SIMPLIFIED FLAMMABLE GAS VOLUME METHODS FOR GAS EXPLOSION MODELLING FROM PRESSURIZED GAS RELEASES: A COMPARISON WITH LARGE SCALE EXPERIMENTAL DATA

V.H.Y. Tam[1], M. Wang[1], C.N. Savvides[1], E. Tunc[2], S. Ferraris[2], and J.X. Wen[2]
[1]EPTG, BP Exploration, Chertsey Road, Sunbury-on-Thames, TW16 7LN, UK
[2]Faculty of Engineering, Kingston University, Friars Avenue, London, SW15 3DW, UK

Gas explosion modelling is used widely to assess explosion loading due to overpressure or drag forces. These loadings depend upon the conditions when ignition is assumed to occur. We consider one of these conditions, namely the volume of a flammable gas cloud, specifically from a release of pressurized gas; and the application to the most commonly used commercial explosion code, FLACS.

There is a number of ways this volume is defined. The three main methods are (i) volume enclosed by the LFL contour surface, (ii) volume bounded by LFL and UFL contour surfaces and (iii) burning velocity weighted volume (Q9). These methods give vastly different flammable volumes. This can result in inconsistent overpressure prediction. As all these methods are currently being used, this situation is not satisfactory.

In this paper, we compared the prediction using different methods against data from the large scale explosion experiments (Phase 3b). Our results showed that the burning velocity weighted volume Q9 significantly underpredicted loads for explosion load higher than 0.1 bar compared with the other two measures which gave neutral to slightly over-conservative prediction of explosion loads.

1 BACKGROUND

Gas explosion is recognized to be one of the key major hazard accident risks in chemical, oil and gas processing facilities. Explosion modelling is used widely to assess these risks. Modelling techniques can vary from simple methods (e.g. multi-energy methods proposed by TNO) to more complex CFD codes (e.g. FLACS). The former is used widely to assess offsite risks, while the latter for on site or assessing potential explosion consequences close to or within the body of the congested facilities.

The consequence of a potential gas explosion varies depending on many factors. One of these is the volume of flammable gas cloud, usually within the volume of the production facilities where density of pipework and equipment form significant congestion.

In explosion consequence assessment, the flammable gas cloud volume definition varies between (a) the volume occupied by congestion, i.e. the body of the processing plant, and (b) the volume to represent the varying concentration field produced by a pressurized gas release within the body of the processing plant. The latter is referred to as "realistic release scenario".

There are a number of "realistic release scenarios" methods being used and these methods could give vastly different flammable volumes. This results in inconsistent explosion load estimations. As gas explosion overpressure loading is one of the key design input to the design of structures and buildings on onshore and offshore production facilities, the use of inappropriate methods could lead to over-design, or worse, a structure not fit for purpose. Similarly, risk would either be over or underestimated.

The subject of this paper is the various methods used in calculating flammable gas cloud volumes in the "realistic release scenario" approach. Specifically, we focus on methods used in the most widely used explosion code in the process industry: FLACS which was developed by Christian Michelsen Research (and latterly by GexCon) with over two decades of research funded by the major oil and gas companies including bp. The comparison with other explosion code will be addressed in future papers.

In this paper, we present our finding on the evaluation of these methods against data from the large scale experiments on explosion under realistic release scenarios, Phase 3b which will be described later.

2 FLAMMABLE GAS CLOUD VOLUME

There are a number of commonly used methods to derive the volume of a flammable gas cloud in a "realistic release scenario". One approach is to use the concentration and turbulence fields calculated for the dispersion phase of the gas release prior to ignition and applied them directly as input to gas explosion calculation. Leaving aside the issue of collecting data to verify this approach, the drawback of this is that it requires a large number of simulations that cannot be realistic completed within reasonable timescale (e.g. that of a typical design project).

A common approach that has been evolved and practiced today is to reduce the flammable gas cloud to a volume which is uniform and at stoichiometric concentration, in order to reduce the number of simulations to a manageable level. This still leave the issue of location and size of the volume. We examine three methods of representing this volume.

2.1 "> LFL": VOLUME BOUNDED BY LFL

This is the net volume of flammable gas above the lower flammability limits (LFL). This method has been used to estimate flammability distance for many years on onshore facilities and at bp for offshore facilities till the completion of the joint industry project on "jet dispersion" (Cleaver 1999).

As this measure includes volume above upper flammability limit (UFL) which is too rich to burn, the view of many is that this measure is over-conservative. This view is supported by previous work (Savvides 2001) indicated that this measure tend to give larger flammable volume than measured.

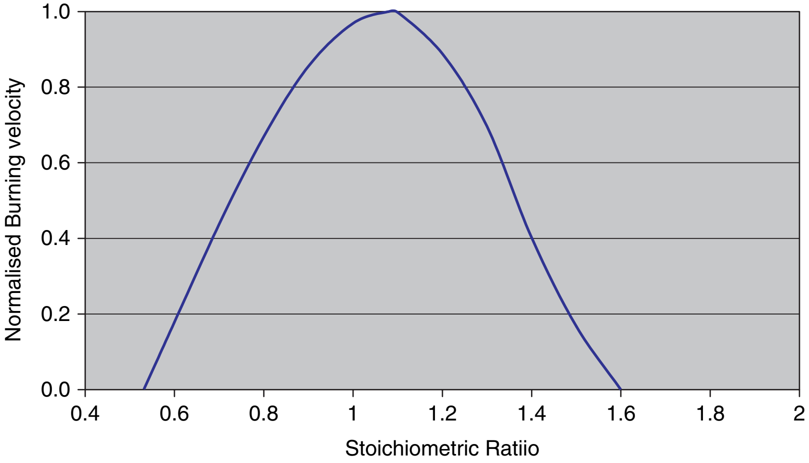

Figure 1. Variation of burning velocity with concentration of methane in stoichiometric ratio. This is taken from the correlation used in FLACS

2.2 "ΔFL": VOLUME BOUNDED BY UFL AND LFL

This is a logical development of the ">LFL" measure above, removing the volume with concentration >UFL, leading to a measure which is not seen to be "overly" conservative.

2.3 "Q9": WEIGHTED EQUIVALENT STOICHIOMETRIC VOLUME

In a pressurized gas release, the resultant flammable gas cloud would have a variation of concentration within it. Q9 is a volume measure which accounts for the effects of gas concentration by weighting the volume with the effect of burning velocity and expansion ratio. Prior to Gexcon introducing Q9 recently, a slightly different quantity, Q5, was used. To all intents and purposes, Q5 and Q9 give identical results. Here, we will only use Q9.

Experiments showed that burning velocity varies with concentration of flammable gas in air. For hydrocarbon, burning velocity is maximum at or near stoichiometric concentration of 1 and dropping off rapidly as gas concentration is rich (stoichiometric ratio > 1) or lean (stoichiometric ratio < 1), reaching zero at UFL and LFL (see Figure 1). Further, the expansion ratio follow similar pattern (Law 2006).

Q9 reduce the contribution of a volume of a parcel of gas to the total flammable volume by the product of these two effects, summarized in equation (1).

$$Q9 = \sum_{i=1}^{i=n} \frac{Vol_i(SE)}{S_{\max} E_{\max}} \qquad \text{Equation (1)}$$

Where

Vol_i = volume of a volume element i
S = burning velocity at the concentration of the Volume element i
E = Expansion ratio at the concentration of the volume element i
S_{max} = Maximum burning velocity of the flammable gas.
E_{max} = Maximum expansion ratio of the flammable gas.

Q9, effectively, puts a heavy weighting for flammable volume close to stoichiometric ratio of 1.

2.4 GENERAL BEHAVIOUR OF THESE MEASURES

These measures give different flammable gas cloud volumes. It can be seen that ">LFL" gives the largest volume, followed by ΔFL, then Q9. Magnitude of explosion loading would follow the same pattern.

We found that Q9 measures are being used increasingly by consultants. We are concerned that there has not been work to verify that this approach is indeed correct. Our observation is that there appears to be little fundamental understanding of the Q9 measures by consultants we encountered. Its application is based on a belief that since there is a varying gas concentration in a gas cloud formed from a pressurized gas release, assuming a uniform gas cloud concentration is thus 'over-conservative', and using Q9 would remove this perceived 'over-conservatism'. As we shall see later, this is not necessarily so.

3 METHODOLOGY

3.1 PHASE 3B – THE FIRE AND BLAST FOR TOP SIDE STRUCTURE PROJECT

We used data produced by the Phase 3b of the Fire and Blast for Topside Structures Project for this exercise.

The objective of the Phase 3b project was to study explosions resulted from the release of high pressure natural gas into a large scale model of an offshore production module. This work was funded by a consortium of international oil companies, including bp, and the UK regulator.

A brief history of the Fire and Blast for Topside Structure Project is as follows. Phase 1 of this project started in 1990 in response to the Piper Alpha accident in the UK sector of the North Sea. Phase 1 (SCI 1992) provided interim guidance to the industry and a review of knowledge in the fire and explosion area. This was followed by Phase 2, which consisted of a series of experiments to obtain data in full scale geometries representative of the offshore environment (SCI 1998). The results of Phase 2 indicated that high explosion overpressure could be generated. As a consequence, Phase 3a was commissioned by the UK Health and Safety Executive to study methods of reducing the severity of gas explosions (Al Hassan 1998).

The Phase 3b (Johnson 2002) tests consisted of laboratory, medium and large scale. In this paper, we employed the large scale data only. Figure 2 shows the experimental test rig which measured about 28 m long, 12 m wide and 8 m high. Natural gas was released within the module and was held constant for each test with release rates varying between 2.1 kg s^{-1} to 11.7 kg s^{-1}, and in direction of one of the three coordinate axes of the test rig. In total, twenty tests were carried out. Gas concentrations were measured prior to ignition and overpressure measured at locations distributed inside the module.

3.2 PREVIOUS WORK ON FLAMMABLE VOLUME

The issue of flammable volume was of concern and this was addressed by a joint industry project, called "Dispersion JIP" which studied the dispersion of releases of pressurized natural gas in a large scale module. This JIP (Cleaver et.al. 1999) took place between the completion of the Phase 3a programme and the start of the Phase 3b programme. The ">LFL" and ΔFL volume measures were evaluated and compared with predictions from FLUENT and FLACS (Savvides et.al 2001). These papers showed that FLACS was able to estimate ">LFL" and ΔFL with little bias. Q9 was not part of the evaluation. The remaining of this paper focuses on the investigation of the estimation of explosion overpressures by using the three volume measures described above.

3.3 MV DIAGRAM

An MV diagram shows the geometric bias and geometric variance of model predictions on a single diagram. It shows systematic overprediction or underprediction (bias), and the degree of scatter (variance).

Figure 2A. A picture of the Phase 3b test rig. It measures about 28 m long, 12 m wide and 8 m high and was a large scale model of a process module on an offshore platform

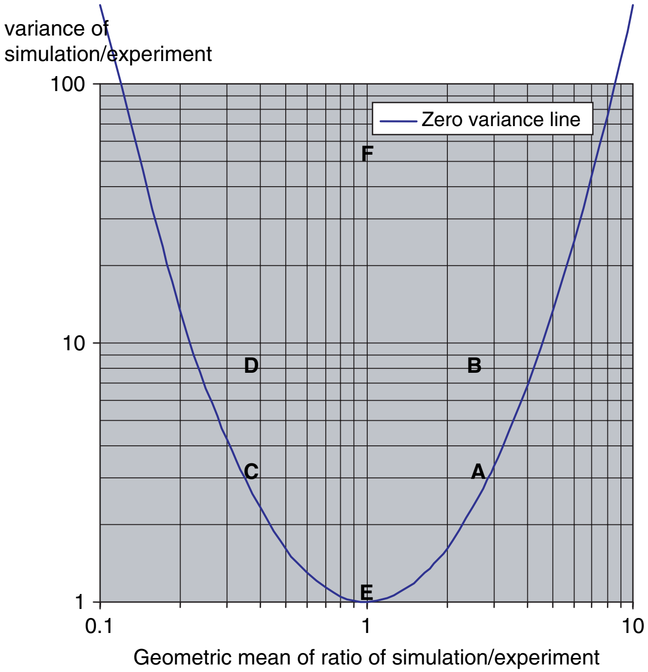

Figure 2B. An MV diagram which shows the behaviour of model predictions when it locates at various locations on the diagram (this supports the main text in the paper)

Hanna (Hanna et.al. 1991) developed the MV diagram for showing dispersion model performance when compared with a large range of data. This was later adopted by the scientific working group in the Blast and Fire for Topside Structure Phase 2 (SCI 1998) and in MEGGE protocol (SCI 1995) as a standard way to show model performance.

Bias indicates on average how much calculation over or under predicts experimental data. If we assume bias is zero, variance gives a measure of the scatter of prediction about the data. A high variance indicates poor consistency; one cannot be sure whether prediction grossly over or under predict. The bias and variance scale on the diagram are defined as:

$$\text{Mean Bias} = \exp\left(\langle \ln(P/O) \rangle\right)$$

$$\text{Variance} = \exp\left(\langle (\ln(P/O))^2 \rangle\right)$$

Where:

P = predicted overpressure
O = observed or measured overpressure
<X> denotes expectation value of X

The MV diagram consists of a number of parallel parabolas which gives line of constant variance. The lowest parabola is the zero variance line. This is illustrated in Figure 3 in which only the zero variance line is shown. Point A is close to the zero variance line: It indicates the model consistently overpredicts and has a very low probability of underprediction. Point B is above A and has a high variance; It indicates that the model, though has a tendency to overpredicts, has a wide range of prediction some are overpredicted and many are underpredicted – model B is less predictable than Model A. Points C and D are similar to Points A and B, but under-predict. Point E is close to the bottom of the lowest parabola; this indicates consistently accurate prediction of experimental data. Point F has a very high variance; a model with this property is of little use in practice as it behaves like a random number generator. Further information can be found in Tam (1998).

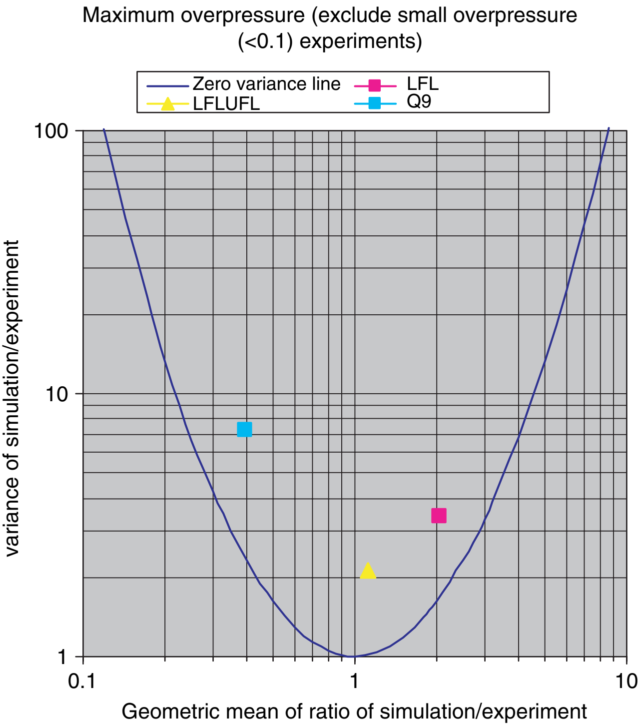

Figure 3. Bias and variance of the three volume measures. It shows that the Q9 measure underpredicts, ">LFL" is conservative and ΔFL is roughly neutral

4 RESULTS

Figure 4 gives a summary of predictions using the three volume measures for maximum overpressure anywhere within the module. The measured pressure data were processed by the experimental team: a rolling 1.5 ms time average was applied to data to remove fast transient effects, e.g. instrument noise. The rolling time-averaged data was used in this exercise.

For this exercise, we have excluded tests which had measured maximum overpressure of less than 0.1 bar. This is because there was large scatter of data at this low pressure. This aspect is discussed later. The trend is as follows: the prediction bias for ">LFL" is higher than ΔFL which is higher than Q9. Specifically, Q9 has a bias towards significant underprediction whereas ">LFL" and ΔFL tend to have a small overprediction or neutral respectively.

When we included the data with overpressure less than 0.1 bar, the relative position of the three measures remained the same. The bias of the Q9 measure is nearly zero and the other two biased towards overprediction. However, Q9 has a very high variance indicating a very wide scatter between predicted and observed values. This result is

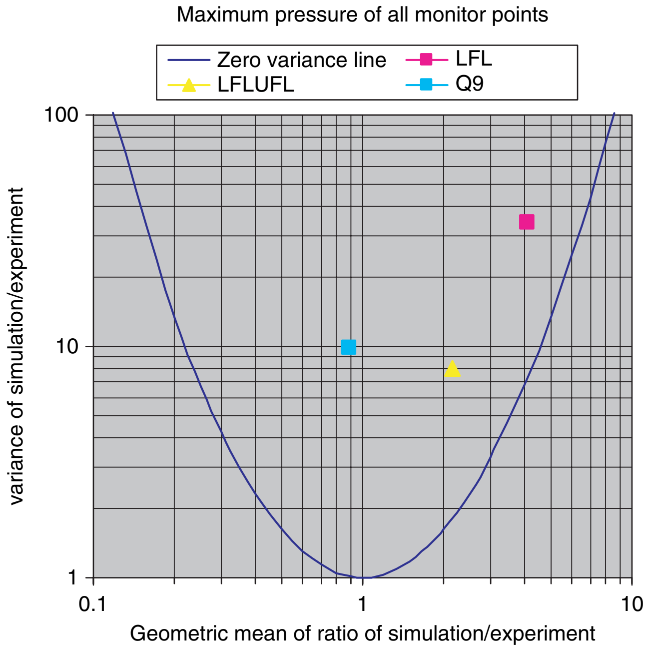

Figure 4. Bias and variance of the three volume measures when all data including those cases with a maximum of <0.1 bar recorded. It shows that the Q9 measure is unbiased but with a larger variance, both ">LFL" and ΔFL are conservative

summarized in Figure 4. The other two measures also have higher variance and showed significant bias towards overprediction.

Taking Figures 2a and 2b together, our results show that all three measures have significant variance for weak explosions (< 0.1 bar). Q9 showed significant bias for underprediction for explosions more than 0.1 bar, and the other two measures exhibit more consistent prediction behaviour (roughly neutral in bias and least variance). The reliability of overpressure predictions is important for structural design and becomes more important as the magnitude of the overpressure increases.

We also considered other ways to compare overpressures, e.g. average overpressure within the gas cloud, within the module. They all demonstrated similar trends. The major difference is that they all show Q9 has a negative bias (i.e. consistent underprediction) even for cases where maximum measured overpressure was less than 0.1 bar.

5 DISCUSSIONS

5.1 GENERAL COMMENTS OF THESE MEASURES

Use of Q9 in preference to the other two measures is widespread. We found that evidence supporting the use of Q9 is based on theoretical argument, sensitivity calculations and ‘experience’. However, we found no supporting evidence against data presented even though data had been openly available for a number of years.

5.2 COMPLEXITY AND ACCURACY

Superficially, Q9 seems to be the most accurate measure out of the three as it accounts for the well known effect of gas concentration on flame speed and expansion ratio. The Q9 measure is certainly the most complicated. It may be a surprise that our results showed that the Q9 measure performs poorly. However, one should not confuse complexity and accuracy.

In reality, the three measures described in this paper are no more than a much simplified and idealized representation of a complex situation. By focusing on a couple of obvious factors, many others are overlooked. Here are a couple of examples:

A Initial turbulence

The turbulence generated by the momentum of a pressurized gas release is an important factor in the development of a gas explosion. A pressurized gas leak can impart a large amount of and high intensity turbulence which may be considered similar to turbulence produced by obstacles. This is not taken account of by the three simple measures discussed here.

B Size of the gas cloud

Limiting the flammable gas cloud to a smaller effective volume reduces the effect of flame acceleration over a larger distance and over longer period of time than that produced by larger cloud volumes and could lead to lower and the wrong distribution of overpressure.

If we take a hypothetical case of a gas cloud which is made up of two equal halves: one half at close to LFL and one half close to UFL. It can be seen from Figure 1 that Q9 would give a near zero flammable volume, whereas ΔFL would produce the whole volume.

Another reason for possible underestimation of flammable volume is that volumes with rich gas mixtures can be diluted with air or with lean gas mixtures during the course of a gas explosion, rendering the rich mixture closer to the stoichiometric ratio of 1.

Applying the Q9 method blindly, it is possible to reach a conclusion that a very large leak of flammable gas would not pose an explosion hazard.

5.3 SENSITIVITY TO POSITION

Gas cloud location can affect calculated overpressure predictions. For a gas cloud volume which is small compared with the process area, the choice of the gas cloud location within the process area becomes important. As Q9 produces the smallest effective gas cloud size for a given scenario, the results will be sensitive to this effect.

We compared the differences of overpressure prediction between the cases where a gas cloud is placed at the centre of the test module and where it is located at the edge for all the cases in the Phase 3b test programme. The mean ratio of overpressure at the centre to that at the edge are 1.3, 1.8 and 3.0 for “>LFL”, ΔFL and Q9 respectively. It shows that the Q9 measure is the most sensitive followed by ΔFL, then by “>LFL”.

5.4 VERIFICATION WITH DATA – A REQUIREMENT

Following the completion of the Phase 3b exercise and publishing of the results, there was no published validation of the methodology for calculating effective cloud volume measures for use with CFD codes.

Any methods used should be verified against experimental data as far as possible. It should be the duty of the model developer or user of the model to verify any new methods against available data. This requirement is stated in the MEGGE protocol (SCI 1995).

6 CONCLUSION

Based on the results of this work, we recommend that the non-conservative flammable cloud volume measure ΔFL be adopted as the basis for FLACS at mid to late stage of an engineering project definition. “>LFL” is a conservative measure which may be appropriate during the early stage of design of a process facility where uncertainties in the design is high. This work does not support the use of Q9.

REFERENCES

Al-Hassan, T. and Johnson, M., Gas Explosions in Large Scale Offshore Module Geometries: Overpressures, Mitigation and Repeatability, OMAE 98, Lisbon, May 1998.

Cleaver, R.P., Burgess, S., Buss, G.Y., Savvides, V., Tam, V., Connolly, S. and Britter, R.E., Analysis of Gas Build-up from High Pressure Natural Gas Releases in Naturally

Ventilated Offshore Modules, 8th Annual Conference on Offshore Installations: Fire and Explosion Engineering, Lord's Conference and Banqueting Centre, London, 30 November 1999.

Hanna, S.R., Strimaitis, D.G. and Chang, J.C., Evaluation of Commonly-used Hazardous Gas Dispersion Models, Washington 1991.

Johnson, D.M., Cleaver, R.P., Puttock, P.S. and Van Wingerden, C.J.M., Investigation of Gas Dispersion and Explosions in Offshore Modules, Offshore Technology Conference, Paper number: 14134, Houston, Texas U.S.A., 6–9 May 2002.

Law, C.K., Combustion Physics, Cambridge University Press (2006), ISBN-10: 0521870526.

Savvides, C.S., Tam, V., and Kinnear, D., Dispersion of Fuel in Offshore Modules: Comparison of Predictions Using FLUENT and Full Scale Experiments, Major Hazards Offshore Conference Proceedings, 27–28 Nov 2001, London, ERA Report 2001-0575

Savvides, C.S., Tam, V., Jon Erik, O., Hansen, O.R. and van-Wingerden, K., Dispersion of Fuel in Offshore Modules: Comparison of Predictions Using FLACS and Full Scale Experiments, Major Hazards Offshore Conference Proceedings, 27-28 Nov 2001, London, ERA Report 2001-0575.

Tam, V., Explosion Model Evaluation, Fire and Blast Information Group, Article R320, Newsletter Issue No 22, May 1998.

The Steel Construction Institute, "Interim Guidance Notes for the Design and protection of Topside Structures Against Explosion and Fire", Report No: SCI-P112, 1992.

The Steel Construction Institute, "Blast and Fire Engineering for Topside Structures, Phase 2, Final Summary Report, SCI Publication Number 253, 1998.

The Steel Construction Institute, Gas Explosion Model Evaluation protocol, Model Evaluation Group for Gas Explosions, European Communities Report, September 1995.