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Developments in vapour cloud explosion blast modeling

W.P.M. Mercx [a,1], A.C. van den Berg [a,*], C.J. Hayhurst [b], N.J. Robertson [b], K.C. Moran [b]

[a] *TNO Prins Maurits Laboratory, PO Box 45, Rijswijk 2280 AA, Netherlands*
[b] *Century Dynamics, Dynamics House, Hurst Road, Horsham RH12 2DT, UK*

Abstract

TNT Equivalency methods are widely used for vapour cloud explosion blast modeling. Presently, however, other types of models are available which do not have the fundamental objections TNT Equivalency models have. TNO Multi-Energy method is increasingly accepted as a more reasonable alternative to be used as a simple and practical method. Computer codes based on computational fluid dynamics (CFD) like AutoReaGas, developed by TNO and Century Dynamics, could be used also in case a more rigorous analysis is required. Application of the Multi-Energy method requires knowledge of two parameters describing the explosion: a charge size and a charge strength. During the last years, research has led to an improved determination of the charge strength (i.e., the class number or source overpressure) to be chosen to apply the blast charts. A correlation has been derived relating the charge strength to a set of parameters describing the boundary conditions of the flammable cloud and the fuel in the cloud. A simple approach may not be satisfactory in all situations. The overpressure distribution inside a vapour cloud explosion is generally not homogeneous and the presence of obstructions causes directional blast propagation in the near field. A CFD approach, in which the actual situation is modeled, supplies case-specific results. An overview of the key aspects relevant to the application of the Multi-Energy method and CFD modeling is provided. Then the application of the two methods is demonstrated for an example problem involving the calculation of the explosion blast load on a structure at some distance from the explosion in an offshore platform complex. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Vapour cloud explosion; Explosion simulation; Blast prediction; Quantitative risk analysis; Source term prediction

* Corresponding author. E-mail: berg@pml.tno.nl

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1. Introduction

Despite many fundamental objections, TNT Equivalency methods are widely used for simple vapour cloud explosion blast modeling. Presently, however, 15 years after its formulation, the TNO Multi-Energy method is increasingly accepted as a more reasonable alternative, for instance in the completely revised Yellow Book (CPR-14E [1]) and in CCPS [2]. The Multi-Energy concept is based on the observation that the explosive potential of a vapour cloud is primarily determined by the obstructed and/or partially confined parts of the cloud.

In these simple methods, the blast from a vapour cloud explosion is modeled by the specification of an idealised explosive charge whose blast characteristics are available in the form of charts. Applying the Multi-Energy method, a blast is modeled by the specification of a hemispherical fuel–air charge, which has two characteristics, namely:

- A charge size E, which is equal to the heat of combustion of the flammable mixture actually contributing to the blast; and
- A charge strength P_0, which may be defined as the explosion overpressure produced. Quantification of both parameters is required to apply the blast charts (Figs. 1 and 2).

According to the current TNO recommendations, the charge characteristics should be specified following a simple safe and conservative approach.

- The charge energy should be taken equal to the full heat of combustion of the flammable mixture present within the area of turbulence generative (boundary) conditions in the cloud, assuming that the fuel is stoichiometrically mixed with air.
- The charge strength should be assumed to be maximum.

Additional recommendations are that, if a user is not satisfied with this safe and conservative approach because it leads to unacceptable overestimates of blast overpressures, he may refine his approach by seeking correlation with experimental data. If the user observes similarity between his problem and an experiment described in the literature, he may estimate a charge strength on the basis of the experimentally observed overpressures.

Over the years, it has appeared that many users were not very satisfied with the safe and conservative approach recommended. In addition, the correlation with experimental data appeared to be not very straightforward because, generally speaking, there is a big difference in configuration between the experiments described in the literature and practical problems (a process plant, for instance).

The projects, GAME (van den Berg and Eggen [3]) and GAMES, sponsored by an international group of industries and authorities, were meant to investigate how to bridge this gap between experiment and practical application.

Section 2 summarises the considerations leading to a choice of a combination of parameters as well as its correlation with experimental data.

A simple approach may not be satisfactory in all situations. Both TNT Equivalency model and Multi-Energy model assume a single value for the overpressure in the exploding vapour cloud as well as point symmetry for blast propagation. Furthermore, the simple models provide the characteristics of a blast wave propagating in an idealised

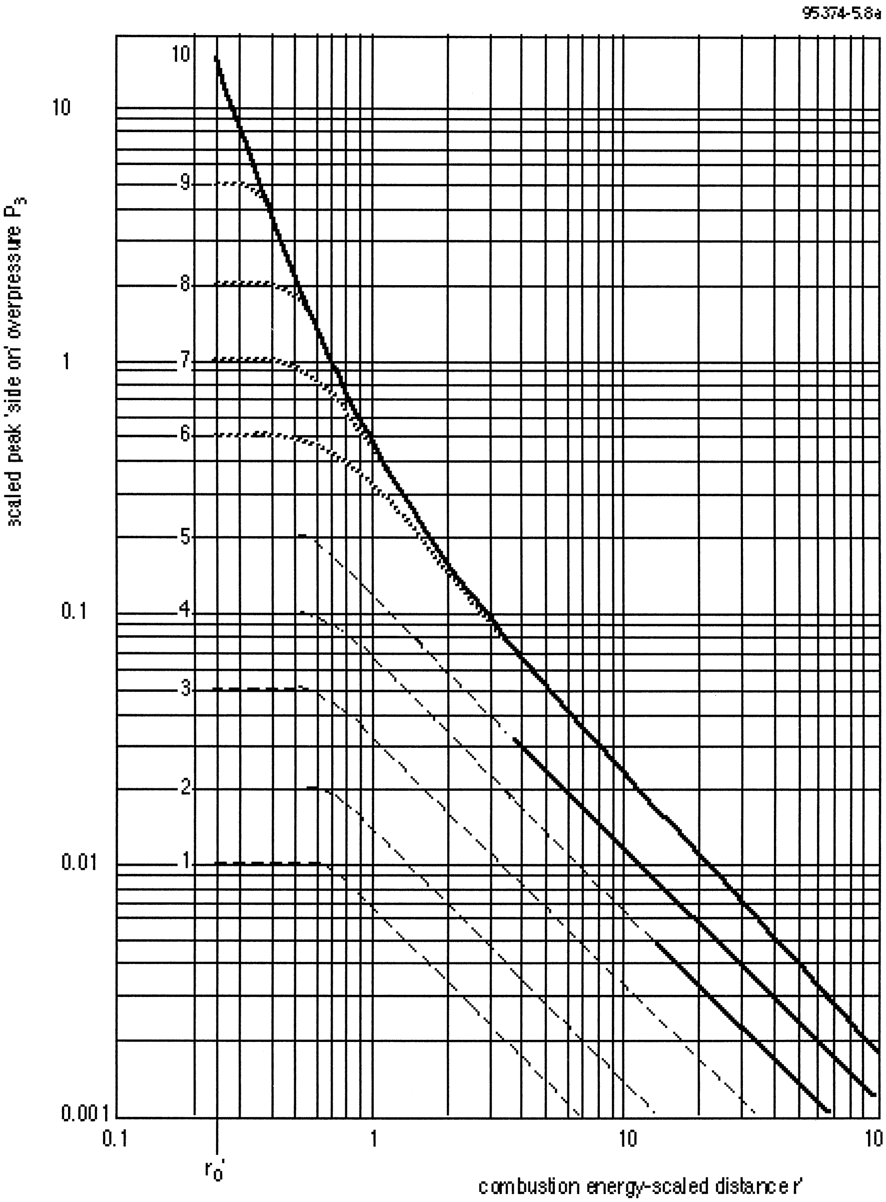

Fig. 1. Chart for blast overpressure according to the Multi-Energy method.

environment: the propagation over a completely horizontal surface without the presence of objects which may interfere with the incident blast wave.

The overpressure distribution inside a vapour cloud explosion is generally not homogeneous and the presence of obstructions inside the vapour cloud causes direc-

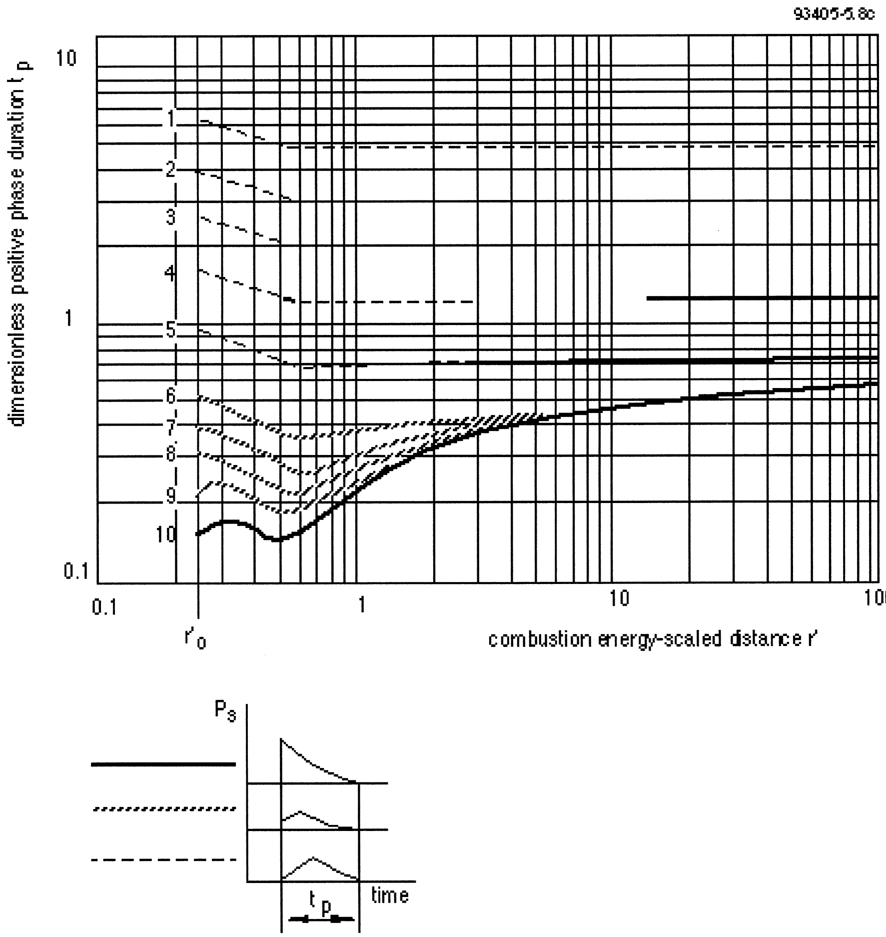

Fig. 2. Chart for blast duration according to the Multi-Energy method.

tional effects in blast propagation in the near field. A computational fluid dynamics (CFD) approach, in which the actual situation is modeled, supplies case-specific results.

The interference of the blast propagation with encountered objects causes the actual load on the objects to be different from the incident blast wave characteristics. Using a CFD code enables the actual load on a structure to be determined.

Section 3 gives a short introduction of CFD modeling of vapour cloud explosion. An example is given to demonstrate the capabilities of a CFD code to calculate the explosion blast load on a structure at some distance from the explosion.

Application of the correlation for the determination of the charge strength to be used in the Multi-Energy model to the same example in Section 4 demonstrates the deficiencies to be solved in order to further improve guidance for the application of the Multi-Energy model.

2. Derivation of correlation to quantify the charge strength

2.1. Introduction

The first objective of the investigation to improve existing guidelines for the application of the Multi-Energy method was to develop a simple guideline to estimate a charge strength in a realistic situation on the basis of experimental data.

Following a procedure very similar to the one used for the drafting of guidelines for gas explosion venting, a combination of parameters was devised by which the conditions, which largely determine the development of gas explosions in obstructed environments, can be characterised. The parameter combination, which should be applicable to realistic situations, was correlated to explosion overpressures available from experimental data.

2.2. Gas explosion

A gas explosion can be well-circumscribed as a process of flame propagation through a flammable mixture, which develops in speed and overpressure by the interaction with its self-induced expansion flow field (CCPS [2]). The development of this process is predominantly determined by three factors.

- The boundary conditions of the expansion flow field. The boundary conditions consist of the close environment surrounding the flame propagation process. The boundary conditions, which may consist of a combination of (partial) confinement and/or obstruction by obstacles, induce a structure in the flow of shear and turbulence. The flame responds to the flow structure encountered by increasing its burning speed.
- The fuel. More reactive fuels develop higher explosion overpressures than less reactive fuels.
- The scale. Experimental data clearly show that similar experiments result in a higher explosion overpressure as their scale increases. The implementation of scale is important because it enables the use of small-scale experimental data for overpressure assessment in full-scale problems.

2.3. The parameter combination

2.3.1. The influence of the boundary conditions

From a review of the experimental datasets, it has to be concluded that all the experiments deal with highly regular obstacle configurations. Obstacles of equal size and shape are regularly configured in rows around the point of ignition. The configurations were fully determined by parameters such as, the overall dimensions, the obstacle diameter, the area blockage ratio in a row of obstacles, and the distance between subsequent rows (pitch).

Parameters, such as area blockage and pitch, apply well in these regular configurations but are not at all defined in a realistic problem such as, for instance, a process plant. A realistic plant is more like an irregularly spaced configuration of objects of irregular shape and size and orientation. Irregularity can only be taken into account by a statistical description. Characterisation must be by average quantities, such as an average size and an average density of objects. In other words, an irregular obstacle configuration must be characterised as an equivalent homogeneous configuration of objects. Some form of irregularity could be taken into account only if sufficient experimental data on irregularly configured obstacles were available. This is not the case.

A homogeneous obstacle configuration is fully characterised by only two parameters: an object density, i.e. a volume blockage ratio (VBR) and an object size (D). A combination of these two parameters is a measure for the spacing between the obstacles. The ratio of a flame path length L_f and the spacing is a measure for the number of obstacles met by the flame propagating from the point of ignition to the outer edge of the configuration.

The number of obstacles met by the flame is the most significant parameter for the development of overpressure. Therefore, a combination of parameters, which characterise the boundary conditions and which are expected to correlate to some degree with the explosion overpressures, is:

$$\frac{\mathrm{VBR} \cdot L_f}{D}, \tag{1}$$

where: VBR — volume blockage ratio, i.e. the portion of volume occupied by obstacles (−); L_f — flame path length, i.e. the longest distance from the point of ignition to an outer edge of the obstacle configuration (m); D — average obstacle size (m).

Because of the feedback coupling triggered by a homogeneous obstacle environment, a flame propagation process develops approximately exponentially both in speed and overpressure. Therefore, an exponential relation is postulated:

$$P_0 \propto \left[\frac{\mathrm{VBR} \cdot L_f}{D} \right]^b. \tag{2}$$

2.3.2. The influence of the scale and the fuel

Scale effects substantially influence the development of the process of turbulent combustion in gas explosions. Similar experiments develop higher overpressures as their scale increases. Presently, two scaling theories, whose results differ only marginally, have found some acceptance. The first was proposed by Taylor and Hirst [4] from the Shell Thornton Research Centre and is based on fractal theory. They state that the ultimate flame speed S_f obtained in some experiment relates to the laminar burning velocity S_l of the fuel–air mixture and the scale Sc, i.e. a linear dimension of the experiment as:

$$S_f \propto S_l^{1.35} \mathrm{Sc}^{0.35} \tag{3}$$

A comparable result is obtained from a second theory, proposed by Catlin [5] from the British Gas Midlands Research Station, which assumes that scale effects in turbulent premixed combustion are predominantly determined by combustion rate reduction because of flame straining. The balance between two characteristic time scales governs the occurrence of flame strain by turbulent mixing: an induction time governing the chemical kinetics of the combustion reaction and a turbulence time scale governing the turbulent mixing.

If on the basis of acoustics, a quadratic relation between overpressure and flame speed is assumed, an approximate relation between the maximum explosion overpressure, laminar burning speed, and scale of the following form can be postulated:

$$P_0 \propto S_l^{2.7} \mathrm{Sc}^{0.7}. \tag{4}$$

If the three factors of influence, namely: the boundary conditions, the mixture reactivity, and the scale, are considered together, a general approximate relation can be postulated:

$$P_0 = a\left[\frac{\mathrm{VBR} \cdot L_f}{D}\right]^b S_l^{2.7} \mathrm{Sc}^{0.7}, \tag{5}$$

where: P_0 — maximum explosion overpressure (bar); VBR — volume blockage ratio, i.e. the portion of volume occupied by obstacles $(-)$; L_f — flame path length, i.e. the longest distance from the point of ignition to an outer edge of the obstacle configuration (m); D — average obstacle size (m); S_l — laminar burning velocity of the fuel (m/s); Sc — a scale factor (m); a, b — constants which determine best fit correlations.

The scale factor, Sc, takes into account the differences in explosion overpressure, which are due to differences in scale alone. On the basis of the present understanding of gas explosion mechanisms, it can be stated that scale effects are predominantly caused by flame straining effects, which are governed by the balance between the chemical kinetics of the combustion and the rate of turbulent mixing. Characteristic turbulent mixing times are proportional to the characteristic turbulent length scales, i.e. proportional to the size of the obstacles, the major origin of the turbulence in the experiments. Therefore, the scale parameter, Sc, is taken equal to the average obstacle size, D.

2.4. Correlation

The postulated combination of parameters was evaluated for all experiments in the selected experimental datasets and correlated with the experimentally observed explosion overpressures in three different datasets selected from the literature:

- a SHELL dataset reported by Harrison and Eyre [6,7];
- a CMR dataset reported by Hjertager [8]; and
- a MERGE dataset reported in Mercx [9].

The postulated combination of parameters was evaluated for all experiments in the selected experimental datasets and correlated with the experimentally observed explosion overpressures. The correlation is graphically represented in the Fig. 3. The graph gives rise to the following conclusions.

- A reasonable correlation of the explosion overpressure with the parameter combination is observed within the MERGE dataset. The quantity and spread of data in the Harrison and Eyre dataset as well as the Hjertager dataset are such that no sound correlation can be derived.

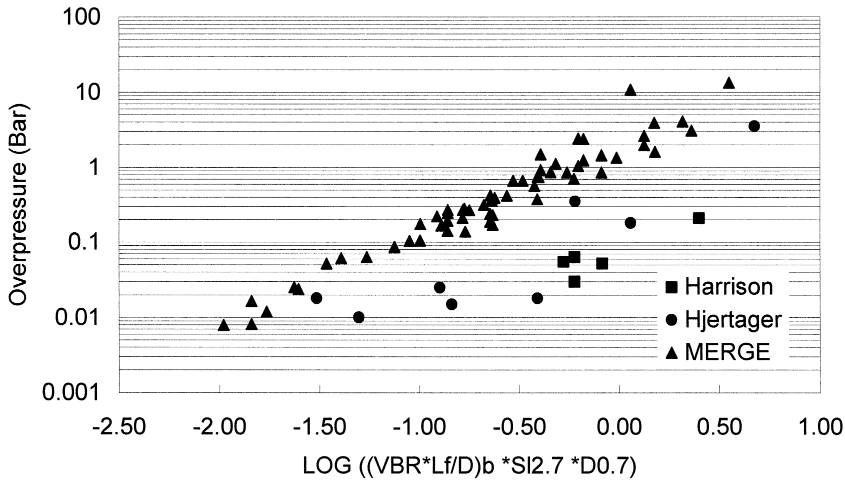

Fig. 3. Observed overpressures dependent on the parameter combination for the three datasets considered.

- If the datasets are considered together, on the other hand, the correlation is poor. It shows that the parameter combination is too global. However, more specific parameters such as, for instance, area blockage and pitch, may give better correlation with experimental data, indeed, but do not apply to realistic problems.
- The parameter combination is the best possible compromise, considering the practical possibilities to parameterise a highly irregular obstacle configuration (a plant), on one hand, and the available experimental data obtained from fully regular obstacle configurations, on the other.
- The data suggest that the MERGE data constitute an upper bound for the experimental data available up to date. Any lack of homogeneity in the obstacle distribution seems to give rise to lower explosion overpressures.

The graph constitutes an instant database, which represents the available relevant data, accessible by the parameter combination. The graphs may well serve as a basis for making a choice of charge strengths in the application of the Multi-Energy method to realistic problems because of the following.

- The graphs give a quick and complete overview of the available relevant data. Having quantified the parameter combination for a problem, the graphs show the range of corresponding overpressures observed experimentally.
- The separate datasets in the graphs are labelled. Characteristic features of the corresponding experimental configurations are clearly indicated. This allows making a more differentiated choice of an explosion overpressure.
- An upper bound choice can be made on the basis of the MERGE dataset. The MERGE dataset was obtained from approximately homogeneous configurations of tubular obstacles. However, obstacle configurations in practical applications are often quite different. Any lack of homogeneity seems to justify the choice of a lower explosion overpressure. The upper bound overpressure can be calculated from Eq. (5) using $a = 0.84$ and $b = 2.75$.

- The Hjertager dataset and the Harrison and Eyre dataset can be used to get an impression of the overpressures to be expected in cases where the orientation of tubular obstacles is predominantly two- and one-directional, respectively.

3. Numerical simulation

3.1. Introduction

A more sophisticated method to determine explosion and blast characteristics is the application of CFD.

AutoReaGas [10], a CFD-based code, has been jointly developed by, and is proprietary to, TNO and Century Dynamics. It comprises two solvers, originally developed at TNO Prins Maurits Laboratory: a ‘Gas Explosion’ (Navier–Stokes) solver and a ‘Blast’ (Euler) solver. The gas explosion solver is used for the analysis of gas cloud explosions, including flame propagation, turbulence and the effects of obstacles in the flow field. The blast solver is used for accurate, efficient capture of shock phenomena and blast waves. These capabilities make AutoReaGas applicable to gas explosions which can occur on both offshore (van den Berg et al. [11,12]) and onshore facilities (Windhorst [13]). Further details of the methodologies used in AutoReaGas are given in Section 3.2. Improvements and validation are continuous processes. These take place in EU research projects like MERGE (Mercx [14]) and EMERGE (Mercx [15]), but also in industry-initiated large-scale validation exercises like in the Joint Industry Phase 2 Project (Selby and Burgan [16]), where blind predictions were performed for full-sized mock-ups of offshore modules.

3.2. AutoReaGas

3.2.1. Gas explosion modeling

The basic concept of a gas deflagration is mathematically modeled as a perfect gaseous fluid which expands as a consequence of heat addition. The gas dynamics is formulated as a set of conservation equations for mass, momentum and energy.

The heat addition is supplied by combustion which is modeled by a simple one-step conversion process of non-reacted fuel–air mixture into combustion products. This is mathematically formulated as a conservation equation for the fuel mass fraction. In the computational mesh, the combustion process is initiated by specifying a certain quantity of combustion products in one of the cells, the ignition point. The subsequent flame propagation through a flammable mixture is a combustion process which takes place in a zone of some thickness which is the interface between the reactants and the combustion products. Such a process can be modeled by any expression for the combustion rate which limits the combustion to places only where reactants and combustion products are mixed. The combustion rate is zero in both the reactants in front of the zone and the products behind the zone. It is non-zero only in cells where reactants and combustion products are present at the same time.

Submodels are available in the code to describe laminar and turbulent combustions as well as a criterion for the transition from laminar to turbulent combustion.

The turbulence, which is the key factor in the mechanism of a gas explosion, is modeled by a $k-\varepsilon$ model which consists of conservation equations for the turbulent kinetic energy k and its dissipation rate ε.

The capacity of present computers sets severe limitations to the grid size. A typical grid size of about $75*75*75$ cells typically requires a CPU time of about a day. Generally, such a grid size allows direct representation of only the largest objects in a practical gas explosion problem. The significant influence of objects of subgrid size on the development of the combustion process in a gas explosion remains unresolved in such an approach.

Therefore, subgrid objects should be taken into account by a subgrid representation. The basic idea for subgrid representation of objects is that the objects are not represented by rigid boundary conditions in the flow field but by a set of cell properties which affect the flow in a way which is representative for the presence of a subgrid object or a configuration of objects.

Cell properties representative for subgrid objects by which the flow is influenced are:

- drag factors dependent on object shape and orientation;
- a source of turbulence kinetic energy; and
- a characteristic length scale of the turbulence.

The mathematical model — consisting of conservation equations for mass, momentum, energy, turbulence kinetic energy, dissipation of turbulence kinetic energy, fuel mass fraction and mixture mass fraction — forms a set of differential equations. For the solution of such a system, the partial differential equations are reduced to a system of algebraic difference equations. This can be done by several techniques such as, finite difference methods, finite elements methods or finite volume methods. In AutoReaGas, a finite volume method has been adopted.

3.2.2. Blast modeling

The assumption of inviscid flow — described by the Euler equations — is justified for the computation of many aspects in the behaviour of blast–object interaction.

A characteristic feature of blast flow fields is the presence of gas dynamic discontinuities like shocks and contact discontinuities. Proper computation of convective transport of discontinuities or sharp gradients is a major challenge in CFD. First-order finite difference schemes are stable, but highly diffusive. They degenerate a convected discontinuity by smearing it over an ever increasing number of grid points. Higher-order finite difference schemes exhibit better performance in convecting a discontinuous distribution but they degenerate it by producing dispersive ripples — a consequence of a different propagation speed for each harmonic the initial distribution may be decomposed in. Moreover, higher-order finite difference schemes are unstable.

To deal with such problems, a variety of methods have been developed during the last two decades. Flux-Corrected Transport (Oran and Boris [17]) is a popular exponent of this class of methods and is used in the blast solver of AutoReaGas.

3.3. Application

Gas explosion and subsequent blast analyses for an offshore platform complex located in southeast Asia were carried out using the CFD-based AutoReaGas software on behalf of Technip Geoproduction in a project of TOTAL (Hayhurst et al. [18]). The complex to be considered consisted of a Production Platform (PP) which was connected by bridges to a Well Head Platform (WP1) and a Quarters Platform (QP). The objective was to predict the overpressures on particular walls of the PP control/electrical switch room and the QP resulting from an explosion on PP, and the overpressures on the PP and QP resulting from an explosion on the WP1. QP and WP1 are located at a distance of approximately 85 m from PP.

Release and ignition source scenarios were assessed for both the PP and WP1. A limited choice of scenarios was considered, given the available resources, with the choices being made in an attempt to cover assumed worst-case scenarios in terms of the effects of the explosion on surrounding equipment and platforms. Analyses typically consisted of two stages of numerical simulation.

- An initial gas explosion analysis in which the process of turbulent premixed combustion and its interaction with the flow generated by geometrical boundary conditions was simulated, using the gas explosion (Navier–Stokes) solver in AutoReaGas.
- A blast analysis to model the propagation of the pressure waves generated during the gas explosion and to estimate the blast loading on adjacent platforms, using the blast (Euler) solver in AutoReaGas.

3.4. Explosion model preparation

Based on design drawings, object databases of the PP and WP1 were generated using the integrated 3D CAD system of AutoReaGas. All major structural members, pipes, vessels and equipment were represented in the model as boxes, cylinders or planes. Particular attention was made to modeling the detail geometry in the region of the ignition sources and regions of possible flame acceleration. A view of the whole complex, as seen in the AutoReaGas CAD model, is shown in Fig. 4.

When the objects database is applied to the numerical grid, each object is automatically defined as either a solid or subgrid object. The user can also specifically request that an object be of a certain type during generation. Solid objects are represented by blocking out the numerical cells whose centres are within the geometrical bounds of the object. If an object has a dimension less than a typical cell dimension or the user has requested so, the object is represented as a subgrid.

Note that in addition to physically solid objects, the grated flooring where it existed on the PP was represented as a subgrid, porous plane with a blockage ratio of 25%. If more than one subgrid object is specified in a single numerical cell, the separate drag contributions are summed and the separate turbulence length scales are averaged.

Several different release scenarios, and ignition source cases were defined by Technip Geoproduction for both the PP and WP1. The description of a particular scenario for the PP and associated results is detailed in Section 3.5. Details of analyses for the WP1 are not included here, but it should be noted that the resulting overpressures were very much lower than those obtained for PP scenarios.

For the PP, a numerical grid consisting of 270,000 uniform cells of side 1.0 m was generated for the gas explosion solver of AutoReaGas. In the plan, the rectangular grid

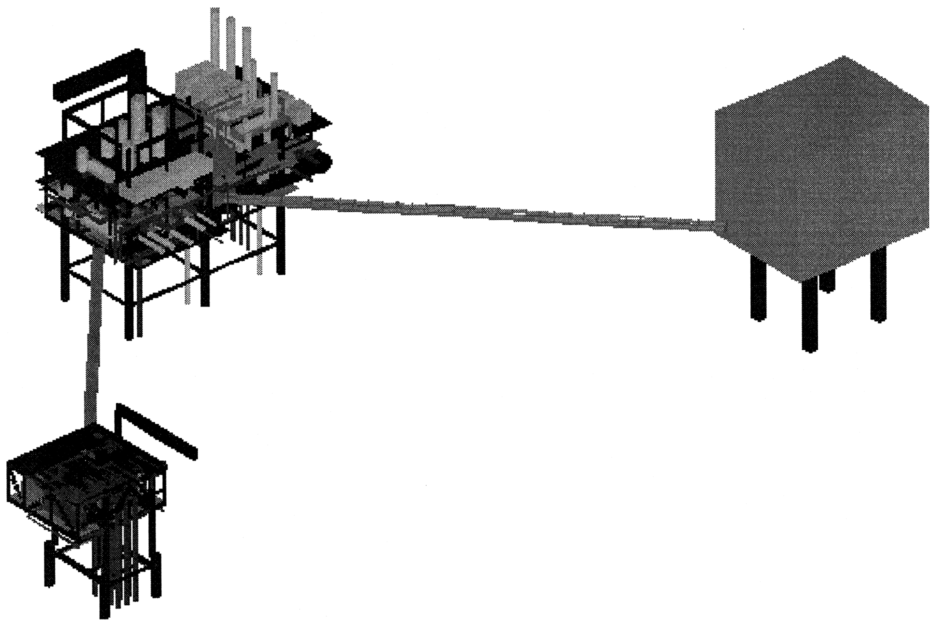

Fig. 4. Offshore platform complex geometry set-up in AutoReaGas.

starts approximately 20 m west, 20 m south and extended approximately 15 m east and 10 m north of the platform perimeter. Vertically, the model extended from sea level to +50 m.

An 'open' boundary condition was applied to all external surfaces of the numerical grid except at sea level, which was represented by an assumed rigid surface. The former boundary condition allows material to flow out of the numerical grid, into a virtual domain at atmospheric pressure and temperature.

3.5. Gas explosion results

Results are given here for the case of a pipe leakage on PP where the release is considered to have filled a very large region of 53 m $\times$ 32 m $\times$ 50 m, thus encapsulating the perimeter of the platform. It was assumed that the gas cloud consisted of a stoichiometric composition of methane and air at ambient conditions.

In the results included here, the ignition source was placed just above the lower deck in the centre of the west wall of the electrical installations room. This particular location was chosen because of the degree of confinement and the number of repeated obstacles in the region.

The explosion analysis on the PP was allowed to run until the pressure wave generated from the explosion reached the boundaries of the numerical grid in the direction of WP1 (at 0.91 s after ignition). At this time (shown in Fig. 5), virtually all the flammable mixtures have burnt and peak overpressures range from 0.5 to 1.5 bar, the

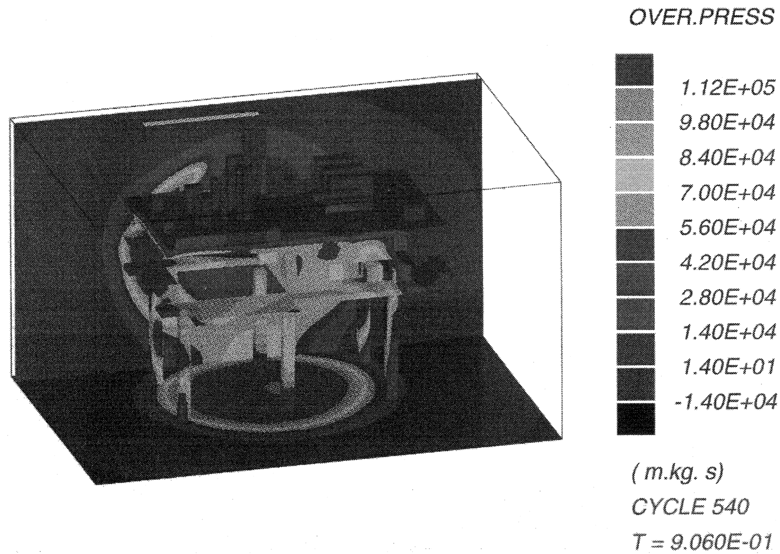

Fig. 5. Gas explosion results, showing the main geometrical entities with explosions overpressure contours in Pascals on these surfaces and on the sea surface.

highest values being found at the west end of the platform at approximately +30 m above sea level. High overpressures are also seen at the sea level due to the reflection of the pressure wave off the surface. The pressures, at the east end, towards the QP are lower than those propagating to the west.

3.6. Blast effects model

To establish the magnitude of the blast loading on the surrounding platforms due to the explosion on PP, the results of the gas explosion analysis were remapped as initial conditions for the blast solver; details of the remapping procedure are given below. The blast model consisted of 378,000 regularly spaced cells each of size 2.0 m in the horizontal direction and 4.0 m in the vertical direction. In the plan, the rectangular grid started at 110 m west, 140 m south and extended to 108 m east and 18 m north of the PP perimeter. Vertically, the model extended from sea level to 120 m. At the time the analysis was done, only uniform cells could be applied; more efficient usage of numerical cells can be achieved using graded cells (a rectilinear grid) and this is available in and routinely used in AutoReaGas.

The numerical representation of the PP, WP1 and QP in the blast model is necessarily cruder than that in the gas explosion models because of the larger cell sizes. Objects in the blast solver representing the platforms may only be defined as solid objects, i.e. objects which are larger than the numerical cells. An ‘open’ boundary condition was applied to all external boundaries of the numerical grid except at sea level, where a rigid surface was assumed.

The initial conditions for the blast analysis were taken to be the results of the PP explosion analysis at about 0.91 s, at which time the combustion process was complete. The pressure, density, internal energy and velocity fields calculated using the explosion solver were remapped into the blast solver numerical grid. Remapping of the gas explosion analysis results into the blast solver numerical grid was necessary because the numerical grids used for the two analyses were not the same. In fact, the volume represented by 16 cells in the explosion solver is equal to the volume of a single cell used in the blast solver. This remapping technique enables a faithful reproduction of the explosion source in the blast analysis. The quality of the remapping process was assessed; for instance, comparison of the overpressure contours at the end of the explosion analysis with those at the start of the blast calculation was made.

3.7. Blast effects results

The blast analysis was allowed to run to a time well after the blast wave generated from the explosion on the PP had passed the QP and WP1. The blast reached the QP and WP1 at around 0.25 s, after the start of the blast analysis, or 1.16 s after ignition. The pressure time histories described below indicated that the positive phase duration for the blast wave was around 0.1 s. The highly three-dimensional and non-hemispherical nature of the blast wave is shown in Fig. 6, where a Mach stem-like reflection from the sea (assumed rigid) can be seen. Analysis of the simulations showed that the strong blast at lower elevations was enhanced as a result of the explosion being initially directed downwards because of a solid floor weather deck on the PP. The ignition source and

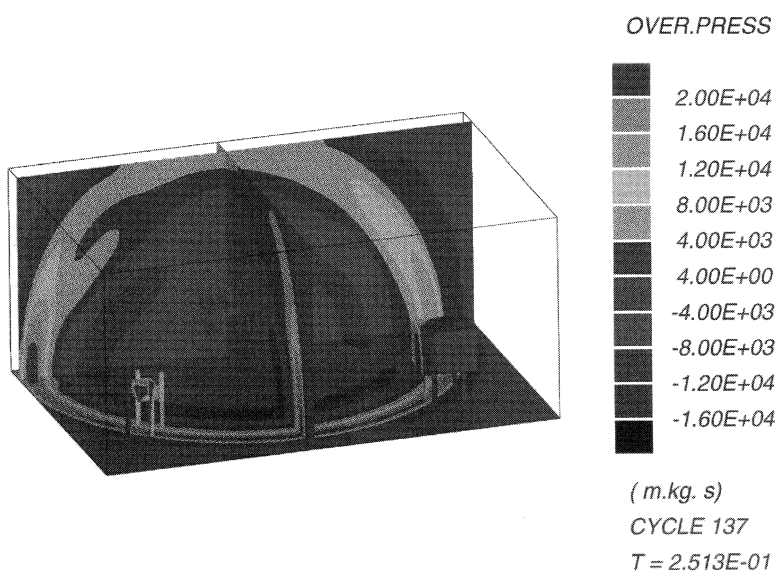

Fig. 6. Blast propagation results, showing blast overpressures on the sea surface and on two vertical planes through the PP and on the WP1 (left), PP (centre, rear) and QP (right).

main congestion on the PP were below this solid floor so the high pressures generated were found to reflect downwards towards the sea.

The reflected overpressure time histories for an array of gauges located on the sides of QP were recorded. The peak reflected overpressures were around 0.25 bar; these relatively high values led to the consideration of design changes.

TOTAL, Technip Geoproduction and the authors considered several design changes. Some of these were adopted and used in subsequent re-analyses of the simulations outlined above. Full details of the considered changes and the related QRA are beyond the scope of this paper. Design changes given serious consideration included lengthening and re-orienting of the bridge from PP to QP, reducing confinement in critical regions of the PP and reducing the risk of the postulated release on the PP and QP. More information on how the code was used in the design process can be obtained from Hayhurst et al. [18].

It should be noted that the simulated pressures generated for the QP were not the only means of assessment; usage of a single analysis methodology is never to be recommended. In fact, there was initially considerable doubt about the believability of the numerical simulations. In particular, the decay of peak pressures with distance from the PP was much lower than was expected, before CFD simulations were conducted. Ultimately, these doubts were removed when the nature of the blast propagation was understood and calculations supplementary to the numerical simulations were presented. The supplementary calculations consisted of assessments with the Multi-Energy model.

4. Application of the Multi-Energy model

4.1. Deficiencies of the correlation

Evaluation of the parameter combination in application to a realistic problem, a plant, may give rise to substantial uncertainties. The estimation of an average obstacle size, for instance, in practical applications may not be very straightforward. Various definitions of an average obstacle size in a non-homogeneous obstacle configuration are possible.

Obstructed areas in practical applications (plants) are often of an aspect ratio (length/width or length/height), much higher than one while the correlation was compiled from experiments of aspect ratio approximately equal to one. While not considered in the correlation, the aspect ratio of an obstacle configuration is an important factor that largely determines the explosion overpressure.

The influence of aspect ratio and also of ignition location becomes apparent when a value for the maximal flame path length has to be determined. The experiments underlying the correlation used an ignition located in the centre of the obstacle configuration, resulting in flame path lengths independent of the direction of the flame. The flame leaves the obstacle configuration almost simultaneously at any boundary. In case of large aspect ratio and/or non-central ignition location, the flame will pass the various boundaries of the obstacle configuration at various points in time. Venting of the explosion starts the moment a flame passes the nearest boundary, thereby influencing the flame propagation in the other directions.

These and other uncertainties came forward during an exercise in which the correlation was applied to a number of realistic plants. Overpressures, obtained by the correlation in various ways, were compared to real overpressures. Because explosion overpressures in realistic plants are not available, they were computed by numerical simulation. To this end, the software package, AutoReaGas™ [10], has been used to provide references for the explosion overpressures against which the results of the correlations were evaluated. The exercises were performed in a follow-up project for GAME called GAMES. The results obtained in the project are currently not yet available for publication. The correlation will therefore be applied to the case presented in Section 3 for which AutoReaGas simulations were performed.

4.2. Application

The Multi-Energy model was applied to the same case as described in Section 3.4 (see Fig. 4). Both the charge size E and the charge strength P_0 have to be determined in order to apply the blast charts (Figs. 1 and 2).

In order to show the influences of the choice for parameter values on the blast overpressure at the location of QP, a number of cases are considered. Results of some of the calculations are given in Table 1.

In case 1, we assume that only the part of the cloud 'entrapped' inside the obstructed region contributes to overpressure and blast. Case 2 assumes (in contradiction to the basic principle of the method) that the whole cloud contributes to overpressure and blast.

Cases A and B differ in the flame path length. For A, we have taken the maximal distance between ignition location and any of the outer edges of the platform and for B, we have taken an average distance to the edge of the cloud involved.

The charge strength was calculated using the correlation (Eq. (5)) with $a = 0.84$ and $b = 2.75$. The higher volume blockage ratio in case 1 (factor 2) results in a higher charge strength in comparison with case 2. The large charge size in case 2 causes the decay of blast overpressure with absolute distance to be much slower than in case 1. Nevertheless, peak side-on overpressure at the location of QP is much lower in case 2.

Table 1
Peak blast overpressure at QP

Parameters	Case 1A	Case 1B	Case 2A	Case 2B
Volume blockage ratio (−)	0.14	0.14	0.08	0.08
Average obstacle diameter (m)	1.04	1.04	1.04	1.04
Laminar burning velocity (m/s)	0.45	0.45	0.45	0.45
Flame path length (m)	32.1	28.1	32.1	34.1
Charge volume (m^3)	46 592	46 592	83 200	83 200
Charge size E (GJ)	191	191	341	341
Charge strength (bar)	5.08	3.53	1.03	1.22
Distance (m)	85	85	85	85
Scaled distance (−)	0.69	0.69	0.57	0.57
Side-on overpressure (bar)	0.12	0.05	0.01	0.01
Reflected overpressure (bar)	0.24	0.10	0.02	0.02

The conclusion must be that, the part of the cloud outside but underneath the platform does not contribute to blast. If this part is omitted, then almost no objects are neglected, as the ratio in volume reduction is equal to the increase in the ratio of the volume blockage ratios.

Therefore, the overpressure for case 1 should be taken as the result for the application of the Multi-Energy method. Still, there is a factor of at least 2 between blast overpressure cases A and B. This is due to the current uncertainties in the determination of the flame path length. Further research is required to come up with an improved result. On the other hand, one should not forget the simplistic and therefore global approach of the method.

In comparison with the AutoReaGas results (0.5 to 1.5 bar locally) for the overpressures inside the charge (the cloud entrapped in the platform), the Multi-Energy results are considerably higher. This result shows that, indeed, the simplistic approach is still a conservative one, as it is expected to be and that more advanced tools like AutoReaGas can be used to come up with a more specific answer.

The results for the blast overpressure show that a more specific answer does not always result in a lower value. Despite the lower explosion overpressures, the numerical calculation resulted in higher peak blast overpressures than the simplified approach.

Close evaluation of the numerical result shows the creation of a so-called Mach stem. Such a stem is created when the incident blast from an explosion in the air and its reflection to the surface interfere, resulting in a shock propagating parallel to the surface. The pressure difference over this shock is equal to the reflected overpressure of the incident shock. In fact, the QP is loaded by this Mach stem and thus by an overpressure twice the original incident overpressure.

A shock wave interaction phenomenon like Mach stem creation is not accounted for in the Multi-Energy blast chart. This chart is for an explosion, which occurs close to the surface like most ‘unconfined’ vapour cloud explosions in onshore situations.

5. Conclusions

In applying the Multi-Energy method for vapour cloud explosion blast modeling, an equivalent fuel–air charge is defined by the specification of a charge size and strength. This paper investigates the potential of experimental data as a basis to develop guidelines for a choice of charge strengths.

Following a methodology used in drafting explosion-venting guidelines, a combination of parameters has been devised. This parameter combination characterises the major determining factors for the explosion overpressure such as the degree of confinement, obstruction and the fuel. The parameter combination is the best possible compromise, considering the possibilities to parameterise a highly irregular obstacle configuration in a realistic problem (e.g. a plant) on one hand, and the available experimental data obtained from fully regular obstacle configurations, on the other.

The parameter combination, correlated with various sets of experimental data, resulted in an instant database in the form of graphs. The graphs show a poor correlation if all the data are considered together. On the other hand, a reasonable correlation is observed within the dataset for obstacles in a three-directional orientation. In the graphs, the individual datasets can be clearly distinguished and are labelled with characteristic features of the experimental configuration. These features allow some differentiation in the choice of a charge strength depending on the obstacle orientation.

The CFD code, AutoReaGas, was used to assist in the consequence and risk assessment of gas explosions that might occur on platforms in an actual offshore platform complex which was under development. One of the simulations performed was used here to demonstrate the capabilities of the code and to be used for comparison with the results of the Multi-Energy model applied to the same case.

Application of the correlation to realistic problems showed that evaluation of the parameter combination is not always very straightforward. The determination of flame path length and average obstacle diameter requires specific further research. The correlation should be adapted such as to include the influence of aspect ratio and ignition location.

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