The Effect of the Transient Stages of an Accidental Release on Gas Cloud Formation

T. D. Coates, Senior Consultant, and C.G. Robinson, Senior Principal Consultant, DNV GL, Holywell Park, Ashby Road, Loughborough, LE11 3GR, UK

The requirement for oil and gas facilities to withstand explosions is an important aspect in their design. Two of the important factors governing the magnitude of a vapour cloud explosion are the size and concentration variation within the gas cloud. Consequently, the prediction of how this gas cloud is formed is similarly significant.

An accidental release of hazardous material will be transient in nature. This may be caused by the conditions in the process stream or due to the activation of emergency systems such as shutdown and blowdown. However, in risk assessments a simplifying assumption often used is to represent releases by a steady state flow rate, for example by calculating the flow rate based upon the initial conditions in the process stream. This is done on the basis that this is the maximum flow rate and thus will represent a worst case. However, this stage of the release may not result in the maximum flammable gas cloud size. In particular, large releases within confined or semi-confined areas can form rich clouds which dilute, and hence have a larger flammable volume, once the release rate starts to decay. Some studies therefore include a time after the release has terminated to capture this effect but the release is still often represented by a steady state stage for a fixed period which instantaneously falls to zero.

This study examines the effect on the gas cloud formation when representing the transient part of the release by an accurate decay profile. This is done by modelling the depressurisation of the isolatable section and then using this as an input to a gas dispersion simulation. A parametric study using Computational Fluid Dynamics has been carried out to examine the effects of release decay rate on gas cloud formation. This has been done for different flow rates which result in different initial gas cloud sizes and subsequent development. The paper also discusses guidance on the representation of transient releases in assessments and the findings from full scale dispersion experiments.

The results of the study demonstrate that the transient stage of a release must be modelled correctly in order for the gas cloud formation to be accurately predicted. If this is not done then the stage of the gas cloud formation which has the potential to result in the highest overpressures may not be predicted.

Keywords: Dispersion, Offshore, Risk Assessment, CFD

Introduction

The requirement for oil and gas facilities to withstand explosions is an important aspect in their design. In general it is not practical to design an offshore platform against the 'worst case' explosion. Therefore, a risk based approach for design against explosion hazards is required. This includes evaluating scenarios involving ignition of a non-homogeneous gas cloud occupying only part of a module. Therefore, the prediction of the size and concentration variation within the gas cloud is an important aspect of a risk based approach. Risk based approaches have become standard (e.g. NORSOK, 2010) and a typical approach is described in Huser, 2000. Guidance on the representation of transient releases in such assessments is discussed within this paper.

This study examines the effect on the gas cloud formation when representing the transient part of the release by an accurate decay profile and compares this with the results obtained from simpler leak profile representations. A parametric study using Computational Fluid Dynamics has been carried out to examine the effects of release decay rate on gas cloud formation. This has been done for different flow rates which result in different initial gas clouds sizes and concentration profiles. The study is limited to high pressure gas releases in semi-confined, congested regions such as offshore modules. Although similar problems arise when modelling transient releases in other situations, for example for onshore plant, the trends in the results in these cases may be different.

This paper also discusses the findings from full scale dispersion experiments.

Gas cloud formation

Many of the basic principles for the generation of gas clouds in offshore process installations are described in Cleaver, 1994. Following a release of high pressure gas in such an environment there are a range of possible outcomes and one of the most important factors is the amount of ventilation compared with the release rate. For relatively small releases, or if the ventilation rate is high, the release will behave in a similar manner to a jet in an unconfined environment provided there is no impaction on solid surfaces. However, if there is insufficient ventilation, or if there is impaction, gas accumulation may occur. The presence of confinement or obstacles will tend to favour the formation of recirculating regions and gas accumulation. The outcome of any particular case is dependent on geometric parameters, such as the volume and aspect ratio of the module (the ratio of the height to the width to the length of the volume), as well as on release parameters, such as the direction, mass flow rate and buoyancy and ambient conditions, such as wind speed and direction.

At any particular time during the gas cloud development there will be a range of concentrations with certain parts of the cloud below the lower flammable limit (LFL), other parts above the upper flammable limit (UFL) and the remaining parts of the cloud within the flammable range that will burn and potentially explode if ignited. A key question is what potential explosion consequences such a developing gas cloud represents. One method that can be used to describe this is the Equivalent Stoichiometric Cloud (ESC). This is a concept developed in the early 1990s by GexCon in an attempt to linearize the expected hazards from arbitrary non-homogeneous, dispersed flammable gas clouds (Hansen, 2013). The idea is that the potential explosion consequences from any non-homogeneous gas cloud can be approximated by exploding a smaller gas cloud at the stoichiometric concentration. One of the main ESC parameters applied in explosion risk assessments is termed Q9 and is defined as:

$$Q9 \ = \sum Volume_{fuel} \frac{SE}{(SE)_{max}}$$

where S and E denote the laminar burning velocity and expansion ratio for the actual concentration and $(SE)_{max}$ is the maximum product of the laminar burning velocity and expansion ratio.

A typical leak profile is shown in Figure 1. The leak profile has a steady state phase in which the pressure in the system is maintained and then a decay phase which represents the depressurisation of the isolated section after Emergency Shutdown (ESD) has been completed. Figure 1 shows an example of a 5kg/s leak which starts at 300s, has a steady state phase lasting 60s and then a decay phase. The corresponding Q9 curve is also shown. This Q9 volume represents the gas within the module. The gas concentration distribution in a plane in the module is shown below the graph. Regions between the LFL and UFL are indicated in brown and above the UFL are indicated in blue.

The gas cloud formation can be visualised in five stages. Stage 1 is before the leak starts when there is no gas in the module. The initial build-up of the gas cloud leads to an initial peak in the Q9 volume (stage 2) before dropping due to the immediate region around the leak becoming increasingly rich (stage 3). Depending on the duration of the leak before detection, this third stage can lead to a steady state in the formation of the gas cloud which can be either higher, lower or the same as the initial peak.

After ESD has completed the leak rate begins to decay as the available inventory diminishes. This can lead to a secondary peak, larger than the first, as the rich part of the cloud begins to disperse. This can be seen in stage 4 of Figure 1 where, although the overall area containing gas decreases, the region above the UFL has dispersed sufficiently so that it has entered into the flammable range. Finally stage 5 occurs once the remaining gas has dispersed to levels below the LFL and, with no new gas entering the module, the flammable volume decreases to zero.

The relative volumes and durations of the different stages will vary depending on the specific details of the release and the environment into which it occurs. In this paper we shall pay particular attention to how the transient stage of the release can affect gas cloud formation.

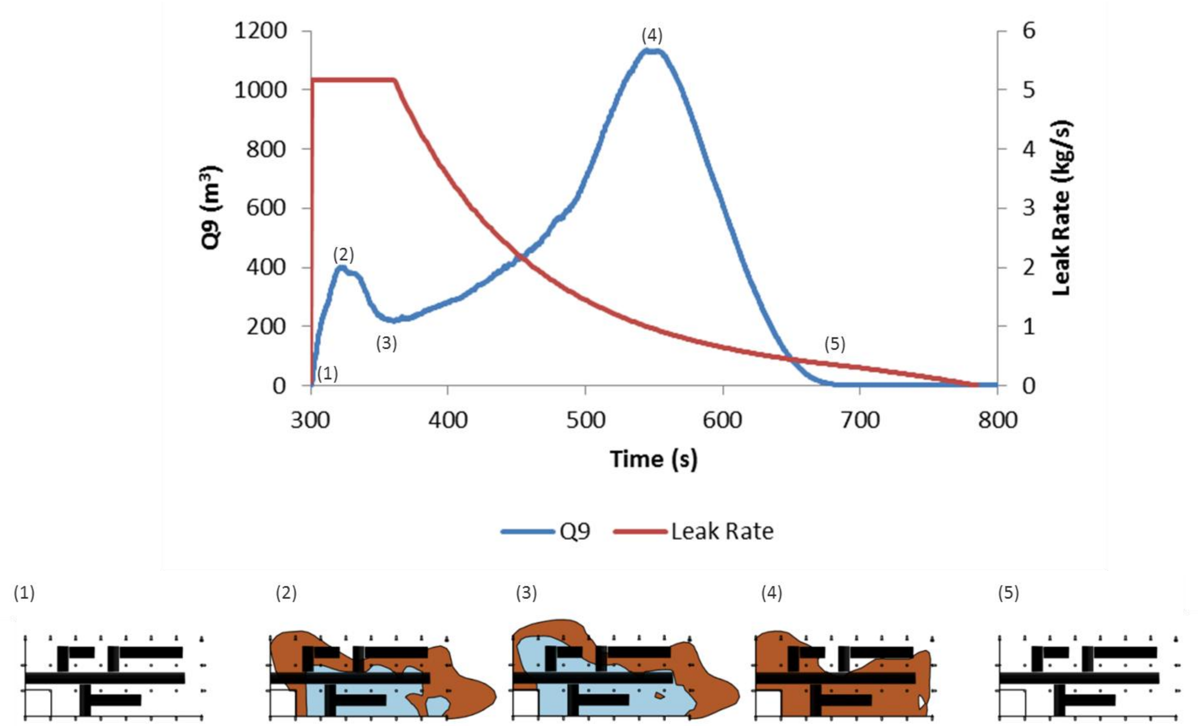

Figure 1: An example of gas cloud formation.

Guidance on the use of transient releases within assessments

Guidance on how explosion loads should be derived is given in a number of documents (NORSOK, 2010; OGP, 2010; CMPT, 1999) and these include some discussion on how and why transient releases should be modelled and this is summarised briefly below.

NORSOK, 2010, Appendix F, states that credible transient leak profiles shall be reflected. This includes modelling of segment inventories, time until isolation and pressure drop due to blowdown and the leak. It points out that it is important that the variation in inventory and pressure should be reflected if a limited number of scenarios are selected as representative. The appendix further states that the effect of any transient behaviour of the leak on gas cloud size and location can be significant and should therefore be accounted for. However, it does not discuss in detail why this is significant and the possible effects of using a steady state release profile or how the results might vary for different inventories. The 2003 version of the NORSOK document did mention that transient source strength must be evaluated with regard to leak rates that are reduced quickly but initially produce rich clouds but this statement is not in the 2010 version. The use of transient profiles as opposed to steady state profiles in probabilistic assessments following the NORSOK approach is one of the sensitivity studies discussed in Bakke, 2003 and was shown to have a significant impact on the calculated explosion loads.

OGP, 2010, discusses release modelling and states that a simple approach is to calculate the initial rate and to assume that this is constant over time. It notes that a more sophisticated approach is to model the time dependence of the release rate and this is often used for studies of offshore facilities, where the time dependence has a significant impact on the likelihood, in particular, of the initial event escalating. It also states that the modelling required for transient releases is more complex but avoids certain issues that arise when initial rate modelling is used, including initial rate modelling leading to over-prediction of the flammable/explosive mass in a vapour cloud. Although this may be true in some circumstances, this fails to highlight the aspect of rich clouds which may dilute with time if a transient release rate is used.

CMPT, 1999, states that the release rate is important because it affects the size of the resulting gas cloud and hence the probability of ignition. It also determines the size of the potential fire or smoke plume. The reduction in release rate (in effect the duration of the release) is important because it limits the damage that the fire may cause. It recognises the fact that large releases of gas inside the platform tend to disperse quickly throughout the module and that the average concentration builds up and then declines at a rate that depends on the gas release rate and the air ventilation rate through module. However, it does not highlight the potential for rich clouds diluting.

The conclusion is that the use of transient profiles is recognised as important in these guidance documents although none of the above references demonstrate the significance of this explicitly in terms of the effect on gas cloud formation.

Full scale experimental studies

There have been two full scale experimental studies of gas cloud formation in offshore modules. Both projects were carried out at the DNV GL Spadeadam test site. They are summarised below.

Dispersion tests were carried out in the test rig constructed in 1994 for the large scale explosion experiments conducted as part of the Blast and Fire Engineering Project for Topside Structures, Phase 2 (Johnson, 2002). The test rig was an all steel construction extending up to 28m long, 12m wide and 8m high (Figure 2). Within the rig, large and small steel obstacles were positioned to simulate typical process plant and pipework that would be found on an offshore installation. The test rig structure was based on a strong bolted framework, with beams on 4m centres, onto which panels could be fitted to provide the perimeter confinement conditions required in the test programmes. A mezzanine deck, consisting of a steel support frame covered with serrated open bar grating, was located at mid-height throughout all of the test rig and was designed to be similar to those found in typical offshore modules. For the experiments involving a high pressure gas release, the gas flow rate was controlled to be nominally constant for each experiment. In all twenty experiments were carried out with a high pressure gas release. Depending on the release and experimental configuration and the weather conditions, realistic releases gave gas clouds that can be fairly uniform over parts of the rig or can have large concentration gradients within them. Though considerable variation in flammable cloud size and concentration was observed in the experiments, under some release and weather conditions, significant portions of the module were filled with a near stoichiometric natural gas-air mixture. These conditions were generally produced by impacting releases where the confinement, release rate and weather conditions resulted in recirculation and gradual accumulation of the natural gas-air mixture within the rig.

Figure 2: Full scale test rig.

The same test rig was used in a Joint Industry Project (JIP) carried out to investigate the dispersion of high pressure releases of natural gas in a congested, partially confined volume. The project was managed by BP and was funded equally by a group of eleven sponsoring companies (Savvides, 2001). In the project, 66 experiments were carried out jointly by DNV GL and Shell Global Solutions in the rig that had been used previously for the explosion experiments carried out as part of the Blast and Fire Engineering Project for Topside Structures, Phase 2. It was shown that a uniform gas concentration was not always produced within the rig, although there may be significant regions in which the concentration is relatively uniform. That is, this result confirms that realistic releases may not always lead to a uniform, near stoichiometric mixture being produced throughout a module, even if such conditions are produced in some part of the module.

Both studies showed that high pressure gas releases in an offshore module can create flammable clouds with significant concentration variations. However, neither study examined the transient decay phase of the release and the corresponding transient gas cloud formation (although two of the 66 tests in the JIP were transient the results were not analysed in detail as part of the project). The next section uses simulations to demonstrate the results that might have been obtained if transient releases had been studied as part of the experimental programmes.

Computational Fluid Dynamics simulations

The Computational Fluid Dynamics (CFD) simulations presented here are based around the large scale experimental programme described in Savvides 2001. The rig was a full scale (28m long x 12m wide x 8m high) representation of a typical offshore module (see Figure 2) and could be adapted to one of three different rig configurations, altering the location and amount of perimeter confinement. For this paper ‘configuration C’ was used; where the West and South faces of the module were completely blocked (along with the roof and floor). The computer model used in the simulations is shown in Figure 3.

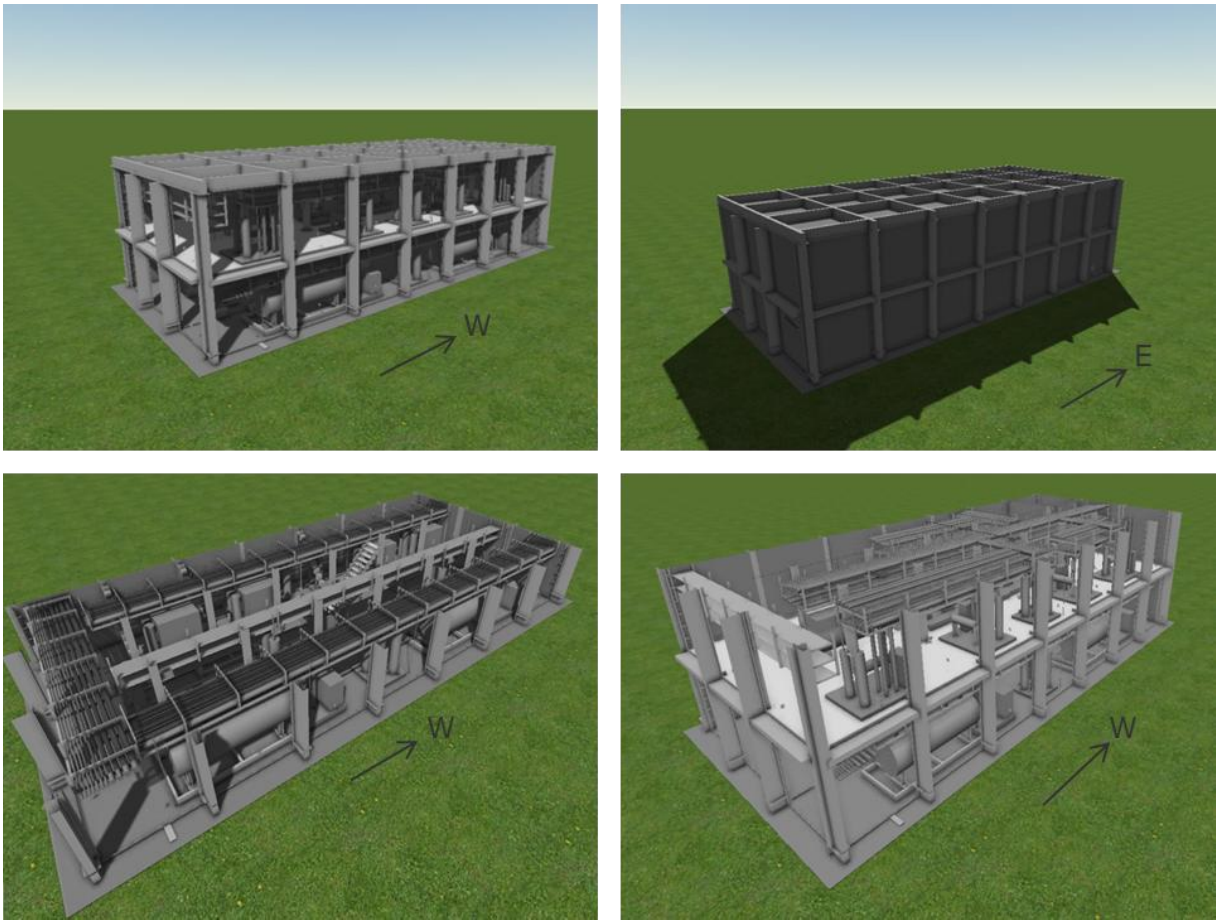

Figure 3: Computer model used in the simulations (top: views from North-East and South-West, bottom: views of the internal congestion from North-East).

The CFD tool FLACS (GexCon, 2014) is applied in this study. FLACS is a specialized CFD toolbox developed especially to address process safety applications such as the dispersion of flammable or toxic gases and gas explosion. FLACS is extensively used for gas dispersion and explosion calculations within many industries. It has become an industry standard and is the required tool by several oil and gas companies for their explosion hazard assessments. It has been validated against an extensive set of experimental test data including explosions in full scale geometries. It has also been validated against the twenty full scale dispersion tests described in Johnson, 2002 (Hansen, 2013).

Two scenarios from the gas dispersion JIP (Savvides, 2001) were selected to be examples for this study as the test conditions were similar, with the exception of differing release rates (5kg/s and 0.8kg/s respectively). The releases were located in the upper level, directed towards the South wall. As the gas composition used in the JIP was non-flammable it was replaced with a methane/propane mix of similar molecular weight for this paper. For both cases the inventory was modelled at a pressure of 34bar and ambient temperature. In the experiment a 4m/s easterly wind (i.e. towards the smaller, closed face) was measured at a height of 5m with an ambient temperature of 14˚C.

One of the most common approaches in calculating the gas cloud size is by establishing the steady state cloud during a leak event. The two scenarios outlined above are used to show the development of the ESC until steady state is achieved (Figure 4). In both cases, after around 600s, a stable cloud size is achieved. The maximum cloud size for the 0.8kg/s release occurs when the cloud achieves the steady state whilst the 5kg/s case sees the maximum occur during the initial development period, around 20s into the release.

In both cases, when the leak is switched off and the simulation allowed to continue, the gas-air mixture above the UFL dilutes and falls into the flammable region giving rise to a new maximum Q9 cloud size (as seen in Figure 5). For the 0.8kg/s release scenario this peak is fairly minor. However, in the 5kg/s release scenario the maximum cloud size increases by 50% when allowing the cloud to dilute after the leak ends.

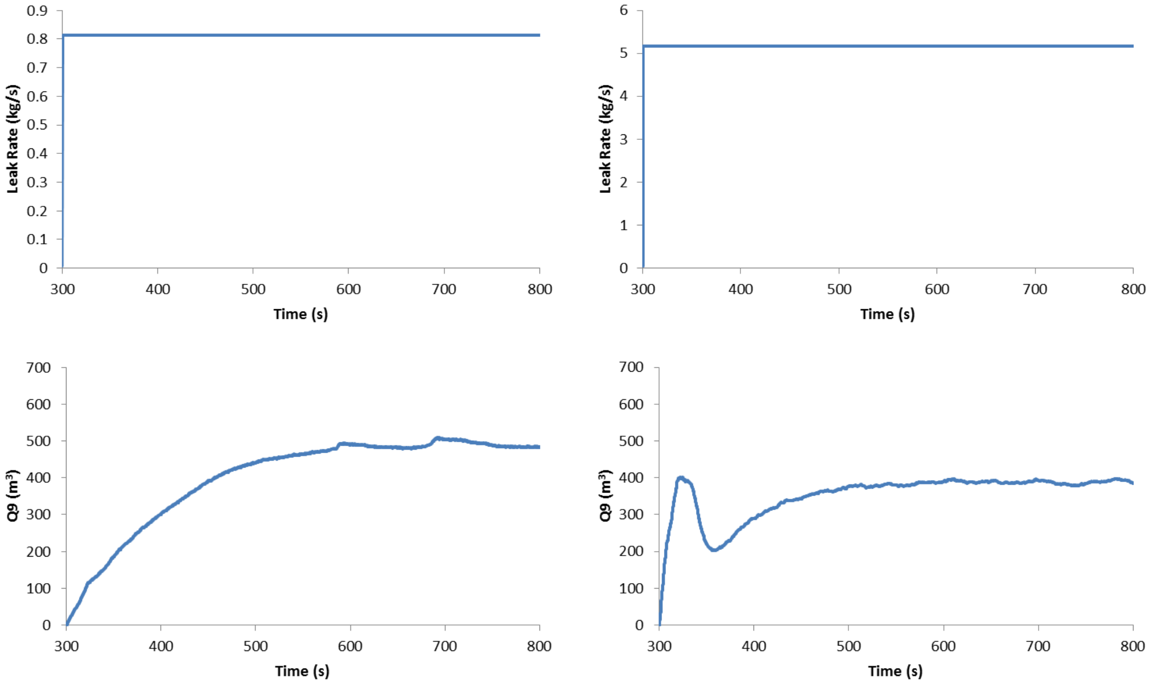

Figure 4: Leak rate and corresponding Q9 development curves for 0.8kg/s and 5kg/s steady state releases.

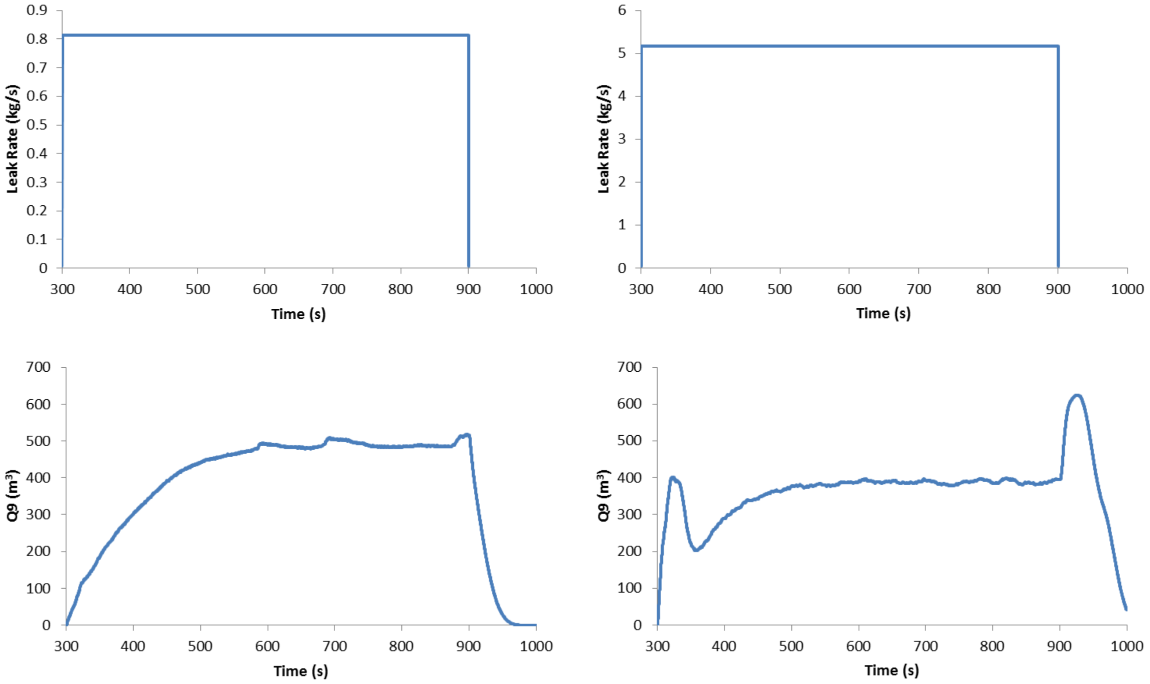

Figure 5: Leak rate and corresponding Q9 development curves for 0.8kg/s and 5kg/s steady state releases including the period after the release has stopped.

Whilst the inclusion of a period after the release has stopped allows for the dilution of the parts of the cloud above the UFL to be captured, the immediate halt to the leak is unrealistic as there would normally be the inventory within the isolatable section to still escape once the ESD is completed. This would lead to a transient leak profile with a decay period once the flow into the isolatable section has been stopped.

To study the effect of the transient stages of an accidental release, the two scenarios above were modelled as steady state releases for 60s (to simulate a 60s time to ESD completion) followed by an exponential decay to model the subsequent outflow of the inventory from an isolatable section. Five different inventory volumes (0m^3, 2m^3, 4m^3, 8m^3, and 16m^3) were investigated to understand the impact that the inventory volume has on the development of the cloud.

Each case was simulated until the volume of flammable gas in the module reached zero after the initial build-up. Figure 6 shows the transient leak profiles for the different cases and the corresponding Q9 curves. It is clear that, for both leak rates, differences are observed in the maximum Q9 size as the inventory volume is increased. This difference is significantly more prominent in the 5kg/s case where the maximum Q9 increases by a factor of approximately 2.75. However, it is also important to note that the maximum Q9 value for the 5kg/s release (obtained using a 16m^3 inventory) is significantly greater than the value obtained using a steady state release over a longer time, even if a period after the release has stopped is modelled (compare with Figure 5). For the 0.8 kg/s release a larger Q9 value is obtained using an extended steady state release as the gas accumulates over a longer time period.

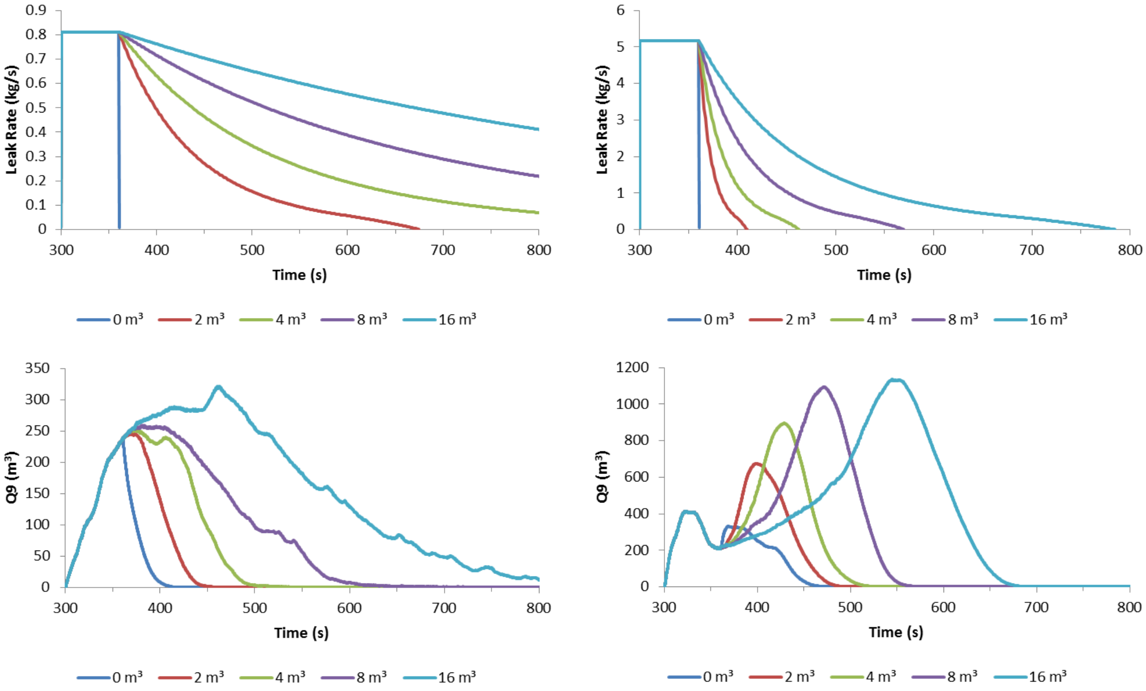

Figure 6: Leak rate and corresponding Q9 development curves for 0.8kg/s and 5kg/s releases with a 60s ESD and transient decay profile depending on inventory volume.

The reason for this behaviour can be explained by considering the flow of gas and air into and out of the module. In the case of the 5kg/s release the gas flow into the module is relatively high and a large part of the mixture is above the UFL. If the flow of gas is stopped abruptly then as discussed previously this will start to dilute and so the Q9 value increases. However, at the same time, parts of the mixture which were flammable are falling below the LFL and the mixture as a whole will also be advected out of the module due to the bulk flow field produced by the natural ventilation and so the Q9 value falls. This latter effect will be particularly noticeable in modules with low confinement and low congestion. In cases with a transient release a flow of gas will continue into the module after ESD has completed. Consequently, although the mixture is moving out of the module and parts are diluting there is still new gas-air mixture being formed. As the transient release rate falls, the ratio of the gas flow to the ventilation rate can reach a point at which much more of the mixture is within the flammable region; therefore resulting in a much higher Q9 value. This process is highly complex and depends on the specific details of the scenario. Therefore, although the above results show that the transient effects are important the results should not be generalised.

As discussed previously the development of the gas cloud will depend on many factors. For example (see Figure 7), if we change the direction of the wind by 180˚ (so that it is flowing towards the open, smaller face of the module) we still see a higher second peak in the Q9 curve which occurs after ESD has completed for the 5kg/s scenario, although this is not as high as before. For the 0.8 kg/s scenario a peak is not observed for either inventory after ESD has completed. However, the Q9 values are much smaller than for the equivalent case with the opposite wind direction.

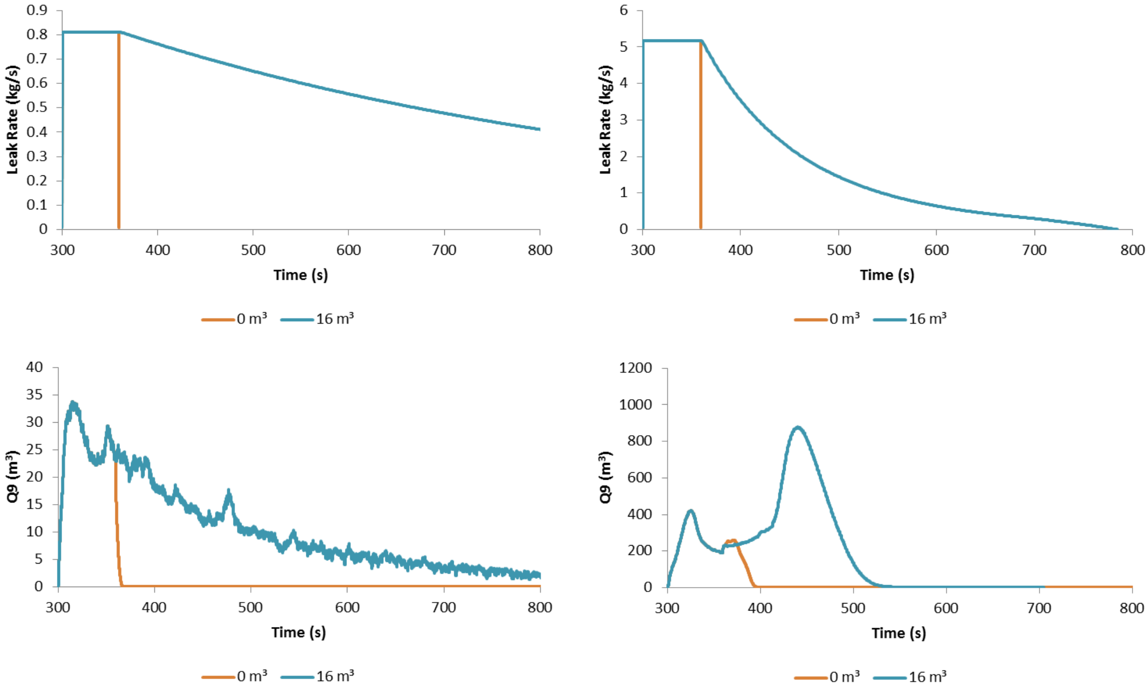

Figure 7: Leak rate and corresponding Q9 development curves for the opposing wind direction of the 0.8kg/s and 5kg/s releases from 0m^3 and 16m^3 inventories with a 60s ESD prior to decay.

Overall, it has been seen that the maximum Q9 volume of gas from an accidental release is very sensitive to the size of the inventory available. In this small study we have seen that, by including the decay from a 16m^3 inventory instead of using a steady state flow rate, the Q9 volume for a small release (0.8kg/s) can increase by more than 35% and for a larger release (5kg/s) the Q9 volume can increase by more than 170%.

Conclusions

The results of the study demonstrate that it is important that the transient stages of an accidental release are modelled correctly when simulating gas cloud formation. If a simple representation using a steady state release is used the maximum gas cloud size can be significantly underpredicted with a corresponding under prediction of the overpressures in the explosion assessment. Improved guidance is required to ensure that assessments adequately address this phenomenon.

The process of gas cloud formation is highly complex and depends on the specific details of the scenario. Therefore, although the results presented in this paper show that the transient effects are important the results should not be generalised.

The study is limited to high pressure gas releases in semi-confined, congested regions such as offshore modules. Although similar problems arise when modelling transient releases in other situations, for example for onshore plant, the trends in the results in these cases may be different. Further studies are required to assess the importance of the transient stages in these cases.

Acknowledgments

The authors wish to acknowledge the work of Loughborough University MSc student Xiaofei Leng and the work described in her dissertation ‘CFD modelling of gas dispersion on offshore platforms’.

References

Bakke, J. R. and Hansen, O. R., 2003, Probabilistic Analysis of Gas Explosion Loads, *FABIG Newsletter*, 34, R469, 22-29.

Centre for Marine and Petroleum Technology (CMPT), 1999, A Guide to Quantitative Risk Assessment for Offshore Installations.

Cleaver, R.P., Humphreys, C. E. and Robinson, C. G., 1994, Accidental generation of gas clouds on offshore process installation, *J. Loss Prev. Process Ind.*, Vol. 7, Number 4, 273-280.

International Association of Oil and Gas Producers (OGP), 2010, Risk Assessment Data Directory; Consequence Modelling, Report No. 434-7.

GexCon, 2014, FLACS User’s Manual, v10.3.

Hansen, O. R., Gavelli, F., Davis, S.G., Middha, P., 2013, Equivalent cloud methods used for explosion risk and consequence studies, *J. Loss Prev. Process Ind.*, Vol. 26, 511-527.

Huser, A., Eknes, M.L., Foyn, T.E., Selmer-Olsen, S. and Thevik, H.J., 2000, EXPRESS – Cost effective explosion risk management, ERA conference. London, November 2000.

Johnson, D.M., Cleaver, R.P., Puttock, J.S., and Van Wingerden, C.J.M., 2002, Investigation of gas dispersion and explosions in offshore modules, OTC 14134, Offshore Technology Conference, Houston, Texas U.S.A., 6–9 May 2002.

NORSOK, 2010, Risk and emergency preparedness analysis, NORSOK Standard Z-013, Edition 3.

Savvides, C., Tam, V., Os, J.E., Hansen, O.R., van Wingerden, K. & Renoult, J., 2001, Dispersion of fuel in offshore modules: comparison of predictions using FLACS and full scale experiments, ERA conference, 27-28 November 2001.