse

ABSTRACT

The aim of the paper is to reveal specifics of the blast wave loading at walls during an accident volume explosion in the industrial vented premises. The external problem of the blast dynamics is investigated by the method of numerical simulation. Analysis reveals the following specific effects, which are generally inherent to the blast impact process: amplification of the cumulated energy in corners by powerful flow behind Mach stem and then after its reflection from the opposite wall; prolonged rarefied action of vortex at the wall edge; intense local thermal and gas-species mixing in a vortex funnel, which can boost up the re-ignition process; interaction at the outer wall face of the shock waves diffracted at the multigate wall edges. The latter three insist on the necessity of the outer flow computing in the region adjacent to premises in order to obtain correct assessments of the blast loads at walls. Transient distributions of the pressure force impulse and overpressure along the premises perimeter are calculated, which clearly reflect the influence of the found gasdynamic effects. The transient fields of the dynamic parameters are processed in the video format, as well. It is concluded that the revealed specifics must be taken into account in the blast mitigation measures, damage assessments and should be reflected in the dynamic criteria of the wall fracture.

1. Introduction

The processes in chemical, refinery and other industries are accompanied occasionally with accident explosions, which have disastrous outcome (Baker et al., 1983; Glass, 1977; Eckhoff, 2005; van Wingerden, 2011). Blast waves are able to produce structural damage to process equipment even at a large distance. An accidental hydrogen release may result in the detonable mixture formation within an equipment enclosure (Beddard-Tramblay et al., 2008). The assessments of the expected structural damage, including escalation sequences, and the associated loss of the process vessels containment are based on the gasdynamic blast wave loads (Salzano and Cozzani, 2006). The main tasks in a technological management, where the gaseous, liquid or solid blast-perilous material processing takes place, are to provide blast-safety works, to mitigate or minimize consequences of such blasts. The generally accepted approach to a blast-safety equipment design is based on the requirement to minimize the local pressure magnitude and to reduce the area where the utmost blast loads can arise. Two methods are typically used for these purposes: mock-ups and numerical simulations (Baraldy et al., 2009; Clutter and Whitney, 2001; Hashimoto and Matsuo, 2007; Karnetsky et al., 2007). The latter method has the advantage in obtaining complete information to describe a phenomenon, i.e. the data which are contained within solutions of the governing equations. The assessment methodics based on mathematical modeling provide the risk assessment as a mathematical relation, which can be estimated and expressed by the quantity. The main risk analyses and risk-assessment methods were summarized by Marhavilas et al. (2011). The review of mitigation of the vapor cloud explosions is done by van Wingerden (2011).

When the blast occurs in premises, the discharged energy remains within a confined volume for a comparatively long time because the reflected waves transfer it back inside. Therefore, the initial blast wave (BW) strength does not allow getting a conclusion about the transient loading magnitude, which walls, partitions, etc. undergo. When the blast wave interacts with any construction element of a building, the complex transient flowfield is being formed as the result of the non-linear gasdynamic effects, such as irregular Mach reflection, attached shocks, vortex funnels, etc. This circumstance makes it difficult to obtain the reliable information concerning the blast loads, which strongly depend on geometry, orientation and sizes of the loaded object (Baker et al., 1983; Glass, 1977).

The re-ignition and re-explosion hazards as well as the

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http://dx.doi.org/10.1016/j.jlp.2017.03.020
0950-4230/

deflagration-to-detonation process strongly depend on the local temperature and pressure values, as well as on the gas species concentrations, which are achieved at the gasdynamic interaction of the shock wave with any particular construction element. Therefore, taking into account a loading surface geometry leads to a significant difference in loads, when compared with the existing simplified methodics. On the other hand, 3-D calculations with accounting of the BW interaction with the enclosure equipment are laborious, expensive and have minor generalization. However, as the results of the present study show, despite the fact that BW interaction with a building particular element depends specifically on blast-to-element disposition, there exist general effects, which can perform repeatedly in various configurations.

Two most important areas of attention divide the blast-in-premises problem onto the internal task (prediction of the BW formation in a combustible volume with the aim to understand the main combustion mechanisms governing ignition and energy release) and the external task (BW propagation and prediction of the consequences of its interaction with the structure elements). The former task mainly serves to provide the initial values for the latter one. However, no typical regime of the accident energy release exists for the internal problem, with the only exception for the quick mixture burn-out. On the other hand, the external problem formulation has no typical room and blasting cloud geometries. Thus, the external problem is multi-parametric, in general it has no rigorous formulation and the only way of studying is to examine particular cases, which can be classified and then generalized. Such general effects of the gasdynamic kind are found in the present paper, which specifically influence the blast wave loads at walls and re-ignition hazards.

The external problem of an accident blast is the subject of the present paper. The dynamics of the blast wave interaction with walls, which is generated by a volume explosion inside industrial premises, is investigated here in the plane-flow approximation. The mentioned above uncertainties in the internal problem formulation impel us to simplify it, so that the initial accidental energy release is supposed to happen rapidly, i.e. the instantaneous detonation model is applied to the blast-perilous volume combustion. The aim of the investigation is to grope the specific gasdynamic effects of BW-wall interaction following the accident blast in premises and to find their influence on the main dynamic parameters, which characterize the blast impact at walls – transient distributions of the peak pressure and the overpressure impulse along the premises perimeter, – by means of the numerical simulation of the disturbed air motion.

2. Formulation of the problem

From the safety standpoint, it is important to consider the explosion inside premises first of all in connection with the building vitality. Even in the case of the uncompleted mixture burn-out there exists an afterburning, which strengthens the leading shock front later. Therefore we assume here a full energy release, or quick detonative regime of a blast-perilous mixture burning-out, which can result in the pressure growth up to tens of atmospheres. Thus, the worst damages to a building can be assessed in this complete explosion scenario for a fixed combustion volume. The influence of a small-scale internal infrastructure (supports, partitions, etc.) on a risk assessment is important for a case of deflagration regime (Ibrahim et al., 2009); therefore, such peculiarities are ignored here.

The mentioned above absence of the typical room and blasting cloud geometries makes it possible to start with a simple one. First of all, for the sake of simplification we ignore the gas motion in the third (vertical) direction, entering the class of 2-D plane approximations of the problem. This class of 2-D motions is justified in the cases, when a combustible mixture or vapor cloud has the elongated upward form, similar to a cylindrical one, so that the floor and ceiling influence prevents gas motion in vertical direction (Fig. 1). Besides, 2-D approximations describe the real gas motions at the intermediate stage between the initial 3-D and the late 1-D geometry in channels (Uystepruyst and Monnoyer, 2015). Nevertheless, despite the simplified scenario adopted here, the revealed in the present paper effects have the general nature and are able to keep their performance in 3-D formulations. The 3-D simulations will alter the values of the parameters obtained here, but the character of the revealed effects remains unchanged.

Secondly, we consider here the simple form of a cylindrical cloud in a parallelepiped premises (Fig. 1), which can be formed by ascending lightweight combustible gas (hydrogen, methane, etc.) or vapors of combustible liquid; some other cloud/premises configurations were considered in our previous studies (Girin and Abramova, 2004; Girin and Kopyt, 2012), which resulted in similar qualitative conclusions as in the present paper. When the quick energy release is assumed, the mentioned above upwardly elongated form of the explosion volume provides initially radial flow from the cylinder volume and makes it possible to regard the after-blast motion as a plane-symmetrical one reducing the consideration to 2-D simulation in the *XY* coordinate plane; the flow portrayal in each of other parallel planes is the same. The origin of the Cartesian coordinate system *XOY* is placed in the left bottom corner of calculation domain, while the axes are parallel to the wall ribs (Fig. 1).

Thus, the calculations are performed in the plane domain, which consists of premises itself of sizes $20 \times 20m^2$, where the blast occurs, and of the attached outer domain of sizes $10 \times 20m^2$ where the free atmosphere with pressure $p_a = 1.013 \cdot 10^5 Pa$ and density $\rho_a = 1.3kg/m^3$ is at rest (Fig. 2); details can also be seen in the initial freeze-frames of the attached video files. The blast wave and reverberated waves are let to run freely into the outer atmosphere through the aperture located at the wall segment $x = 10m,\ 10 < y < 14m$. The explosive energy release occurs within the round of radius $R_{bl} = 2m$, which is centered at the point $x_c = 16m$, $y_c = 8m$. It is assumed that a blast-perilous mixture burns out instantly at $t = 0$ with the pressure increase up to the value $p_{bl} = 20atm$ corresponding to the released specific energy $Q_{bl} = p_{bl}/(\gamma_{pr} - 1)\rho_{mix} = 8.7MJ/kg$. The initial pressure rise in the explosion volume corresponds approximately to burn-out of 52% of hydrogen in air (volume concentration). The supposition about quick and full energy release leads us hereunder to the worst damage scenario. The thermodynamic state of the burnt products is essentially different with respect to that one of the air.

We treat the air as an ideal, non-heat-conductive perfect gas with the specific heat ratio value $\gamma = 1.4$. The system of equations of adiabatic non-stationary gas motion in Eulerian form is integrated with the help of the Godunov finite-difference scheme (Godunov, 1957; van Leer, 1979) on a fixed grid with the total cell number $1.5 \cdot 10^6$, so that the cell density is 2500 $cells/m^2$ and the unit cell area is $0.02 \times 0.02\ m^2$, which corresponds to the smallest mesh elements in calculations of Uystepruyst and Monnoyer (2015). This fine mesh provides sufficient accuracy in the flow calculations; in particular, the numerical code/scheme successfully captures all the fine non-linear gasdynamic elements (shock fronts, irregular Mach reflection, the vortex generation and structure, blast wave diffraction at the aperture's edges, non-linear transversal interaction of shocks, both inside and outside the premises). The fine vortex structure shown below in Fig. 5 indicates a sufficient cell density. The computational code was tested in a series of one- and two-dimensional non-stationary problems (Girin and Abramova, 2004; Girin and Kopyt, 2012); the total sequence of results corresponding to the sequence of decreasing cell sizes showed

Please cite this article in press as: Girin, O.G., Specific effects of a blast wave impact in vented premises, Journal of Loss Prevention in the Process Industries (2017), http://dx.doi.org/10.1016/j.jlp.2017.03.020