A SURVEY OF CURRENT PREDICTIVE METHODS FOR EXPLOSION HAZARD ASSESSMENTS IN THE UK OFFSHORE INDUSTRY

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Abstract
This paper describes some results of a recent survey of predictive methods that are currently in use for explosion hazard assessments in the UK offshore industry. Three categories of models, namely empirical models, physically-based models and numerical models, are addressed in the survey. A brief description is provided on the key features of the models for each category and the potential advantages and limitations in their application.

Key Words explosions, offshore, empirical models, physically-based models, CFD codes

1. Introduction

This paper describes the major features of an update to a previous OTH report on explosion modelling for offshore structures produced by British Gas (Ref 1) for the Department of Energy. The new OTH report (Ref 2) has been prepared by NNC Ltd for HSE.

Explosions have been historically regarded as consisting of two general categories: confined and unconfined. Confined explosions typically occur in heating plant or inside buildings, involve relatively low levels of turbulence and have been treated historically using venting guidelines. Unconfined explosions, which typically occur in industrial process plant and are now generally known as Vapour Cloud Explosions (VCEs), do not involve an obvious confining geometry but still can produce high overpressures. The reason for generation of these high overpressures is that they occur when the vapour cloud is ignited in the vicinity of plant structures with two key simultaneous geometric features - dense spatial distributions of obstacles in the path of the flamefront and a configuration of parallel planes (such as compartment boundary walls or piperack layouts) which provide a degree of confinement for the explosion. The dense spatial distribution of obstacles increases the rate of volume production of burnt gas by increasing the flame speed due to turbulence generated ahead of the flame by these obstacles. The configuration of parallel planes restricts the expansion of the burnt gas so that the flamefront interacts with the structure generating the turbulence.

Offshore explosions may encompass confined explosions and vapour cloud explosions as described above, but may also involve levels of confinement intermediate between what it is typically associated with confined explosions and VCEs. A key feature of an offshore explosion is that the level of congestion of pipework and equipment tends to be greater than what might be typical for an industrial process plant, because of the high economic incentive to produce as compact a layout as possible on an offshore platform. Another key aspect of an offshore explosion is that the overall structural integrity of an offshore platform needs to be maintained for some time, since the evacuation of personnel from the platform is more difficult to achieve than for a land-based installation. This in turn leads to the requirement that the combustion zone of the explosion needs to be explicitly modelled in order to predict

the overpressures which occur in offshore modules.
The three general categories of modelling methods for prediction of overpressures in gas explosions are empirical models, physically-based models and numerical models. These modelling methods are reviewed for applicability to the offshore explosion problem. Specific computer programs for modelling explosions are also reviewed.

2. Empirical Models

2.1 Introduction

The three main types of empirical model are:-

(i) Venting guidelines
These guidelines have been historically used for estimation of overpressures or relief area requirements for vented confined explosions occurring in industrial heating plant or rooms in buildings. These guidelines take the form of simple formulae for overpressure or required relief area, or may be described by graphs or nomograms. They are simple enough to enable hand calculations to be performed.

(ii) Venting guidelines based on small-scale offshore module experiments
In recent years, experimental studies have been performed on small-scale models of offshore modules. Test data from these experiments can potentially be used to develop a simplified graphical approach for estimation of overpressure in a congested volume.

(iii) Complex empirical models developed for offshore applications
These models are based on experimental work in highly congested volumes and can be regarded as complex venting guidelines which take account of a large number of parameters which contribute to explosive overpressures, including details of obstacle layouts. Usually these models are computer-based because of the number of the parameters involved.

2.2 Venting Guidelines

Venting guidelines are reviewed in detail in Ref 1 and summarised in Ref 2. These guidelines include the vent ratio method, vent coefficient method, Bartknecht method, Bradley and Mitcheson's method, Runes method, Decker's method, Cubbage and Simmonds formulae, Cubbage and Marshall formulae, Rasbash formulae and NFPA 68. In the offshore industry use is made of venting guidelines in conjunction with turbulence factors for estimation of overpressures in offshore explosions.
Application of venting guidelines to offshore explosion scenarios is not supported when test or analysis results for explosions occurring in offshore process modules are reviewed. As an example, experimental observations indicate that overpressures in propane-air explosions in congested volumes are typically twice as high as overpressures generated in methane-air explosions. Venting guidelines would suggest that only a 15-30% difference in peak overpressure between the two different fuels is expected.
The concept of applying a turbulence factor to the laminar burning velocity for an offshore module explosion is investigated in the results shown in Table 1. In this table, the turbulence factor required to give agreement between the Cubbage and Simmonds formula for the P2 pressure peak and experimental pressure results for a scale model of a congested offshore module are tabulated against vent coefficient. Using the conventional form of the Cubbage and Simmonds formula, a turbulence factor of up to 30 is required, which is well in excess of values quoted in the literature (e.g. up to 10 is quoted in Ref 3).

2.3 Venting guidelines based on small-scale offshore module experiments

Experiments involving gas explosions in small-scale congested offshore modules have been conducted to an increasing extent in the last ten years. These experiments have been carried out to assist in the understanding of explosion processes in congested volumes, to assist in the development of complex empirical models and physically-based models, and to test the accuracy of predictions by numerical models. Some experimenters (e.g. Hjertager et al in Ref 4) have published data for explosive overpressures as a function of the vent coefficient. This data is potentially applicable as a venting guideline, and Ref 4 has been used for this purpose in the offshore industry.

2.4 Complex empirical models developed for offshore applications

2.4.1 COMEX

The COMEX program has been developed by Veritec, now part of DNV Technica, and is based on results from 700 experiments carried out by DnV. The test program sponsors were Det norske Veritas, Shell, Norsk Hydro, Amoco and HSE. COMEX is used in conjunction with another explosion modelling program BANG, which is used for sensitivity studies, and a probabilistic analysis program called PROEXP. The latter program provides a probability distribution for explosive overpressure taking account of gas leak rate, gas composition, ventilation rate, module volume, ignition location and time to ignition.

COMEX is described in Ref 5. It is based on empirical correlations which consider an empty enclosure, vent size, vent location, blockage ratio for obstacles, type of obstacles and number and location of obstacle grids. The range of application for COMEX and the complementary program BANG are given in Table 3.

As is the case with any empirical model, there is doubt about the validity of extrapolation to larger scales or volumes.

The program is considered to produce conservative overpressures in congested off-shore modules in cases where there are openings on one wall or two opposite facing walls. The accuracy is more doubtful for cases where modules have large openings on several boundary walls.

2.4.2 VENTEX

VENTEX is a model developed by Shell which is generally similar to COMEX. It was developed using experimental data obtained from DnV involving a large number of tests on a 35 m^3 volume and a smaller number at 425 m^3 volume, together with in-house experimental data from work carried out by Harrison and Eyre on empty enclosures which highlighted the effect of external explosions.

The modelling approach is that the basic overpressure in an empty enclosure is calculated and then correlations from experimental data are applied to give multiplying factors for the number of obstacles, location of obstacles and other parameters. The correlations involve an error between -30% and +100% for prediction of overpressure against the various parameters. The final overpressure is given by the product of the basic overpressure and these multiplying factors.

The range of application for VENTEX is given in Table 3. The commercial availability of the program is unknown.

VENTEX has been validated for prediction of overpressures on three scale model off-shore modules, which indicated agreement to within a factor of 2.2 of the observed pressure. VENTEX has been found to be significantly conservative in relation to predicting overpressures in the recent SOLVEX series of experiments which consider a volume of 550

m^3. For this reason, Shell TRC now prefer the more theoretically based explosion analysis program SCOPE2.

One feature in VENTEX which is not present in other phenomenological models is the capability to model mixtures of several flammable gases, although this is restricted to alkanes (paraffinic hydrocarbons).

VENTEX is a generally similar program to COMEX and is considered to produce conservative overpressures in congested off-shore modules within the range of application of the program, including restrictions on multiple venting paths.

2.5 Overall assessment of empirical models

Venting guidelines are not suitable for predicting overpressures in highly congested modules in offshore platforms. As noted in table 1 it is difficult to assign a turbulence factor and the approach has a poor physical basis.

Explosions on offshore platforms are most likely to occur in highly congested volumes such as the process modules and wellhead module. However, it is potentially feasible for a gas release under the platform to enter other relatively uncongested rooms on an offshore platform via the HVAC system. In these conditions venting guidelines might be applied. The only venting guidelines recommended in Ref 1 and 2 are the Cubbage and Simmonds Formulae, Cubbage and Marshall Formulae, and Bartknecht nomograms. These should be applied for initially quiescent gas-air mixtures in vessels with relatively smooth walls, subject to limitation on parameters given in table 2.

Use of the venting guideline based on Hjertager test results (Ref 4) may be applied in highly congested volumes for design concept studies for an offshore platform, in cases where equipment layouts are insufficiently defined to use more sophisticated methods. Use of this guideline is considered to be preferable to use of venting guidelines in conjunction with turbulence factors. Limitations on the use of the Hjertager test results are given in table 2.

The complex empirical models discussed in Section 2.4 may be used for modelling of offshore explosions occurring in congested volumes such as process modules, taking account of the range of application for the programs given in table 3.

The main advantage of complex empirical models over numerical models (discussed in section 4) is that they provide a quick and cost-effective hazard assessment tool for studying the effect of different equipment layouts and different venting arrangements on explosive overpressure, and thus can be used to assist the detailed design phase of a project. They would also meet the requirement for multiple analyses coupled with sensitivity studies often required for risk assessments. Disadvantages of these models in comparison with numerical models are that substantial judgement by the analyst may be required to idealise equipment layouts into the obstacle grid arrangements required by these programs, the ability to represent multiple venting paths may be restricted, and leading shock wave effects associated with high flame speeds (> 150 m/s) which in turn lead to complex reflection effects within the enclosure (Ref 6) are not likely to be represented in the small-scale experiments.

3. Physically-based models

3.1 Introduction

Physically-based models are models which represent the major physical processes or 'phenomena' in the overall explosion process. Physical principles, in conjunction with experimental data, are invoked to represent the explosion process rather than solving the fundamental differential equations for the fluid, as is the case with the numerical models discussed in Section 4.

These models are much more economical to use than numerical models and they also avoid potential scaling limitations associated with the complex empirical models described in Section 2.4.

3.2 Types of physically-based model

The two main types of physically- based model are:

(i) Confined explosion type

These models can only represent low levels of turbulence and provide a theoretically based alternative to venting guidelines for single chamber empty vessels.

(ii) High turbulence type

These models can represent high levels of turbulence generated by obstacles and so could be used to model vapour cloud explosions and offshore explosions.

3.3 Confined explosion type physically-based models

These models have been developed to assist in the understanding of vented gas explosions in the situations normally covered by venting guidelines. The models typically assume the overpressure within the enclosure is uniform, which is known as the isobaric assumption. Examples of models in this category are given in Ref 7 and Ref 8.

3.4 High turbulence-type physically-based models

3.4.1 CLICHE

CLICHE (Confined Linked Chamber Explosion) was originally developed by British Gas to study explosions involving flame propagation from one room to another. A volume is modelled as a sequence of interlinked chambers where the isobaric assumption is retained for each individual chamber. In the context of modelling a process module on an offshore platform, the module would need to be idealised as a sequence of chambers along the longest dimension of the vessel. Mass and energy conservation equations for each chamber, together with equations for mass flowrate between chambers and ideal gas equations of state, are used to develop a coupled system of ordinary differential equations which are solved at successive timesteps.

CLICHE also includes a wrinkled laminar and turbulent combustion model. The turbulent combustion model is due to Bray (Ref 9), with the wrinkled laminar combustion model based on balloon experiments carried out by British Gas.

Theoretical details for CLICHE are reported in Ref 10. CLICHE is incorporated into the commercially available CHAOS software package. The range of application of the program is summarised in table 3.

CLICHE has been validated against explosion experiments conducted by TNO in a semi-circular test rig with repeated obstacles in a pattern of concentric circles, as described in Ref 10. Validation has also been performed against a series of $^1/_5$ scale and $^1/_3$ scale off-shore module tests, with CLICHE predicting conservative overpressures in 20 out of 23 tests.

Features of the model include the ability to model any ignition position, non-uniform gas concentrations, irregular obstacle arrays and multiple venting paths. Currently the model does not consider vent opening at a significant overpressure; it assumes vents are uncovered or are covered by structurally weak panels. This restricts the ability to represent vapour cloud explosions which may involve unintentional venting due to failure of structural boundary walls. An external explosion model is currently not included in CLICHE, but the pressure enhancement effect caused by an external explosion is expected to be less significant for a congested volume than for an uncongested volume.

The main advantage of using CLICHE in modelling offshore explosions is that it has similar overall capabilities to the numerical models discussed in Section 4, but is potentially quicker and more economical to use because of the simplified modelling approach.

3.4.2 SCOPE2

The SCOPE2 program was devised by Shell TRC to provide a more fundamentally based explosion overpressure prediction program.

The theory underlying SCOPE2 was published in the open literature in 1991 (Ref 11) in the form of the earlier SCOPE1 version of the program. The modelling approach is presented in Ref 11 in a reasonably detailed algorithmic form which enables a reader to develop a simple computer program.

The basic steps in modelling the explosion are:

(i) A congested volume is modelled as a box with a vent at one end and the ignition source remote from the vent, with equipment idealised as obstacle grids between the ignition source and the vent.
(ii) One dimensional flow from the ignition source to the vent is assumed with the flow velocity calculated from expansion ratio and burning velocity. This effectively requires a predominant venting path for the explosion to be identified.
(iii) Self-acceleration (wrinkling of the flame front) is considered in the absence of obstacles.
(iv) The enhancement of burning velocity as the flame passes through an obstacle array is considered using a model which takes account of the obstacle dimensions, flow velocity and a number of parameters which depend on the particular fuel and its concentration. The turbulent burning velocity model is based on the Fractal approach of Gouldin (Ref 12).
(v) The maximum pressure inside the enclosure prior to flame emergence is calculated from the drag pressure associated with the flow velocity at the vent with consideration of flow blockage from the nearest obstacle grid to the vent.
(vi) An empirical correlation for the effect of the enhancement of pressure inside an enclosure due to an external explosion is then used to calculate the maximum pressure inside the enclosure.

SCOPE2 represents an enhanced version of the SCOPE1 program. Full details of any improvements in the methodology and capabilities of SCOPE2 over SCOPE1 are expected to be reported in the open literature during 1994.

The range of application for SCOPE2 is summarised in table 3. SCOPE2 is available to sponsors of the SOLVEX project, but the commercial availability of the program is unknown. A program based on Ref 11, EXTRAN, has been written by NNC Ltd. EXTRAN includes an enhancement over Ref 11 in that it calculates the duration of the explosion, which is necessary for structural analysis. The range of application is summarised in Table 3.

The earlier version of the program, SCOPE1, was validated (Ref 11) against a series of experiments in a 35 m^3 volume conducted by Det norske Veritas (DnV). These experiments considered obstacle grids made up of pipes or boards. SCOPE2 was also found to under-predict explosive overpressures obtained in DnV tests carried out at a larger scale of 425 m^3 volume by at least a factor of two. Concerns over the scaling issue and doubts about the representability of the DnV tests at 425 m^3 volume (the tests were carried out in a tunnel with the explosion not venting into free space) resulted in the SOLVEX test programme being initiated by Shell, which has been conducted using a congested volume of 550 m^3. SCOPE2 was found to give reasonable agreement with the SOLVEX tests. Additional validation for SCOPE2 has also been carried out based on eighty experiments at $^1/_6$ of the SOLVEX scale.

The major advantage of the model is that it represents the only simplified method available in the open literature for representing highly turbulent gas explosions where the combustion zone is explicitly modelled.

The method provides a rapid hazard assessment tool for explosions occurring in congested off-shore modules. However the assumption of a predominant venting path may cause difficulties in an off-shore module explosion scenario where multiple venting paths are available. In the report on the Piper Alpha enquiry (Ref 13), reduction of explosive overpressures (particularly with regard to retro-fitting existing platforms) by introducing multiple venting paths is discussed. These vent paths include provision of grated floors and/or ceilings rather than solid decking, provision of open ends for the module and weakening or removal of parts of walls between modules. Provision of these multiple venting paths tends to break up the system of confining planes which drive the gas flow through obstacle arrays and produces high overpressures. The application of SCOPE 2, which has a predominant vent path assumption, to such a situation would require careful interpretation of the results.

3.5 Overall assessment of physically-based models

Use of confined explosion-type physically-based models should be limited to uncongested volumes for modelling of offshore explosions. This restriction on use is similar to that for traditional venting guidelines discussed in section 2.5. The only advantage of these models over traditional venting guidelines is that they avoid the excessive conservatism associated with certain venting guidelines, and they are not subject to scaling limitations.

The high turbulence type physically-based models discussed in section 3.4 may be used to represent explosions in congested volumes such as process modules, taking account of the range of application given in table 3. Advantages and disadvantages of this type of physically-based model compared with numerical models are similar to those given for the complex empirical models in section 2.5. Advantages of this type of model over complex empirical models are that there is greater confidence in extrapolating to larger scales, and information on the duration and shape of the explosive pressure-time history is usually available.

4. Numerical Modelling

4.1 Introduction

Numerical modelling methods involve the direct evaluation of the fundamental partial differential equations governing explosion processes. The motivation for using them is that they could, in principle, offer a means of obtaining accurate predictions over a wide range of conditions and geometrical arrangements. This section reviews the models which are currently in use for the prediction of explosions in the partially confined conditions of

offshore platforms.
All the current models are based on the subdivision of the domain of interest into a large number of small cells in each of which the conservation equations for mass, momentum and energy are solved. The approach has two major limitations. The first is that some of the processes involved in explosions, especially turbulence and combustion, cannot be fundamentally represented by differential equations. This necessitates the use of modelling approximations and a reliance on experimental data for the calibration of the models. The second limitation is that the development of explosions depends on fine-scale processes such as flames and flow around small objects. This means that accurate predictions require a large number of small cells. The models fall into two groups distinguished by their discretisation techniques. The first group contains those models which use a finite volume approach involving first order accuracy in space and time. These are FLACS, μFLACS, EXSIM AND REAGAS. The second group of codes, COBRA and EXPSIM, use second order discretisation methods.

4.2 Review of numerical models

The models described here are all currently being used to assess the effects of explosions on offshore platforms. The models are all under continuing development. Characteristics of the numerical models are summarised in Table 4.

4.2.1 FLACS

The FLACS code has been under development for over ten years at Christian Michelsen Research (CMR), Norway. It was described at length in Ref 1. The current version is FLACS-89 (Ref 14) which is used by several offshore operators. This is about to be superseded by FLACS-93. The main developments have been in the field of front-end links to CAD systems and back-end links to structural engineering codes. It is also claimed that the accuracy of the treatment of flames has been improved. FLACS uses a finite volume numerical method on a 3-dimensional cartesian mesh. The discretisation is first order in both space and time with the use of upwind differencing for convection terms and fully implicit time stepping. This ensures the stability of the solutions making the code robust in general applications but at the expense of introducing potentially significant numerical diffusion. The code has the facility for the partial blocking of cell volumes and faces which allows the representation of the accelerating effect of sub-grid scale obstacles.
Turbulence is modelled by the commonly used two-equation k-ϵ model. Extra source terms are used to model the generation of turbulence by obstacles. In regions containing many obstacles the equation is not solved and the length scale of turbulence is fixed instead.
Combustion is modelled as a single step process. Transport equations are solved for the fuel fraction and a mixture fraction. The rate at which fuel is burnt is assumed to depend on the dissipation time for turbulent eddies (Ref 15). Adjustments allow for extinction when dissipation times are shorter than reaction times and enhancement when turbulence levels are low in the initial flame regime (Ref 16, 17). The numerical diffusion in the code tends to thicken flames and increase burning rates. It also makes flame speeds dependent on the mesh spacing. The latest version of the code has been improved in this respect but the methods are unpublished as yet.
There has been extensive validation of FLACS (Ref 1, Ref 18-20). Generally the code is found to predict the correct trends but is not always conservative in its predictions of peak pressures. Errors of the order of +/- 40% are claimed. This magnitude of error is to be expected with a first order scheme and insufficient mesh points for full resolution of the

field variables. The mesh requirements are such for 3-dimensional solutions that checks for mesh independency are seldom made. It is probable that the meshes required for mesh independency are so fine that they cannot be realistically used with present day computing powers.

FLACS was designed for offshore explosion analysis and has now accumulated a body of validation and user experience in this field. There is now an appreciation of the magnitude of errors to be expected. Within the limits of these expectations the code may be applied with confidence to cases for which the physical parameters, such as the gases involved, the initial conditions and the geometrical blockage factors, are inside or close to the ranges over which the code has been validated. The problem of mesh dependency of the solutions means that different users may obtain different results. While mesh independency cannot be expected care should be taken over mesh selection and possibly minimum requirements should be specified.

4.2.2 μFLACS

This code is a commercially available simplified version of FLACS for use on personal computers.

The code contains the same physical modelling and numerical scheme as FLACS. A specially written front-end allows the code to be run in the Windows environment. It provides geometry building blocks and automatic meshing. In order to achieve reasonable run times the number of mesh points is limited and the explosion scenarios are restricted. Stoichiometric mixtures only are treated. μFLACS and FLACS results have been compared for a range of modules represented with the geometry limitations imposed by FLACS and good agreement has been demonstrated. μFLACS models are not claimed to be as versatile or as accurate as full FLACS treatments. The code is intended to be used as a screening tool for identification of explosion scenarios producing worst-case overpressures for subsequent modelling using FLACS.

4.2.3 EXSIM

EXSIM has been developed at Telemark Institute of Technology (TMIH) and Telemark Technological R&D centre (Tel-Tek) since 1989 (Ref 21). It is based on the development work carried out at CMR and in fact seems to be identical to FLACS-89 in its numerical modelling aspects. The current version is EXSIM-92. The numerical method appears to be identical to that used in FLACS-89. Early validation studies for FLACS should therefore be relevant to EXSIM. Separate validation exercises have been carried out including, modelling of experiments in 1/5 and 1/33 scale offshore modules (Ref 4, 21). The general findings are that on average the code predicts peak pressures to within about +/-40% of measured values. It is also reported that predicted pressures are on average about 90% of measured values with a variation of a factor of 2. These errors are of the same order as those reported for FLACS.

The code should perform in a similar manner to FLACS. Provided that it is used within the validated regime and sensible meshes are used peak pressures should be predicted to within the error limits specified above.

4.2.4 REAGAS

REAGAS has been developed by TNO - Prins Maurits Laboratory, The Netherlands. It was described in Ref 1 as a 2-dimensional model but has now been extended to three dimensions. It is used to only a limited extent by its originators.

The numerical model is similar to that used in FLACS. The combustion model was reported to be basically similar to that in FLACS but the treatment of the early stages of combustion was not considered adequate for large explosions. There is no evidence that this situation has changed. Validation is claimed against a 1/4 scale offshore module but this work has not been published. This code could perform in a similar manner to FLACS but at present it does not have the same degree of validation or user experience.

4.2.5 COBRA

This is a new development by British Gas in conjunction with Mantis Numerics. As yet there are no published reports of the modelling or the numerical methods.

COBRA is a 3-dimensional finite volume code with the choice of cartesian or polar coordinates. An adaptive meshing scheme is used which is reported to give second order accuracy in space and time. Explicit time stepping is used in transient problems. The code has no facility for partial blockages and so relies on fitting the mesh to fine-scale obstacles. Turbulence is represented by the two equation k-ϵ model which includes compressibility effects and accounts for sub-grid solids. There is an option to use a one equation k-1 model in near wall regions and presumably in regions with a high density of fine-scale obstacles. The k-1 model might be more appropriate in these regions because the length scale can be fairly well-defined close to surfaces. A Reynolds stress model is also being implemented. This will potentially be more generally applicable but at the cost of greater computational effort. Details of the combustion model are not known but it is claimed that it models chemical kinetic and flow field effects while maintaining a realistic flame thickness and also gives accurate predictions of turbulent burning velocities.

It is claimed that mesh independent solutions can be achieved but no indication is given of how many mesh points are required to achieve this. The use of a second order scheme should reduce the number of cells needed although the computational effort for each cell may be increased. The adaptive mesh will also reduce the number of cells required because it allows the use of fine meshes only where they are necessary.

Validation is still in progress and reports have not yet been published but it is claimed that peak pressures are predicted to within +/- 20%.

The COBRA code is clearly an attempt to produce an accurate numerical model of explosions. The achievement of second order accurate mesh-independent solutions will effectively remove numerical errors from the predictions. The accuracy of the results will then depend only on the adequacy of the physical models and how well the geometry has been represented. The accuracy is likely to have been gained at the expense of long run times and large computer memory requirements. The code is likely to be available only to the specialist user. It could be a valuable tool for developing models for the representation of turbulent combustion. It could also be used to provide solutions for situations of general interest, for which experiments are not available, against which other codes could be validated.

4.2.6 EXPSIM

The EXPSIM code has been developed by Snamprogetti Ltd for the prediction of partially confined offshore explosions and is extensively used by them (Ref 22).

EXPSIM is a finite-element model based on 2-dimensional rectangular elements. It is believed to be second order accurate in time and space and it uses explicit time stepping. There is no facility for partial blocking of cells and so geometrical features must be modelled by fitting the mesh to them.

The k-ϵ model is again used to represent turbulence but in this case sub-grid effects are accounted for by making empirically determined adjustments to the constants in the turbulent viscosity equation.

Combustion is modelled as a multi-step process but no other details are known.

The use of a second order finite element method requires that the mesh be fine enough to give adequate resolution before results can be achieved. Mesh independent results are claimed. In-house validation tests have been carried out but the results are not published.

EXPSIM uses an accurate numerical scheme and so its predictions are limited by the modelling of turbulence and combustion. Its major drawback is that it is only 2-dimensional and so cannot model the geometrical details of an offshore module. The code has proved to be useful for simple geometries (Ref 22).

4.3 Overall assessment of numerical models

The range of codes available for explosion modelling can be divided conveniently into two groups on the basis of the accuracy of their numerical methods. The two groups of codes have essentially different objectives.

The first group, which includes FLACS, μFLACS, EXSIM and REAGAS, have first order accurate numerics and their aim is to improve on the phenomenological models. They give a much more detailed description of an explosion and can readily be applied to general geometries and conditions. The advantages of this group of models over the second group are that they are sufficiently robust for dissemination to trained non-specialist users and they run relatively quickly on moderately sized computers. Ultimately they could be developed into standard engineering tools for the design and assessment of offshore modules. Their main disadvantage is that their predictions are of limited accuracy. This is unlikely to improve while the current numerical methods are retained but an increasing body of validation tests should give a better feel for their predictive capabilities. Guidelines on meshing would help to standardise the results achieved.

The second group of models, which includes COBRA and EXPSIM, have potentially accurate numerical schemes and thus present the new possibility of obtaining accurate predictions of explosions. Their large demands on computer resources and the probably less robust behaviour of their second order numerics means that they are likely to remain specialists' tools. At present their accuracy is limited by the quality of the physical models of turbulent combustion but these codes provide vehicles for the further development of the models and hence a greater understanding of explosions.

5. Conclusions

This paper reviews the applicability of empirical models, physically-based models and numerical models for modelling of offshore explosions.

Use of simple venting guideline methods should be restricted to uncongested volumes and conceptual design studies.

Complex empirical models, high turbulence-type physically-based models and numerical models may be used for representing explosions in congested offshore modules such as process modules. The range of application for programs in these modelling categories is summarised in tables 3 and 4.

Complex empirical models and physically-based models provide a cost-effective alternative to numerical models and facilitate the application of risk assessment techniques. An encouraging range of validation information is available for the physically-based models, and these models are considered to be more reliable in extrapolation to large scale than the complex empirical models.

Increasing use is being made of numerical models for explosion hazard assessment. There are more models available and they are becoming easier to use. There is also a wider range of encouraging validation studies and a generally greater availability of the necessary computing power.

The most commonly used numerical models are those based on first order accurate finite difference methods such as FLACS and EXSIM. These have been shown to be readily applicable to a variety of geometries and initial conditions. Validation work is beginning to quantify the reliability of these models. Their predictions are limited by the approximations in both the numerical methods and the constraints on the number of mesh points which can be used.

Numerical models with more accurate numerical methods are coming into use and being validated. They are likely to be more difficult to use and more demanding in terms of computer power.

Acknowledgements

This paper is published by permission of the Health and Safety Executive. The authors wish to thank the organisations that contributed information on their computer programs that are used for explosion modelling.

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TABLE 1
TURBULENCE FACTORS REQUIRED TO ACHIEVE EXPERIMENTAL PRESSURE RESULTS FOR 1/5 SCALE OFFSHORE MODULES

Vent Parameter (1/K)	Vent Coefficient (K)	Turbulence factor applied to Cubbage and Simmonds venting guideline to achieve experimental pressure result for propane explosion			
		M25 separator module		M24 compressor module	
		(a)	(b)	(a)	(b)
0.46	2.2	30.5	8.3	20.6	5.6
0.92	1.1	17.4	4.7	10.2	2.8
1.98	0.5	19.7	5.4	19.7	5.4
2.85	0.35	8.5	2.3	7.5	2.0
4.78	0.21	3.5	0.95	-	-

(a) Pressure calculated using $P_2 = 58S_oK$
(b) Pressure calculated using $P_2 = 58S_oKV^{1/3}$

(P_2 pressure peak is greater than P_1 pressure peak for vent coefficients and volume applicable to module tests; also the module tests considered initially open vents for which the P_1 pressure peak is not applicable)

TABLE 2
RANGE OF APPLICATION FOR RECOMMENDED VENTING GUIDELINES

Method/Formula	Range of application
Cubbage and Simmonds	$V < 300m^3$ $Lmax : Lmin < 3$ $K < 5$ $W < 24$ kg/m^2 $Pv < 20$ mbar
Cubbage and Marshall	$V < 300m^3$ Lmax : Lmin < 3 2.4kg/m^2 < W 24 kg/m^2 20 mbar < Pv < 500 mbar KW < 73kg/m^2 So < 1 m/s
Bartknecht nomograms	$V < 100$ m^3 Lmax : Lmin < 5 100 mbar < Pv < 500 mbar 200 mbar < Pmax < 2000 mbar
Venting guideline based on Hjertager test results	Lmax : Lmin < 3.2 K < 2.2 V BR < 0.3 V < 500 m^3 Pv < 20 mbar

V Volume
Pv Vent relief pressure
L Enclosure dimension
K Vent coefficient
Pmax Maximum pressure
So Burning velocity
VBR Volume blockage ratio
W Relief vent weight per unit area

Computer program	Venting arrangements	Geometry details	Ignition position	Types of explosive gas-air mixtures handled	Other conditions	External explosion considered
Physically-based models						
CLICHE	Single or multiple vents; no limitation on vent area; opening of vents at significant pressure not currently considered	General cuboid shape; no limitations on volume or aspect ratio (but only validated for low aspect ratios); single or multiple compartment (approach for treating multiple compartments is simple and not currently validated)	Any	Built-in data for methane, propane, oxygen-enriched methane (latter used in British Gas experimental work); any gas concentration, non uniform and uniform concentration; could be extended to other gases fairly easily	Accuracy of code reduced at very high pressures	No, but British Gas have a separate model for external explosions which is potentially available
SCOPE2	Single or multiple vents, limitation on venting area being currently assessed. Opening of vents at significant pressure considered	Cuboid shape, single compartment. Limitations on aspect ratio currently being assessed, but expected to be up to 3	Furthest position from vent	Uniform concentration of methane, propane, or ethene. Maximum burning velocity mixture, other mixture concentrations can be handled. Mixtures of several flammable gases currently being assessed	Overpressures should not exceed one bar; regular obstacle arrays	Yes
EXTRAN	Essentially single vent. Vents should be uncovered or low strength	Cuboid shape, single compartment. Aspect ratio limit expected to be less than 4	Furthest position from vent	Uniform concentration of methane, propane with built-in data for maximum burning velocity mixture	Overpressures should not exceed one bar; regular obstacle arrays	Yes
Complex empirical models						
COMEX (and complementary program BANG)	Single or multiple vents located in one or two opposite faces, grated or louvred areas considered. Vent opening at significant pressure not considered by COMEX but considered by BANG	General cuboid shape. COMEX can handle a single compartment, BANG multiple compartments, aspect ratio less than 3 to 4	End ignition position only for COMEX, central position only for BANG	COMEX handles a near stoichiometric mixture of propane only, BANG a maximum burning velocity mixture of methane only. Uniform concentration only	Regular obstacle arrays	Yes
VENTEX	Essentially single vent with ignition at point furthest from available vent. Vents should be low strength and lightweight and located on one or two faces; caution should be used if venting occurs in three or more directions	Cuboid shape with single compartment, aspect ratio not greater than 10 and less than 3 for reliable use	Further position from vent (less than 10 m distance for reliable use of program); low energy spark type ignition	Uniform concentration of alkanes, including methane and propane. Mixtures of several flammable gases are handled	Volume is completely filled with gas; gas mixture is initially quiescent, obstacles are uniformly spaced with same geometry	Yes

TABLE 3
RANGE OF APPLICATION FOR PHYSICALLY-BASED MODELS AND COMPLEX EMPIRICAL MODELS

TABLE 4
NUMERICAL MODELS

Program Characteristic	FLACS, EXSIM	REAGAS	COBRA	EXPSIM
Discretisation	Finite volume cartesian	Finite volume cartesian	Finite volume cartesian, polar adaptive	Finite element rectangular element
Dimensions	3D	3D	3D	2D
Numerical accuracy	dx, dt	dx, dt	dx*dx, dt*dt	dx*dx, dt*dt
Time steps	implicit	implicit	explicit	explicit
Obstacles	porosity mesh fit sources	porosity mesh fit sources	mesh fit sources	mesh fit
Gases	hydrocarbons	methane, propane	any	any
Properties	built in	built in	some built in	
Mixtures	yes	no	yes	yes
Structures	simple wall failure	simple wall failure	no	no
Combustion	single step eddy break-up initial flame model extinction	single step eddy break-up	single or multi-step eddy break-up Arrhenius	multi-step
Turbulence	k-ϵ obstacle sources	k-ϵ obstacle sources	k-ϵ, RSM k-l near walls obstacle sources compressibility	k-ϵ modified viscosity
Mesh convergence	no	no	yes	yes
Validation	extensive	yes	in progress	yes
Error in peak pressure	± 40%		± 20%	
Conservative	no	no	yes	no
Confidence	in confined areas near validation conditions	near test conditions	reasonable	in confined areas ~ 2D geometries