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Gas Explosion Handbook

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Abstract

The handbook gives a brief introduction to gas explosion safety, based on current knowledge of the subject and on experience in applying this knowledge to practical problems in the industry. The handbook consists of four major parts:

The sections in the first part "Introduction" contain the description and physics of gas explosion phenomena, definitions and loss experience. Under "Background and Basics", cloud formation, gas explosions, blast waves and structural response are described. The part "Practical Aspects" relates the information presented in "Background and Basics" to different industrial situations. The final part on "Tools and Analysis" focuses on what one can do to improve gas explosion safety.

Contents

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1. Foreword

This handbook has been written as a part of Christian Michelsen Research's (CMR) research programme "Gas Safety Programme 1990–1992" (GSP90-92). The participants of the programme are: BP Norway Limited U.A., Bundesministerium für Forschung und Technologie, Conoco Norway Inc., Elf Petroleum Norge A/S, Esso Norge A/S, Gaz de France, Health and Safety Executive, Mobil Exploration Norway Inc., Norsk Hydro, Norwegian Petroleum Directorate, N.V. Nederlandse Gasunie, Phillips Petroleum Company Norway and Statoil.

The purpose of this handbook is to give a brief introduction to gas explosion safety, based on our current knowledge of the subject and on our experience in applying this knowledge to practical problems in the industry. Because of the intended brevity and simplicity of the handbook the information provided may in some cases be strongly simplified and/or incomplete. For in-depth information on the various subjects the reader is referred to the literature described in the References at the back of the handbook.

The user of this handbook is intended to be a process, design or structural engineer, but the handbook should also be useful for safety engineers.

1.1. How to read the handbook

The handbook is divided into 16 chapters. The individual chapters can be grouped in four categories: i) Introduction, ii) Background and Basics, iii) Practical Aspects and iv) Tools and Analysis. The chapters of each category are shown in Fig. 1.

The chapters in the first category "Introduction" contain the description and physics of gas explosion phenomena, definitions and loss experience. Under "Background and Basics", cloud formation, gas explosions, blast waves and structural response are described. The part "Practical Aspects" relates the information presented in "Background and Basics" to different industrial situations The final part on "Tools and Analysis" focuses on what one can do to improve gas explosion safety. In particular a description is given of the FLACS and μFlacs codes, and how these tools can be applied for predicting the consequences of gas explosions in an industrial environment.

When writing this handbook, it was our intention that the reader could start directly in one chapter listed under "Practical Aspects" or "Tools and Analysis" and use the other chapters for supplementary information. However, if the field of gas explosions is new to the reader, we would recommend going through Section 2 and Section 3 as a first introduction to the subject. Section 16 contains a list of terms and expressions.

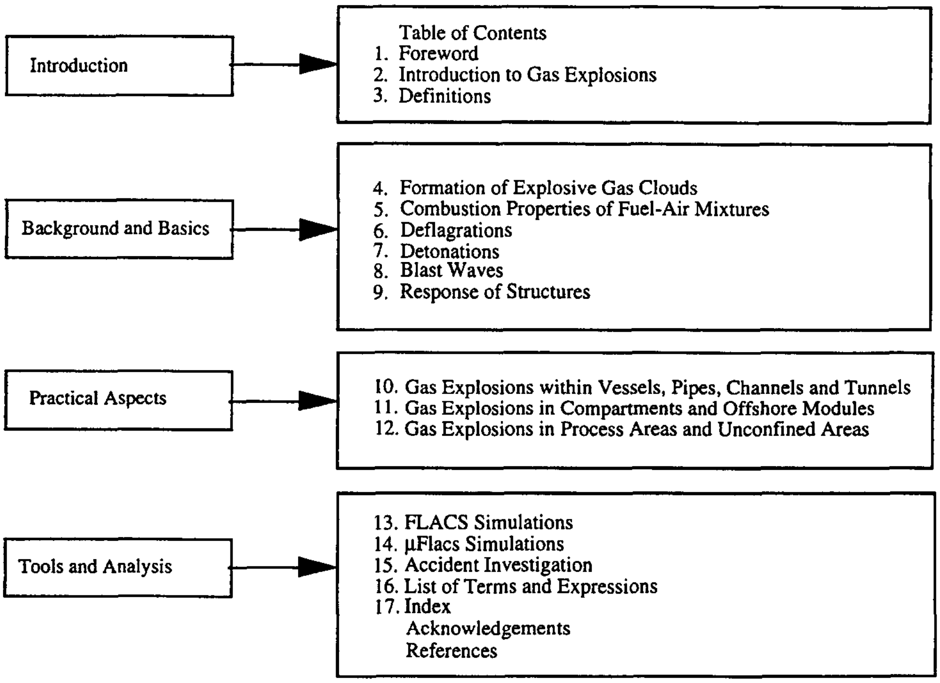


Fig. 1. Organisation of the handbook.

To avoid too much cross-referencing and thereby making the use of the handbook more cumbersome, there is a certain amount of overlap between what is contained in the two first parts and the two last parts. This makes each of the two halves more self-contained and the handbook may therefore be used as a reference work without having to read it all.

1.2. Objectives of the handbook

Today there is a lot of information available in scientific papers and reports on gas explosions. However, in most cases the practical implications of this information are very hard to extract. A need for a handbook with simpler presentation of the available information that can be used in the industry, has therefore been identified.

This handbook summarises the main results and experience from our previous research programmes and consultancy activity on gas explosion safety ([135]). We are focusing on pressure build-up during gas explosions. Important areas of gas explosion safety, such as how to prevent leaks and what is the ignition probability, are not covered. In this handbook we assume that the premixed combustible gas has been generated and ignited. Phenomena of flame propagation and pressure build-up are discussed. The important factors influencing pressure build-up are pointed out and some simple guidelines are presented. The use of numerical codes (FLACS and μFlacs) for simulation of gas explosions in industrial environments is also covered(Fig. 2).

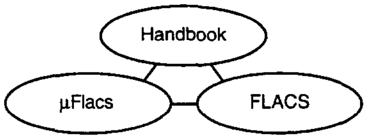


Fig. 2. The Handbook, μFlacs and FLACS constitute a complementary set of tools.

The handbook is one of three tools for analysis of gas explosions, which have been provided by CMR. The two other tools are FLACS and μFlacs. FLACS is the most advanced code of the two. FLACS is used for detailed analysis, while μFlacs is a PC screening tool and does not require the same amount of detailed input and resources as FLACS. Our goal is that the handbook, FLACS and μFlacs are used together in gas explosion analyses as supplementary tools. Which tool to use will depend on the stage of the analysis and the detail of information required.

Our intention is that the CMR gas explosion handbook is a ''live'' document that will be updated when new information is available. Further comments and suggestions for improvement of the handbook will be gratefully received.

1.3. Gas explosion activities at CMR

In the late 60s and in the 70s, large oil and gas fields were discovered in the North Sea. It was recognised that gas explosions might constitute a hazard for the drilling and production installations in the North Sea and that the knowledge about gas explosions in industrial environments was limited. At Chr. Michelsen Institute's Dept. of Science and Technology (CMI-DST, from June 1992 Christian Michelsen Research — CMR), gas explosion research was started in the late 1970s as part of the programme ''Sikkerhet På Sokkelen''. Since then gas explosion research has been an important activity at CMI/CMR, as shown in Fig. 3. The gas explosion research was a continuation of the research work on dust explosions. The dust explosion research work is described by Eckhoff , 1991 [68].

In the period 1980–1990 CMI carried out two major research programmes on gas explosions. A total of 80 man-years of research have provided new insight into gas dispersion and gas explosions in industrial environments. The primary objectives of the work have been to generate know-how and tools for minimising the effect of accidental

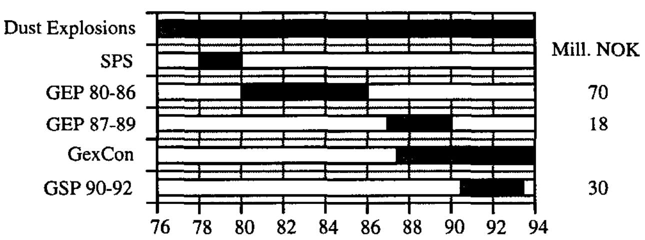


Fig. 3. Research programmes and consultancy activity on explosions at CMR.

explosions. CMI 's strategy has been to combine large- and small-scale experimental work with the development of advanced fluid-dynamic codes.

In GEP 80-86 pressure development due to flame acceleration by obstacle-generated turbulence was studied. This mechanism was identified as being mainly responsible for explosions occurring in complex geometries typically found on offshore platforms. The phenomenon was studied both in small and large scale (0.2 m^3 and 50 m^3) for geometrical layouts of increasing complexity. The most complex layout was a scale 1:5 offshore module. Different gases and ignition strengths were studied, as were ignition positions and vent arrangements.

Results from these experiments served two purposes: they provided new insight about flame acceleration in complex geometries and also data for validation of computer codes developed for explosion overpressure prediction. These codes, which were named FLACS (Flame Acceleration Simulator), were developed in the modelling activity which concentrated on modelling of compressible, turbulent reactive flows and on numerical solution of the resulting set of partial differential equations. Some results from the research have been published in the open literature ([55,56,113,121,122]).

Following the seven-year programme which ended in 1986, a three-year programme focusing on gas dispersion in complex geometries and on explosions in onshore plants was initiated in 1987. The objectives of the programme were to provide more knowledge by performing experiments and to apply this knowledge to evaluate an enhanced FLACS code, taking into account gas dispersion and explosions for different fuels mixing with air.

GexCon, CMR's gas explosion consultancy, was established in 1987. GexCon is an independent unit that operates in close cooperation with CMR's Gas Explosion and Process Safety section. Through GexCon CMR's research has already had an impact on engineering practice. CMR personnel are used actively by the industry as consultants on gas explosion safety. Our experimental facilities are used to test the integrity and functionality of equipment and structures exposed to gas explosions of predetermined strength. The FLACS code is used extensively to provide quantitative information about pressure loads from accidental explosions, both offshore and onshore. Since 1989 more than 40 projects have been performed for specific plants and installations. This work includes safety analyses, explosion simulations using FLACS, experimental studies and gas explosion courses including demonstrations of actual explosions.

In 1990 a new large multi-sponsor programme was started. The objective of this programme is to improve gas safety. This may be achieved by providing knowledge, predictive techniques and testing procedures/facilities, and by transferring results to the industry in such a way that everyday working procedures, rules and regulations as regards both design and operations may take proper account of state-of-the-art knowledge. Many of the current R and D subjects are general in the sense that they are of importance both offshore (exploration/production/storage/transport) and on-shore (transport/storage/processing/utilisation) [135]. These are described briefly below.

1.4. Experimental test programme

The objective of this part is to provide knowledge which is directly applicable to engineering work, to provide data for validation of simulation codes, and also to provide tests of equipment and explosion safety concepts. For instance work is done on developing: · knowledge on how real process streams (fuel mixtures) explode · guidelines for use of water deluge systems for explosion protection · knowledge on how to ensure integrity of vital equipment by assessing loading on structural parts and equipment · knowledge about the effect of small, complex process equipment on explosions · data on how mist explosions compare with gas explosions in large-scale geometries.

1.5. Enhancement of FLACS

Emphasis is put on improving FLACS interfaces (both to users and to other software) to facilitate its use, and on improving the predictive capability of FLACS. The objective of this part of the programme is hence: · to provide a comprehensive simulation package for integrated safety analysis and design, using a common framework and user interface. The simulation package will be an extension and improvement of CASD/FLACS · to increase the accuracy and reliability of the code by improving physical submodels and numerical solution schemes

1.6. Applied safety technology

Many smaller industrial companies do not have access to the often large amounts of knowledge and expertise in specialised areas which exist in safety research groups today. Furthermore, technology transfer is frequently considered as the final activity of research projects. In this programme, technology transfer to the industry is a major continuous effort from the very beginning and constitutes one of the three main parts of the programme.

During the last decade research has focused on developing knowledge which is now at a stage where guidelines and practical results can be formulated. Large amounts of data that can be analysed and systemized now exist. Areas where CMR at present is making an effort along these lines, include: · gas explosion handbook · PC tool for gas explosion analysis (μFlacs) · safety walls designed with regard to working environment, gas dispersion (natural ventilation) and gas explosion safety (these three aspects may not be compatible!) · water deluge systems for explosion mitigation.

1.7. Disclaimer

Christian Michelsen Research AS accepts no legal liability or responsibility whatsoever for the consequences of unqualified use or misuse of this book or any results thereof.

2. Introduction to gas explosions

We have all heard about accidental gas explosions and the destruction they can cause. Fortunately most of us will not experience accidental explosions. However, preventing them from happening requires a good understanding of what a gas explosion is and what can be done to reduce the frequency and consequences of such events.

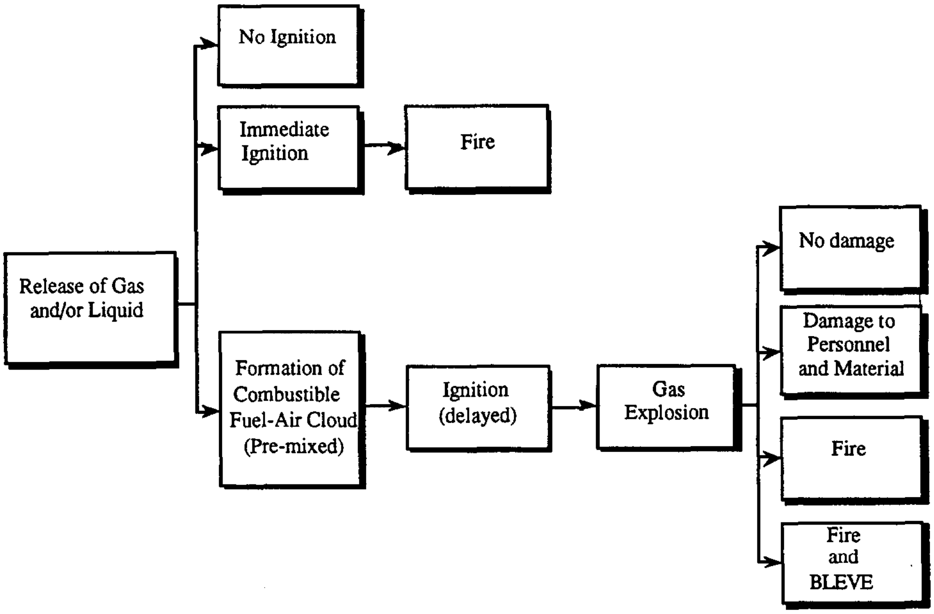


Fig. 4. An event tree showing typical consequences of accidental releases of combustible gas or evaporating liquid into the atmosphere.

The objective of this chapter is:

(i) to give an introduction to the field of gas explosions

(ii) to give an overview of loss experience

(iii) to show how we can use our knowledge to improve safety.

This chapter briefly covers these aspects of gas explosions. It is intended to be a first introduction to the field, and should be read the first time the handbook is used.

2.1. What is a gas explosion

We define a gas explosion as a process where combustion of a premixed gas cloud, i.e. fuel–air or fuel/oxidiser is causing rapid increase of pressure. Gas explosions can occur inside process equipment or pipes, in buildings or offshore modules, in open process areas or in unconfined areas. When we are talking about a gas explosion as an event, it is a more general term. It is then common to include the events both before and after the gas explosion process, see Fig. 4.

Fig. 4 shows what can happen if combustible gas or evaporating liquid is released accidentally into the atmosphere. If the gas cloud, formed from the release, is not within the flammability limits or if the ignition source is lacking, the gas cloud may be diluted and disappear. Ignition may occur immediately, or may be delayed by up to tens of minutes, all depending on the circumstances. In case of an immediate ignition (i.e. before mixing with air or oxidiser has occurred) a fire will occur.

The most dangerous situation will occur if a large combustible premixed fuel–air cloud is formed and ignites. The time from release start to ignition ranges from a few seconds to tens of minutes. The amount of fuel ranges from a few kilograms to several tons.

The pressure generated by the combustion wave will depend on how fast the flame propagates and how the pressure can expand away from the gas cloud (governed by confinement). The consequences of gas explosions range from no damage to total destruction. The pressure build-up caused by the gas explosion can damage personnel and material or it can lead to accidents such as fires and BLEVE's (domino effects). Fires are very common events after gas explosions.

When a cloud is ignited the flame can propagate in two different modes through the flammable parts of the cloud. These modes are:

(i) deflagration

(ii) detonation

The deflagration mode of flame propagation is the most common. A deflagration propagates at subsonic speed relative to the unburnt gas, typical flame speeds (i.e. relative to a stationary observer) are of the order of $1–1000\,ms^{-1}$. The explosion pressure may reach values of several barg, depending on the flame speed (see Section 6.1.).

A detonation wave is a supersonic (relative to the speed of sound in the unburnt gas ahead of the wave) combustion wave. The shock wave and the combustion wave are in this case coupled. In a fuel–air cloud a detonation wave will propagate at a velocity of $1500–2000\,m\,s^{-1}$ and the peak pressure is typically 15–20 bar.

In an accidental gas explosion of a hydrocarbon–air cloud (ignited by a weak source — a spark) the flame will normally start out as a slow laminar flame with a velocity of the order of $3–4\,m\,s^{-1}$. If the cloud is truly unconfined and unobstructed (i.e. no equipment or other structures are engulfed by the cloud) the flame is not likely to accelerate to velocities of more than $20–25\,m\,s^{-1}$, and the overpressure will be negligible if the cloud is not confined.

In a building or in an offshore module with process equipment as shown schematically in Fig. 5 the flame may accelerate to several hundred meters per second. When the gas is burning the temperature will increase and the gas will expand by a factor of up to 8 or 9. The unburnt gas is therefore pushed ahead of the flame and a turbulent flow field is generated. When the flame propagates into a turbulent flow field, the effective burning rate will increase and the flow velocity and turbulence ahead of the flame

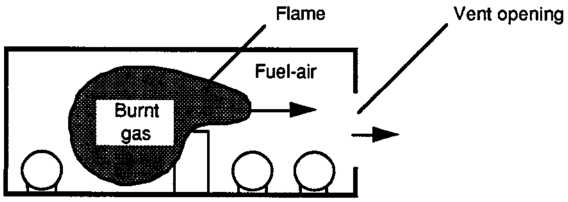


Fig. 5. Gas explosion in a partly confined area with process equipment.

increases further. This strong positive feedback mechanism is causing flame acceleration and high explosion pressures and in some cases transition to detonation.

In a confined situation, such as a closed vessel, a high flame velocity is not a requirement for generation of pressure. In a closed vessel there is no or very little relief (i.e. venting) of the explosion pressure and therefore even a slow combustion process will generate pressure (constant volume combustion, see Section 5.9).

The consequences of a gas explosion will depend on:

- type of fuel and oxidiser
- size and fuel concentration of the combustible cloud
- location of ignition point
- strength of ignition source
- size, location and type of explosion vent areas
- location and size of structural elements and equipment
- mitigation schemes

Gas explosions may be very sensitive to changes in these factors. Therefore it is not a simple task to estimate the consequences of a gas explosion.

2.2. Loss experience

If we review the annual list of accidents in the Loss Prevention Bulletin (IChemE) we will find that there are many serious explosions each year. In addition there is a large number of minor explosions or near-accidents which are never reported.

[1], has reviewed the hundred largest losses in the hydrocarbon process industry, from 1957 to 1986 (see Fig. 6). He found that 42% of these accidents were caused by vapour cloud explosions. In his classification vapour cloud explosions include gas explosions within buildings as well as outdoors (unconfined explosions). Events classified as explosions constitute 22%. These explosions are probably run-away reactions, explosions in solids, BLEVE's, loss of containment, and gas explosions internally in process equipment.

When we look into the details of the individual accidental explosions that have happened, we will find a large variety in size of the explosion and loss experience. From accidental records we can learn that gas explosions have a tendency to repeat themselves in similar conditions. It is therefore important to investigate accidents, report the findings in open literature and take corrective actions.

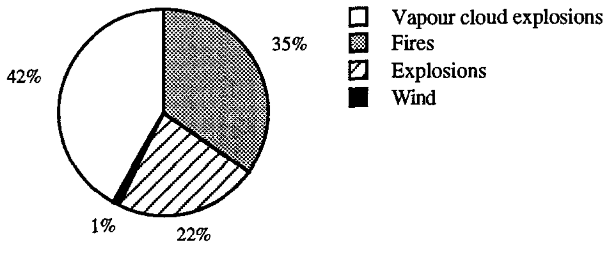


Fig. 6. Distribution of types of loss for the 100 largest losses in the hydrocarbon process industry from 1957 to 1986 [1].

2.2.1. Flixborough, 1974

The explosion in the Nypro plant at Flixborough on 1 June 1974 is one of the most serious accidents in the history of the chemical industry. At Flixborough, the plant was totally destroyed and 28 people were killed and 36 others were injured on site. Outside the plant, 53 people were reported injured and 1.821 houses and 167 shops suffered damage. The cost of the damages was over 100 mill. dollars ([2]). The cause of the Flixborough explosion was a release of about 50 tons of cyclohexane, probably caused by failure of a temporary pipe. The flammable cloud was ignited about 1 minute or so after the release. A very violent explosion occurred. The blast was equivalent to an explosion of about 16 tons of TNT. The characteristic of the gas explosion at Flixborough is that the dense fuel (cyclohexane) was able to form a huge flammable gas cloud and that the confinement and obstructedness within the plant were causing high explosion pressures. From the Flixborough incident we can learn (i) if the inventory had been smaller, the flammable gas cloud would have been smaller, i.e. reduce inventory (ii) control of plant and process modification is important (iii) use blast resistant control rooms and buildings.

2.2.2. Brahegatan, 1983

On 3 March 1983 there was a hydrogen explosion in an open street in Stockholm ([3]). The event occurred when gas cylinders where unloaded from a lorry and hydrogen suddenly started to leak out. The hydrogen was stored in a bank of 18 cylinders which contained about 10 kg. of hydrogen. The blast wave from the explosion broke windows in a range of about 90 m. 16 people were injured. From the Brahegatan incident we can learn that hydrogen is very reactive and even in open areas explosions with hydrogen can be very violent.

2.2.3. West Vanguard, 1985

At the night of 7 October 1985 a blow-out occurred on West Vanguard when the rig was drilling at Haltenbanken in the Norwegian sector ([4]). The escaping gas was sucked into the engine room and a very violent gas explosion occurred. The side wall of the engine room was blown open and one man was killed. As is typical for such an accident, a fire followed the explosion. Fortunately, the main integrity of the rig was not damaged seriously and the rest of the crew were rescued. From the West Vanguard incident we can learn that escaping gas can be sucked or diffused into confined areas through ventilation ducts. Location of air intakes should therefore be chosen carefully.

2.2.4. Ice cream factory

In an ice cream factory the refrigerating system containing ammonia was leaking during a fire. Suddenly the whole basement exploded and the building was partly destroyed. From this incident we can learn that even substances like ammonia, burning very slowly, can cause severe gas explosions if they explode inside a confined area.

2.2.5. Devnya, 1986

There was a very serious explosion and fire in a PVC factory in Devnya, Bulgaria, 1986 ([5]). The accident was caused by a pipe failure. The pipe had not been X-rayed.

17 people were killed in this accident, among them 8 women working in the laboratory. From the Devnya incident we can learn that: (i) inspection is a key factor to safe operation (ii) all activities not absolutely necessary for the operation of the plant (such as laboratory work) should be removed from potentially hazardous areas.

2.2.6. Berge Istra

On 30 December 1975 the oil/ore carrier M/S Berge Istra ([6]) sank in the Molucca Sea. Two of the crew were rescued. They reported a rapid series of three massive explosions followed by the immediate sinking of the ship. In October 1979, the sister ship M/S Berge Vanga disappeared in the Atlantic Ocean. Practically nothing is known about that incident. No-one was rescued.

The rapid sinking of Berge Istra indicates that a gas explosion in the double bottom of the ship ripped the ship structure open and water flooded the double deck and the engine room.

From the Berge Istra event we can learn that: (i) gas explosions can damage the integrity of large constructions, like a supertanker, and (ii) a flammable gas cloud in a confined volume, like the double bottom of a ship, will easily generate damaging pressures.

2.2.7. Road accident

Two people were driving in a car with a plastic bag filled with oxygen/acetylene. After 4–5 km the bag exploded. The two people in the car were fairly lucky, their only injuries were ear drum ruptures and some hair burnt off. The car suffered damages for NOK 60000. The two people intended to have some fun by making a 'bang'. One of them, a car mechanic, filled acetylene and oxygen from an acetylene torch in a plastic bag, when he dropped by the garage where he was working. This episode may sound to be an uncommon one, but it is not. In Norway, during the last five years, we have heard about two other explosions caused by people trying to make 'bangs' in a similar way to the two people in the car. From this road accident we can learn: (i) one should not play around with premixed combustible gas; it is very dangerous (ii) most people do not have the slightest idea of how dangerous combustible gas can be if it is not handled with care [120].

2.2.8. Piper Alpha, 1988

Piper Alpha is the 'Flixborough accident' in the offshore industry. At Piper Alpha a rather small gas explosion in a compressor module caused fires which subsequently resulted in rupture of the riser. The main part of the platform burned down. 167 people were killed. The gas explosion overpressure was calculated by the FLACS code ([7]) to be about 0.3 bar for the most likely gas cloud. From the Piper Alpha incident we can learn that a gas explosion can easily result in a domino effect and loss of control. Installations should be designed to avoid domino effects.

2.2.9. Deodorant factory

As a result of environmental concerns, freon as a driver gas in deodorant atomisers, was changed to butane. After a short time of production, the main part of the factory was destroyed by a gas explosion ([8]). From the deodorant factory accident we can learn that process modification must be controlled.

2.2.10. Port Hudson, Missouri, 1970

In this incident, liquid propane was released from a pipeline. The gas cloud flowed into a valley and about 20 min after the release started, the gas cloud exploded violently. The explosion was probably a detonation. The explosion started as an internal explosion in a pump house and this triggered the unconfined cloud to detonate. From Port Hudson we can learn that explosions in confined areas can initiate detonations causing high pressures in unconfined areas.

2.2.11. Rafnes, 1988

The incident at Rafnes, Norway, in 1988 is known as a large fire. However, the first incident was actually a gas explosion. The people sitting in the blast resistant control room, felt the whole building shake. There was no major damage caused by the explosion, and no one was injured. The explosion pressure was likely to have been in the order of 100 mbar or so.

The Rafnes plant was designed with blast resistant buildings. If the release that occurred at Rafnes had happened in an old-fashioned plant, it is very likely that the consequences of the gas explosion would have been quite different. This is an example of protection that worked as was intended. From the Rafnes incident we can learn: (i) control rooms and buildings should be blast resistant, (ii) fire is a common event after an explosion, and (iii) it is possible to build a blast barrier that can mitigate and protect against the consequences of a gas explosion.

2.3. Analysis and management of gas explosion safety

Loss experience shows that prevention of gas explosions by reducing the risk of accidental releases, formation of explosive clouds and ignition only, is not sufficient. The frequency of gas explosions is still not low and the consequences of a gas explosion can be dramatic. Therefore, we have to build in a last barrier against gas explosions in our facilities. That can be done by performing safety analyses and by following good engineering practice. By doing so, the risk of gas explosions can be reduced strongly. The objective of this section is to discuss how we can apply the knowledge of gas explosions and the tools for predicting such incidents to make this last barrier effective.

Ref. [9] discusses a Norwegian model for managing safety in offshore development projects. Some examples of the activities in safety management presented by Pappas, are shown in Fig. 7.

In development projects, gas explosion hazards should be taken into consideration from day one. It is in the early phase of the development project (i.e. conceptual study) that major decisions such as location of different areas, separation of areas and overall layout (that will influence the vent arrangement and the process itself) are made. In the detailed engineering phase the final calculation of gas explosion loads is one important activity. In the fabrication and installation phase, checking that design is followed is a main activity. In all these stages, it is important to have good understanding of gas explosion hazards and to apply simple guidelines and good engineering practise.

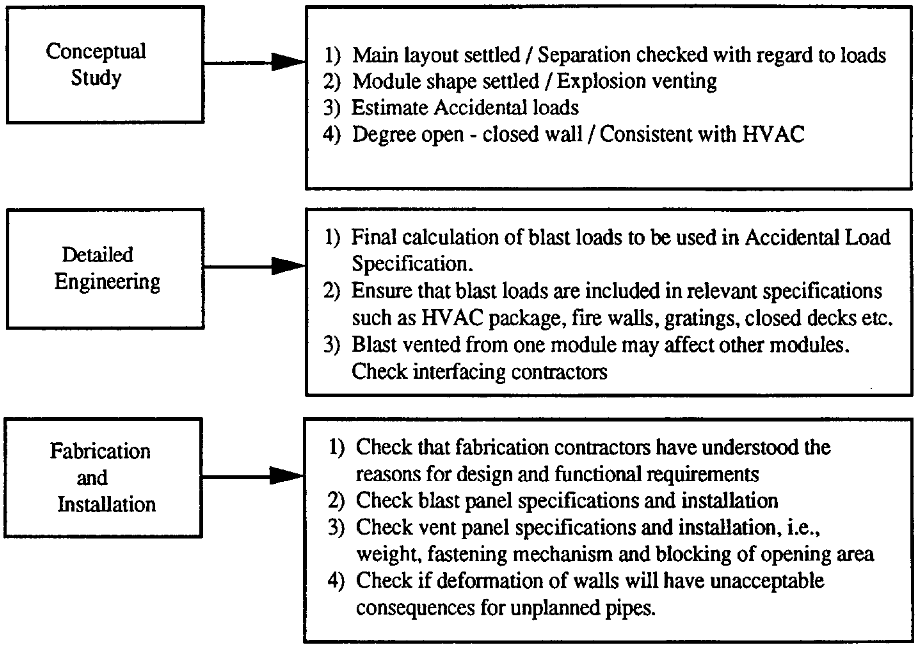


Fig. 7. Examples of activities in safety management in an offshore development project [9].

To estimate consequences and loads from gas explosions is often part of a risk analysis. As shown in Fig. 8, a typical risk analysis consists of 5 elements. The risk consists of the frequency and the consequences of an event. (Risk = frequency * consequence.)

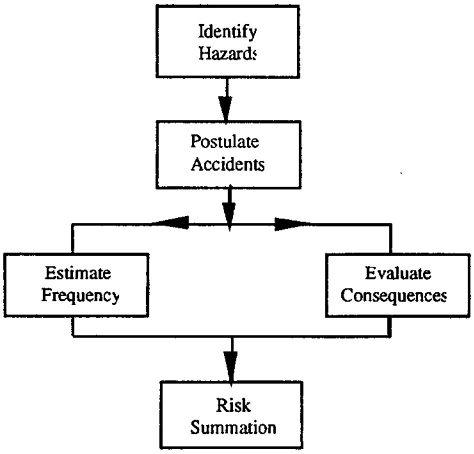


Fig. 8. Risk analysis [11].

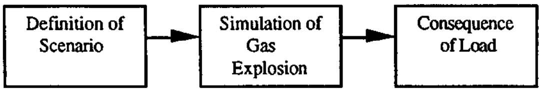


Fig. 9. Consequence evaluation of gas explosions.

The elements in consequence evaluation are shown in Fig. 9. When we are using FLACS for simulation of gas explosions, the FLACS simulation is one part of the consequence evaluation. Definition of scenario (i.e. size of gas cloud, ignition location, vent arrangement etc.) is a very important part of the consequence analysis. Definition of scenario is also related to the frequency estimates. One example is that the larger the gas cloud, the lower is the frequency of its occurrence. In gas explosion analysis, the results of gas explosion simulations are very sensitive to certain parameters. One of them is the ignition point location. In some cases, by moving the ignition point and keeping the other parameters constant, the explosion may change by orders of magnitude in pressure. This is a fact that should be recognised when consequence and risk analyses are made.

The benefits we can obtain from a consequence analysis are:

- assessment of risk in formal risk assessment studies
- improved design and operation
- supporting decision making
- transfer of knowledge
- cost benefit
- safety

3. Definitions

Combustion terminology a disaster area is the title of an article by [10]. They pointed out that combustion nomenclature is in an unholy mess. Words like 'burning velocity', 'flame speed', 'flammable', 'inflammable', 'non-flammable', 'deflagration' and 'detonation' are often used wrongly. This is also our experience.

This lack of coherent nomenclature makes it very difficult for those who want to use the results from gas explosion research in practical safety work in the industry. Even the phenomenon that we are talking about has several names: 'gas explosion', 'gaseous explosion', 'unconfined vapour cloud explosion', 'vapour cloud explosion' or 'fuel–air explosion'. In this handbook we have decided to use the term 'gas explosion'. We find this term the simplest, the least confusing, and the most general term for explosions caused by burning of premixed fuel–air or fuel–oxidiser in gas phase.

The objective of this chapter is to present the definitions used in this handbook. You may find different definitions in other literature.

3.1. Explosion

We define an explosion as an event leading to a rapid increase of pressure. This pressure increase can be caused by: nuclear reactions; loss of containment in high

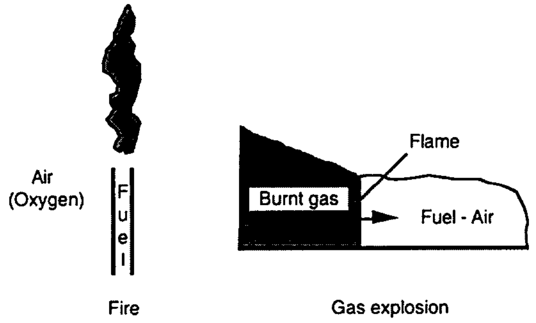


Fig. 10. Illustration of jet fire and gas explosion.

pressure vessels; high explosives; metal water vapour explosions; run-away reactions; combustion of dust; mist or gas (incl. vapours) in air or in other oxidisers.

3.2. Combustion

The burning of gas, liquid, or solid in which fuel is oxidised involves heat release and often light emission. Combustion of methane (CH_4) in air can be described by the chemical equation:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 2(3.76N_2) + \textit{Energy}$$

The chemical products from complete combustion of a hydrocarbon fuel are mainly CO_2 and H_2O (vapour). The combustion process will result in an increased temperature caused by the transformation of chemically bound energy into heat. It should be emphasised that the above equation constitutes a strong simplification of the real combustion process.

Combustion of gaseous fuel in air can occur in two different modes. One is the fire, where fuel and oxygen are mixed during the combustion process. In the other case the fuel and air (or another oxidiser) are premixed and the fuel concentration must be within the flammability limits. In general the premixed situation allows the fuel to burn faster, i.e. more fuel is consumed per unit time (see Fig. 10).

3.3. Gas explosions

We define a gas explosion as a process where combustion of a premixed gas cloud, i.e. fuel–air or fuel–oxidiser, is causing a rapid increase of pressure. Gas explosions can occur inside process equipment or pipes, in buildings or offshore modules, in open process areas or in unconfined areas.

The consequences of a gas explosion will depend on the environment in which the gas cloud is contained or which the gas cloud engulfs. Therefore it has been common to classify a gas explosion from the environment where the explosion takes place: (i) Confined Gas Explosions within vessels, pipes, channels or tunnels (ii) Partly Confined Gas Explosions in a compartment, buildings or offshore modules and (iii) Unconfined Gas Explosions in process plants and other unconfined areas. It should be pointed out

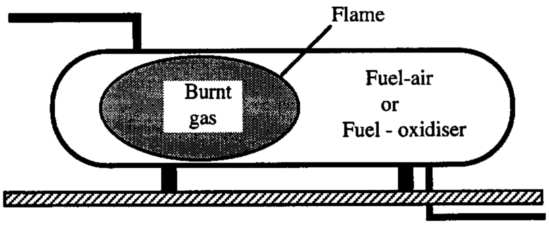


Fig. 11. Confined explosion within a tank.

that these terms are not strictly defined. In an accidental event it may be hard to classify the explosion. As an example, an unconfined explosion in a process plant may also involve partly confined explosions in compartments into which the gas cloud has leaked.

3.4. Confined gas explosions

Confined gas explosions are explosions within tanks, process equipment, pipes, in culverts, sewage systems, closed rooms and in underground installations. Confined explosions are also called internal explosions (Fig. 11).

Typical for this kind of explosion is that the combustion process does not need to be fast in order to cause serious pressure build-up. Section 10 covers gas explosions within vessels, pipes, channels and tunnels in more detail.

3.5. Partly confined gas explosions

Partly confined explosions occur when a fuel is accidentally released inside a building which is partly open. Typical cases are compressor rooms and offshore modules. The building will confine the explosion and the explosion pressure can only be relieved through the explosion vent areas, i.e. open areas in the walls or light relief walls that open quickly at low overpressure. As discussed in Section 11 both size and location of explosion vent areas are important for the resulting explosion pressure (Fig. 12).

3.6. Unconfined gas explosions

The term unconfined was used to describe explosions in open areas such as process plants. Large scale tests have demonstrated that a truly unconfined, unobstructed gas

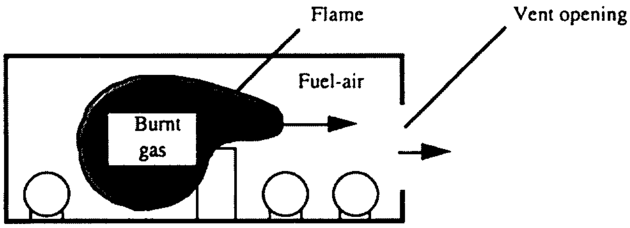


Fig. 12. Gas explosion in a partly confined area with process equipment.

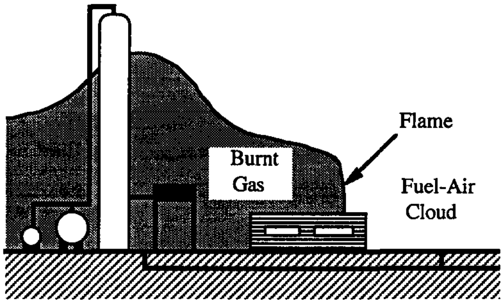


Fig. 13. Gas explosion in a process area.

cloud ignited by a weak ignition source will only produce small overpressures while burning (flash fire). The term unconfined gas explosions should therefore be used with care. In a process plant there are local areas which are partly confined and obstructed. In case of a deflagration it is these areas that are causing high explosion pressures (Fig. 13).

However if an unconfined cloud detonates the explosion pressure will be very high, in the order of 20 bar g and in principle independent of confinement and obstructions.

3.7. Vapour cloud explosions (VCE)

There is no essential difference between a vapour cloud explosion and a partly confined or an unconfined gas explosion. In this handbook we will use the term gas explosion and we will not differentiate between vapour cloud explosions and gas explosions.

3.8. Flame speed and burning velocity

Flame speed, S, is defined as velocity of the flame relative to a stationary observer i.e. the ground or an other fixed frame. The burning velocity, U, is the velocity of the flame front with respect to the unburnt gas immediately ahead of the flame. The relation between flame speed, S, and burning velocity, U, is therefore:

$$S = U + u$$

where u is velocity of the unburnt gas just ahead of the flame. For Stoichiometric hydrocarbon–air mixtures S is of the order of $8U$ (Fig. 14).

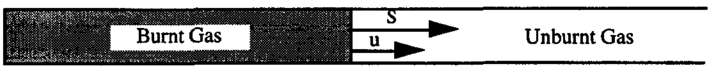


Fig. 14. Flame propagation in a tube. The flame speed, S, is defined as the velocity of the flame relative to the ground or another fixed frame. u is the velocity of the unburnt gas ahead of the flame.

3.9. Burning rate

The burning rate ($kg\,s^{-1}$) is the amount of fuel consumed by the combustion process per time unit. The burning rate is a measure of the rate of energy release in an explosion. The burning rate may also be defined as mass of fuel consumed per unit time and volume.

3.10. Deflagrations

A deflagration is defined as a combustion wave propagating at subsonic velocity relative to the unburnt gas immediately ahead of the flame, i.e., the burning velocity, U, is smaller than the speed of sound, C, in the unburnt gas. The velocity of the unburnt gas ahead of the flame is produced by the expansion of the combustion products.

In an accidental gas explosion the deflagration is the common mode of flame propagation. In this mode the flame speed, S, ranges from order of $1\,m\,s^{-1}$ up to $500-1000\,m\,s^{-1}$ corresponding to explosion pressures between a few mbar and several bar.

For strong deflagrations, shock waves may propagate ahead of the deflagration (i.e. the flame).

3.11. Detonations

A detonation is defined as a combustion wave propagating at supersonic velocity relative to the unburnt gas immediately ahead of the flame, i.e., the detonation velocity, D, is larger than the speed of sound, C, in the unburnt gas.

In simple terms, a detonation wave can be described as a shock wave immediately followed by a flame (ZND theory). The shock compression heats the gas and triggers the combustion. However, an actual detonation wave is a three-dimensional shock wave followed by the reaction zone (Fig. 15).

For fuel air mixtures at ambient pressure the detonation velocity can be up to $2000\,m\,s^{-1}$ and the maximum pressures produced are close to 20 bar.

A detonation can either: (i) be initiated directly by detonating a high explosive charge, or (ii) be produced when a deflagration accelerates because of obstacles and confinement and transits into a detonation.

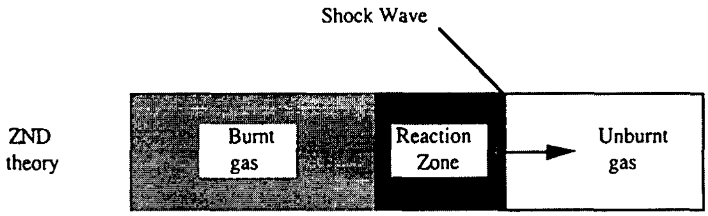


Fig. 15. A detonation wave can be described as a shock wave immediately followed by a flame (ZND theory).

Fig. 16. Illustration of particle trajectories in laminar and turbulent flows.

3.12. Turbulence

In fluid dynamics we divide the flow into laminar and turbulent regimes. Laminar flow means that the fluid flows in laminars or layers, while turbulent flow is characterized by an irregular random fluctuation imposed on mean (time-averaged) flow velocity. Fig. 16 shows the trajectory of a particle in laminar and turbulent flows.

Whether the flow is laminar or turbulent depends mainly on flow velocity u, characteristic dimension of the geometry L, and kinematic viscosity ν. The Reynolds number, Re, is defined by:

$$Re = \frac{uL}{\nu}$$

and is a dimensionless parameter characterizing whether the flow regime is laminar or turbulent.

Fig. 17 shows the flow field around a cylinder in a crossflow for different Re. The characteristic length scale, L, for this geometry is the diameter of the cylinder. For a low Re and low flow velocity, the flow around the cylinder is laminar. For higher Re vortices develop in the wake of the cylinder and the flow in the volume will be turbulent.

The turbulence is very important for how fast the flame can propagate in a premixed gas cloud. The turbulence will wrinkle the flame front and increase diffusion of heat and mass and thereby cause higher burning rate.

3.13. Hydrodynamic instability

The interface between a light and a heavy gas is stable if the fluid is accelerated in the direction of the positive density gradient. However, if the fluid is accelerating in the other direction, the interface is unstable (Fig. 18).

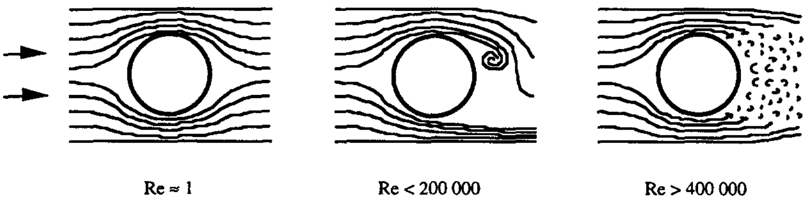


Fig. 17. Cylinder in a crossflow at different Reynolds number, Re.

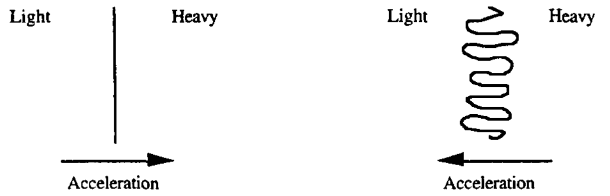


Fig. 18. Acceleration of density gradient illustrating the Taylor instability. Left is stable and right is unstable.

This hydrodynamic instability phenomenon also occurs in gas explosions. If the flame front is exposed to a compression wave propagating from the heavy gas (i.e. fuel–air) into the light gas (i.e. burnt gas) or a rarefaction wave propagating in the opposite direction, the flame front becomes wrinkled (unstable) and the burning rate increases.

This instability phenomenon is known as a Taylor instability.

3.14. Flash fires

A flash fire is the term for a slow deflagration of a premixed, truly unconfined, unobstructed gas cloud producing negligible overpressure.

Thermal effects are the main hazard.

3.15. BLEVEs

BLEVE is an acronym for Boiling Liquid Expanding Vapour Explosion. The BLEVE is an explosion caused by the flashing of liquids when a vessel with a high vapour pressure substance fails. The failure of the vessel is often caused by an external fire as shown in Fig. 19.

If the substance released is a fuel, the BLEVE can result in very large fire balls. Rocketing vessels are also hazards related to BLEVEs. Fig. 19 and Fig. 20 show a BLEVE and a fire ball in a tank car accident, but BLEVEs can also happen in process areas or in offshore modules.

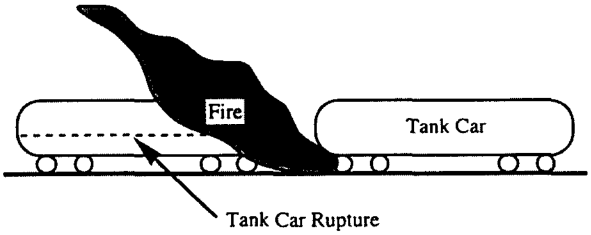


Fig. 19. A situation that can lead to a BLEVE.

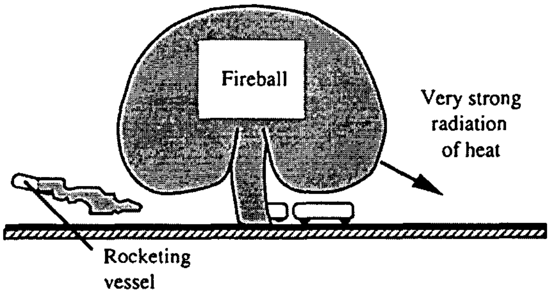


Fig. 20. Fire balls and rocketing vessels are often the main hazards of a BLEVE.

3.16. Shock wave

A shock wave in a gas can be defined as a fully developed compression wave of large amplitude, across which density, pressure, and particle velocity change drastically [12].

The thickness of a shock wave is of the order of the mean free path and may be treated as a discontinuity (Fig. 21).

A shock wave propagates at supersonic velocity relative to the gas immediately ahead of the shock, i.e., the gas ahead is undisturbed by the shock. The propagation velocity of the shock wave depends on the pressure ratio across the wave. Increasing pressure gives higher propagation velocity.

3.17. Blast wave

A blast wave can be defined as the air wave set in motion by an explosion [12] (Fig. 22).

The term blast wave includes both sonic compression waves, shock waves and rarefaction waves. Fig. 23 illustrates in principle different types of blast waves. We can have (i) a shock wave followed by a rarefaction wave, (ii) a shock wave followed by a sonic compression wave and then a rarefaction wave, (iii) a sonic compression wave and a rarefaction wave. The type of blast wave depends on how and when the energy is

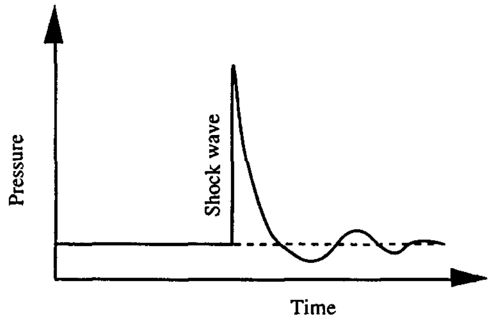


Fig. 21. A shock wave followed by a rarefaction wave.

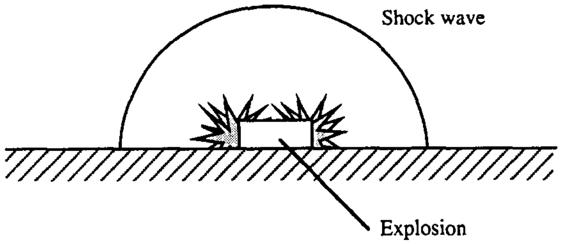


Fig. 22. Free field blast wave.

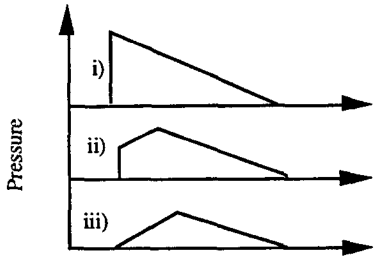


Fig. 23. Blast waves.

released in the explosion and the distance from the explosion area. For strong explosions category (i) is typical. Weak explosions gives initially category (iii), but the wave can be shocking up and end as category (i) when it propagates away from the explosion.

Blast waves from TNT explosions and other military tests are often divided into ranges depending on the peak overpressure. In order to avoid confusion we should use the same classification for blast waves from gas explosions. The classification is given in Table 1. It should be noted, however, that this classification is not fully consistent, since by definition mid-distance pressures can be said to occur inside a gas explosion of for instance 0.5 bar overpressure. One should therefore ensure that the range classification is applied only to sufficiently strong gas explosions and only outside the cloud.

In this handbook we will use the term free field blast as a definition of a propagating hemispherical blast wave outside the exploding cloud.

Table 1
Classification of close-in, mid distance, and far field blast waves [13].

Classification	Peak overpressure	
Close-in range	> 10 psi	> 0.69 bar
Mid-distance	0.5–10 psi	0.034–0.69 bar
Far-field	< 0.5 psi	< 0.034 bar

3.18. Pressure

Pressure is a type of stress which is exerted uniformly in all directions; its measure is the force exerted per unit area [12].

In fluid dynamics we often use the terms (i) static pressure, (ii) dynamic pressure and (iii) stagnation pressure.

Static pressure is what we normally call the pressure. The strict definition of static pressure is: (a) the pressure that would exist at a point in a medium if no sound waves were present, or (b) the normal component of stress, the force per unit area, exerted across a surface moving with the fluid, especially across a surface which lies in the direction of the flow [12].

Dynamic pressure is the pressure increase that a moving fluid would have if it was brought to rest by isentropic flow against a pressure gradient [12] The dynamic pressure can also be expressed by the flow velocity, u and density, ρ.

$$p_{\mathrm{Dyn}} = \frac{\rho \cdot u^2}{2}$$

Stagnation pressure is the pressure that a moving fluid would have if it was brought to rest by isentropic flow against a pressure gradient [12]. The stagnation pressure is the sum of the static and the dynamic pressures.

$$p_{\mathrm{Stag}} = p_{\mathrm{Stat}} + p_{\mathrm{Dyn}}$$

For blast waves and shock waves we use the terms side-on pressure and reflected pressure. The side-on pressure is measured perpendicular to propagation direction of the wave. Side-on pressure is the static pressure behind the shock wave. The reflected pressure is measured when the wave hits an object like a wall head-on. Since reflection is not an isentropic process there is a difference between stagnation pressure and the reflected pressure. These definitions of side-on and reflected pressures are illustrated in Fig. 24.

4. Formation of explosive gas clouds

When combustible gas or evaporating liquids are accidentally released into the atmosphere, a combustible fuel–air cloud may be formed.

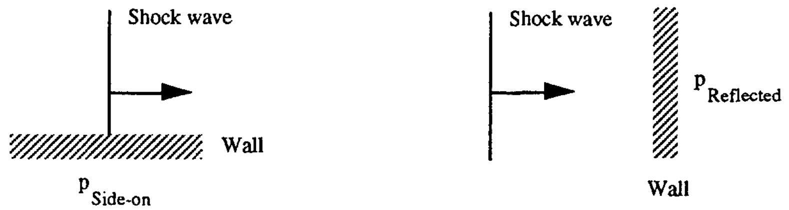


Fig. 24. Side-on pressure and reflected pressure.

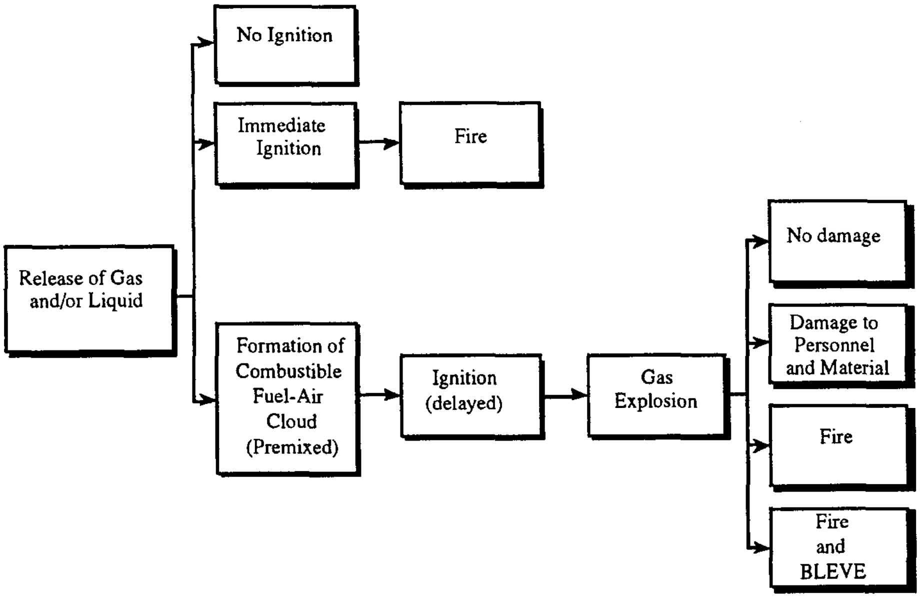


Fig. 25. An event tree showing typical consequences of accidental release of combustible gas or evaporating liquid into the atmosphere.

Fig. 25 shows possible events in case of an accidental release.

If the gas cloud formed by the release is outside the flammable concentration range (i.e. outside LFL and UFL), or the ignition source is lacking no combustion will occur. Subsequently the gas cloud will dilute and disappear. In case of an immediate ignition, a fire will develop. The most dangerous situation, however, will occur if a large flammable premixed fuel–air cloud is formed and ignites. A serious explosion may then result.

The objective of this chapter is to:

(i) Describe the difference between a jet release and an evaporating pool.

(ii) Describe experimental results from jet releases in a 1:5 scale model of an offshore module.

(iii) Describe FLACS code facilities for simulation of gas dispersion.

(iv) Discuss the formation of a combustible gas cloud and ignition.

4.1. Jet releases and evaporating pools

The released substance can be a gas, an evaporating liquid or a gas-liquid (two phase) flow. The source will be characterized as a jet release (i.e. gas, two phase or evaporating liquid), or a diffuse release, i.e. evaporating pool. A jet release and a diffuse source are shown in Fig. 26.

The two sources have quite different characteristics. The jet release will have a high momentum and establish a strong flow field caused by additional air entrainment. Recirculation zones may be generated where the gas concentration can reach a com-

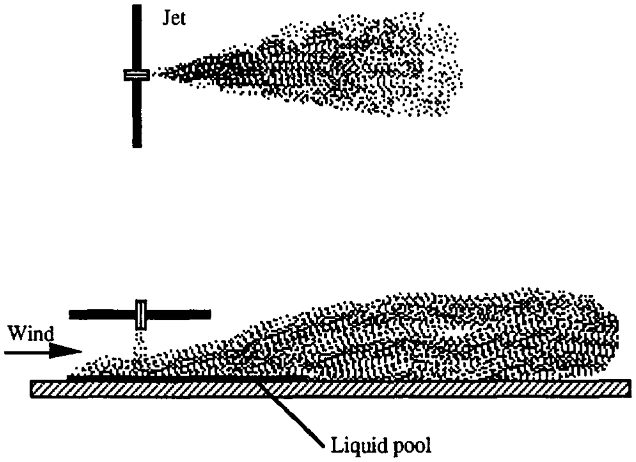


Fig. 26. Jet release and evaporating pool.

bustible level. For jet releases in a building or offshore module, the recirculation can result in build-up of large combustible clouds. The evaporating pool will act as a diffuse release source and the wind forces and buoyancy will control the dispersion process. The flow velocities will be much lower than for the jet release. If the evaporating liquid forms a dense gas, a layer of combustible gas may be formed at the ground level, or in a lower compartment. Similarly in an open area a dense gas cloud will have the tendency to intrude into confined spaces such as buildings. The intrusion of combustible gas into such confined or semi-confined spaces poses serious problems. As discussed in Section 6, Section 7 and Section 10 to Section 12, confinement will generally cause high explosion pressures.

4.2. Gas dispersion tests in a 1:5 scale offshore module

Bjørkhaug and Bjerkevedt [14] have performed gas dispersion tests in a 1:5 scale offshore module.

Gaseous methane and propane were released inside a module through various nozzles (4–20 mm diameter). The reservoir was a 3 m^3 tank and the initial pressure was 5–20 barg. The module had forced ventilation with a bulk flow velocity of 0 $m\,s^{-1}$ to 1.0 $m\,s^{-1}$.

One of the objectives with this test was to establish the degree of homogeneity of the cloud in the module. Fig. 27 shows the concentration versus time at two different locations at the same level. The upward-pointing release starts at 20 s. In the early phase there is a difference in concentration, but after about 10 s. the curves are quite similar.

Fig. 28 shows the concentration in two similar tests at the same place but at different heights.

In these tests there are relatively small variations in concentration.

Further the effect of forced ventilation was investigated. Fig. 29 shows the concentration in three tests with the same source but with different wind velocities (i.e. bulk flow) through the module.

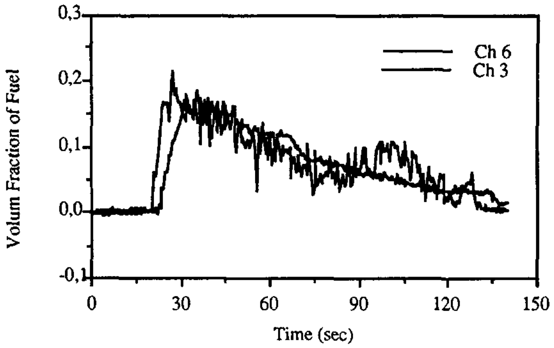


Fig. 27. Concentration measures at two different locations.

Initially the concentration rise was similar for all three cases, at a certain concentration level however, the transportation of fuel out of the module was equal to the leak rate and the concentration profile is flattening out. The higher the wind speed, the lower the concentration where the concentration profile is flattening out. As the reservoir is emptied, the concentration gradually decreases. If the fuel concentration was on the rich side, it would have to pass through the flammable region.

The main findings from these experiments are:

· For a medium and large jet release, the dispersion pattern in the module is dominated by the jet, while the actual concentration level is depending on the natural ventilation.

· For a small jet release, both the dispersion pattern and the concentration level is dominated by the natural ventilation.

· The general trend in the experiments was that gas concentration was very homogeneous and showed less spatial variation than previously anticipated.

· In the presence of a moderate natural ventilation both propane and methane disperse in a similar manner.

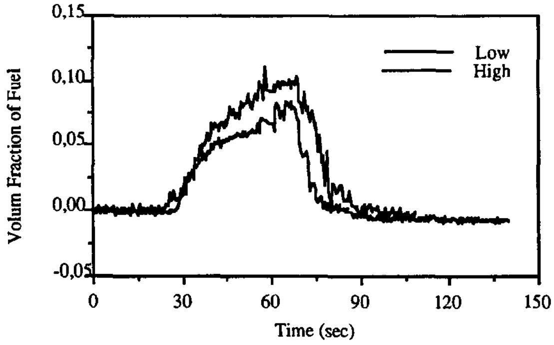


Fig. 28. Concentration measurements at different heights in two tests.

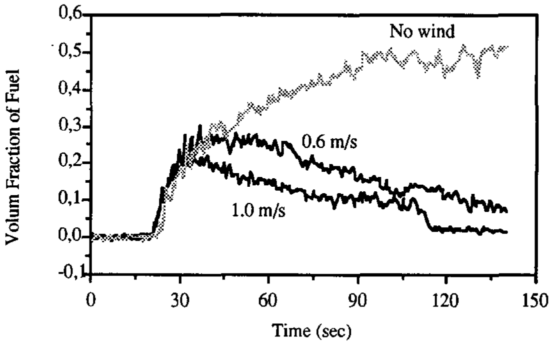


Fig. 29. Concentration as function of time for different wind velocities through the module.

4.3. Gas dispersion simulations using FLACS

Storvik [15] has used FLACS89 to simulate high momentum jet leaks and subsequent gas dispersion in a scaled-down model of an offshore module.

Gas dispersion simulations with high momentum jet leaks usually require many hours of CPU usage because of short time-step and long leak durations (several minutes).

In FLACS89 the high momentum jet is modelled analytically conserving the mass and momentum flow, and is coupled to the resolution of the flow field in the simulation domain. This procedure reduces the need for high spatial resolution near the jet and is an effective approach to simulate high momentum leaks.

Forced ventilation is simulated using a wind as boundary condition. This is useful for simulation of gas dispersion with specified wind speed and turbulence parameters.

In summary: FLACS89 has built-in facilities for handling realistic gas dispersion scenarios including external wind fields, various types of leak sources (jet or diffuse) and wall-functions to account for boundary layer effects.

Fig. 30 shows an example of a contour plot from a jet release in an offshore module. Shaded areas show fuel concentration within the flammability limits. The high momentum jet and a fairly homogeneous gas cloud on the upper deck can be identified. The plot also depicts how the gas on the upper deck is diluted by the flow from the lower deck through the grating in the intermediate deck.

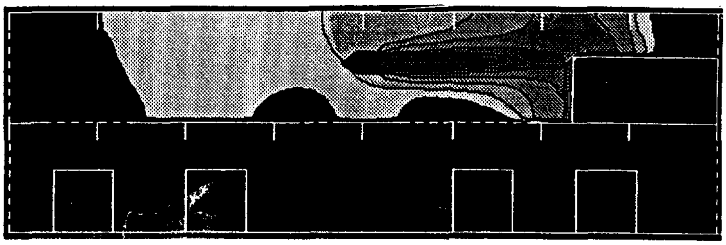


Fig. 30. FLACS simulation of gas dispersion from a jet inside an offshore module. Shaded areas show flammable regions.

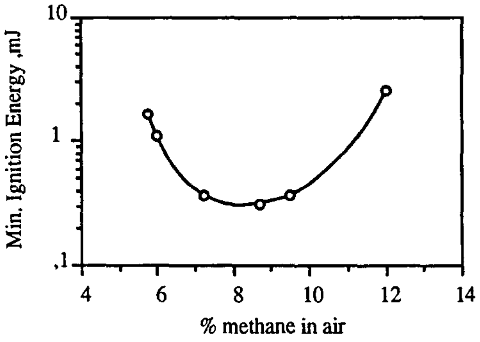


Fig. 31. Minimum Ignition Energy.

Results from FLACS dispersion simulations can be used as input parameters to characterize gas clouds in FLACS gas explosion simulations.

A modified version of FLACS has been used to simulate release of gas from high pressure pipelines [16], taking non-ideal gas effects into account. The results showed that the lower flammability limit of gas–air mixture reaches its most remote downstream position relatively early, before retracting somewhat because of increased entrainment of air.

4.4. Gas cloud and ignition

To ignite a gas cloud requires an ignition source with sufficient strength. The minimum ignition energy depends on fuel concentration and type of fuel (Fig. 31).

As the reservoir is emptied, the release rate will gradually be reduced and the gas concentration in the cloud will decrease. A weak ignition source will 'sit and wait' until the gas cloud has the right composition before it ignites. In several accidental gas explosions the time from the release was initiated until the explosion occurred was 10–20 min. In such cases it is probable that the gas concentration is decreasing at the time of ignition. It should be stated, however, that this is speculative (Fig. 32).

When the ignition source is strong the gas cloud will be ignited when the edge of the cloud reaches the ignition source. If the ignition source is weak, however, the source may fail to ignite the cloud in the early phase of the dispersion process or ignite only a

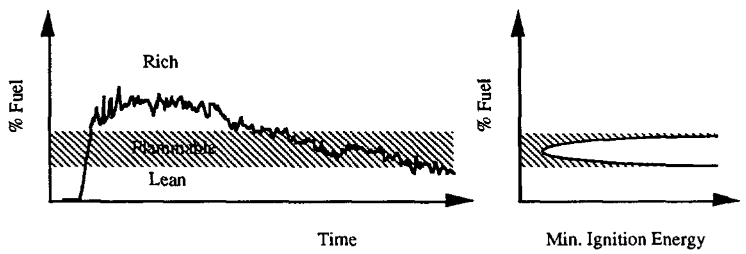


Fig. 32. A weak ignition source may ignite the cloud as the release reservoir is emptied.

small part of the cloud. Subsequently, a homogeneous large gas cloud may be formed. This cloud enters into the flammable concentration as the reservoir is emptied and a weak ignition source may ignite the cloud. This discussion shows some of the complexities involved in assessing ignition probability and formation of explosive gas clouds.

4.5. Ventilation in compartments

Kletz [17] claims that "the best building has no walls". This is true with respect to gas explosion safety. In an open building the natural ventilation will enhance the gas dispersion and if an explosion occurs, the open areas will relieve the pressure. If the release rates are small there is no doubt that mechanical ventilation systems can counteract the formation of explosive gas clouds. However, for a massive release, the forced ventilation rate will in general be too low.

A ventilation system may also transport gas from one area to another.

4.6. Guidelines

· Avoid enclosed compartments.

· Avoid the possibility of intrusion of combustible gas through ventilation systems, etc. into confined areas like buildings, tunnels, sewer systems etc.

5. Combustion properties of fuel–air mixtures

The consequences of a gas explosion will depend strongly on the type of fuel and oxidiser and the fuel and oxidiser concentration. Through years of research and safety work in the industry, essential characteristic properties for characterizing the reactivity and damage potential of various combustible substances have been established. These data are the backbone of gas explosion safety work in the industry. An excellent source of information on such data is the US Bureau of Mines reports:

- Coward and Jones [18], Bureau of Mines Bulletin 502.
- Zabetakis [19], Bureau of Mines Bulletin 627.
- Kuchta [20], Bureau of Mines Bulletin 680.

The book by Nabert and Schön [21] is also a good information source.

The objective of this chapter is not to list up characteristic data for fuel–air mixtures, but to:

(i) define the terminology and

(ii) point out the importance of these properties, i.e. how these properties can be used to evaluate explosion hazards for a fuel

5.1. Flammability limits (LFL and UFL)

A premixed fuel–air mixture will only burn as long as the fuel concentration is between the upper and lower flammability limits, i.e. UFL and LFL.

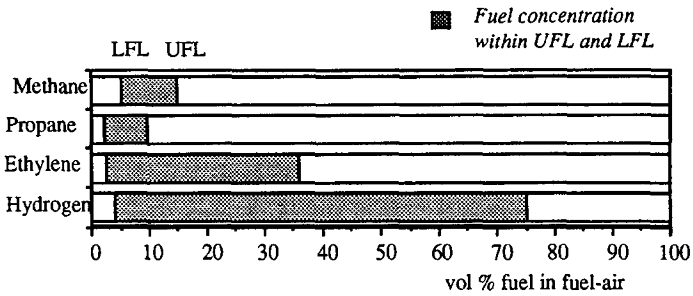


Fig. 33. Flammable range for fuel–air mixtures at 1 atm. and 25°C.

The flammability limits are experimentally determined data. The flammability limits in air depend on initial temperature and pressure. Standard test conditions are 25 °C and 1 atm.

Fig. 33 shows the flammable range for some fuel–air mixtures.

The wide flammable range of hydrogen tells us that it is easy to get a flammable cloud of hydrogen in air. For propane and methane, the flammable range is much narrower, but as discussed in Section 4.4, an ignition source may 'sit and wait' until the cloud can be ignited and explode. If the UFL has been passed, one has to go through the flammable concentration in the dilution process. It is good practice to operate safely below the LFL.

As shown in Fig. 34 the flammable range will widen when the initial temperature is increasing. Changes in initial pressure will for hydrocarbons in air not change the LFL significantly, but the UFL will increase.

Flammability limits for fuel mixtures may be calculated by Le Chatelier's law:

$$LFL_{Mix} = \frac{100}{C_1/LFL_1 + C_2/LFL_2 + \cdots + C_i/LFL_i}$$

where C_1, C_2....C_i [vol.%] is the proportion of each gas in the fuel mixture without air [20].

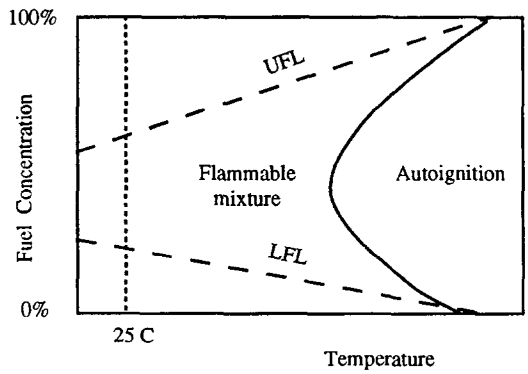


Fig. 34. The effect of temperature on LFL and UFL.

Table 2
Stoichiometric concentration in air for various fuels

	Hydrogen	Ethylene	Propane	Methane
% fuel (vol)	30	6.5	4.0	9.5
($g m^{-3}$)	26.9	81.7	79.1	67.8

Von Niepenberg [22] used Le Chatelier's rule for predicting flammability limits for fuel mixtures containing inert gas. Hustad and Sønju [23] found a good agreement between experiments and Le Chatelier's law for LFL at elevated temperature and pressure for fuel mixtures. It should be noted, however, that the formula does not work properly for H_2 and for unsaturated hydrocarbons. It is also only valid if the components are similar chemically.

5.2. Explosion limits

Same meaning as flammable limits, i.e. UEL = UFL and LEL = LFL. We recommend using the term flammability limit instead of explosion limit.

5.3. Stoichiometric compositions

The Stoichiometric composition is defined as the composition where the amounts of fuel and oxygen (air) are in balance so that there is no excess of fuel or oxygen after the chemical reaction has been completed.

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 5(3.76N_2)$$

For practical purposes the Stoichiometric composition (Table 2) can be regarded as the composition giving the highest explosion pressure for a single component fuel. (Exceptions to this exist, e.g. acetylene–air).

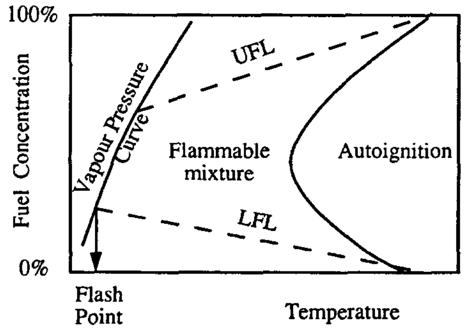


Fig. 35. Flash point.

Table 3
Flash point for various fuels [20].

	Propane	JP4	Kerosene	Diesel fuel (60 cet)
Flash Point (°C)	< − 104	− 18	52	40–50

5.4. Flash points

The flash point of the fuel is the minimum temperature at which it gives off sufficient vapour to form a flammable mixture with air, near the surface of the liquid or within the vessel (in all locations) used. Operating at temperatures lower than the flash point of the liquid fuel will not lead to a flammable mixture being formed unless a mist cloud (e.g. because of splashing) is generated (Fig. 35).

Flash points for some fuels can be found in Table 3.

5.5. Minimum ignition energy

The minimum ignition energy is a measure of required energy for a localised ignition source, like a spark, to successfully ignite a fuel-oxidiser mixture. As shown in Fig. 36 the ignition energy depends on the fuel concentration. For most combustible fuels the minimum ignition energy is between 0.1 and 0.3 mJ in normal ambient air. However, hydrogen, acetylene and carbon disulphide have one order of magnitude lower minimum ignition energy [20].

5.6. Autoignition temperature

When a flammable mixture is heated up to a certain temperature, the chemical reaction will start spontaneously. As shown in Fig. 37 this critical temperature for fuel–oxidiser is called the (minimum) autoignition temperature, AIT. The precise definition is: the autoignition temperature is the lowest temperature of a hot wall adjacent to the fuel–air mixture which can lead to ignition.

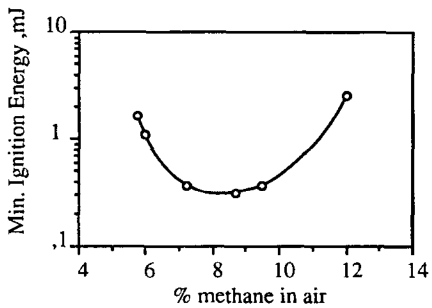


Fig. 36. Ignition energy for methane in air at 1 atm. and 25 °C.

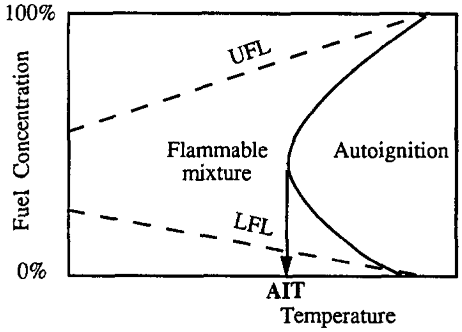


Fig. 37. Autoignition temperature, AIT.

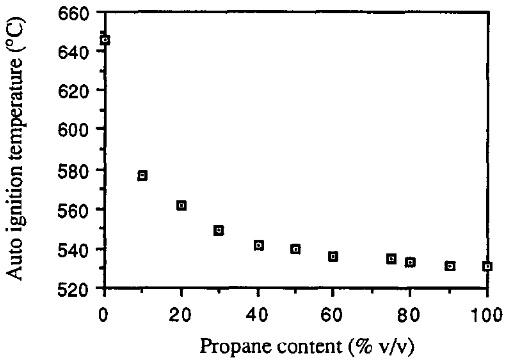


Fig. 38. Autoignition temperature of methane–propane mixture as found in a 1 l ignition bomb (stoichiometric mixtures).

For most pure hydrocarbon derivatives in air, the AIT lies between 540 °C (methane) and 210 °C (n-decane). For mixtures of hydrocarbons, the AIT lies between the AIT of the pure hydrocarbons as shown in Ref. [24] (see Fig. 38 and Table 4).

5.7. Heat of reaction

In combustion technology, we use heat of combustion as a measure of the chemically bound energy in the fuel. This property is usually given as energy per mass of fuel, i.e. $J\,kg^{-1}$ fuel. Regarding gas explosions, the heat of combustion may be misleading. Some fuels can have low values for heat of combustion, but still have a high gas explosion

Table 4
Minimum autoignition temperature (AIT).

	Hydrogen	Ethylene	Propane	Methane
AIT (°C)	520	520	450	540

Table 5
Heat of reaction and heat of combustion [25] for fuel–air mixtures.

	VCM	Hydrogen	Methane	Propane	Ethylene
Heat of reaction [MJ m^{-3}] per m^3 Stoichiometric gas mixtures	3.7	3.2	3.4	3.7	3.9
Heat of combustion [MJ kg^{-1}] (Low value)	18.6	120	50	46	47

potential. With respect to gas explosion hazards, the heat of reaction of the premixed fuel–air is a more relevant property characterizing the energy content. This tells us how much energy per volume can be released in a gas explosion. One should note however, that the reaction rate depends also on other parameters, like the diffusivity of the fuel (e.g. hydrogen which is very diffusive). Table 5 lists heats of reaction and combustion for some fuels including VCM (vinyl chloride monomer).

5.8. Adiabatic flame temperature

The adiabatic flame temperature is the (maximum) temperature obtained when a fuel oxidiser is burning at a constant pressure with no heat loss (to walls, equipment, etc.). This is also a parameter characterizing the energy content of the mixture. Fig. 39 shows the adiabatic flame temperature for methane–air as function of methane concentration. The maximum adiabatic flame temperature occurs close to the Stoichiometric composition (i.e. 9.5% methane in air). For most hydrocarbon–air mixtures this maximum value is the same as for methane, i.e. about 2000 °C.

5.9. Constant volume and constant pressure combustion

When the premixed cloud burns, the temperature of the gas will increase. From the ideal gas law:

$$\frac{p}{\rho T} = \text{Constant}$$

we know that increased temperature will cause increased pressure, p, or decreased density, ρ, (i.e. expansion) or a combination of both.

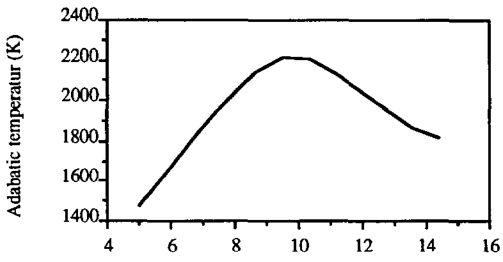


Fig. 39. Adiabatic flame temperature for initial conditions 1 atm. and 25 °C.

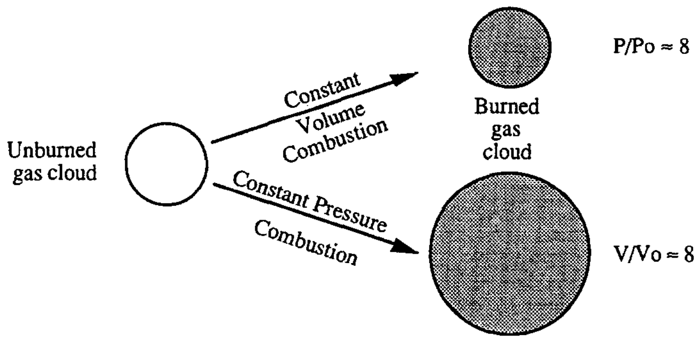


Fig. 40. Constant volume and pressure combustion.

The parameters characterizing the pressure increase and the expansion are data for constant volume combustion and constant pressure combustion, respectively. Fig. 40 illustrates these two situations.

Some data on pressure ratios and expansion ratios can be found in Table 6.

It should be noted that pressure for constant volume combustion is not the maximum pressure that can be obtained in a gas explosion. Dynamic effects, such as pre-compression can cause much higher local explosion pressures: The energy released in the early part of an explosion may precompress the still unburnt gas, which then upon burning will reach a higher pressure than if it were at its initial pressure.

The pressure for constant volume combustion is the pressure that may be obtained in closed vessels when the burning rate is low.

5.10. Laminar flame speed

The laminar flame speed is an experimentally determined property characterizing the propagation velocity of the flame normal to the flame front into the reactants under laminar flow conditions.

Table 6
Pressure, P, (absolute) and volume ratio (V/V_0) for Stoichiometric fuel–air mixture at initial conditions 25°C and 1 atm (1.013 bar) [25].

	Hydrogen	Ethylene	Propane	Methane
P (bar)	8.15	9.51	9.44	8.94
V/V_0 (-)	6.89	8.06	7.98	7.72

Table 7
Laminar flame speed for Stoichiometric composition [26].

	Hydrogen	Ethylene	Propane	Methane
$S\,(\mathrm{m\,s^{-1}})$	28.0	6.5	4.0	3.5

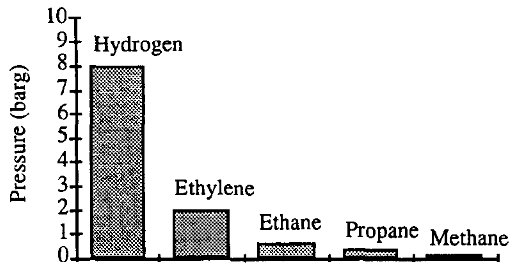


Fig. 41. Comparison of explosion pressure for various Stoichiometric fuel–air mixtures in a 10 m wedge-shaped vessel [28].

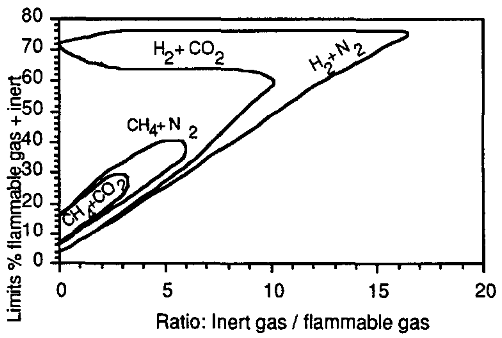


Fig. 42. Flammability limits as function of the ratio of inert gas to flammable gas.

Table 7 gives some data for laminar flame speed.

For hydrocarbon–air mixtures one may say that the higher the laminar flame speed, the more reactive is the mixture.

5.11. Pressure build-up potential

At present no single property exists which can be used for characterisation of the pressure build-up potential of a fuel–air mixture. The characteristic properties already discussed, gives only some indication. The pressure build-up in gas explosions depends strongly on the geometry where the explosion occurs. The individual fuels may behave

Table 8
Flammable concentration range in air [27].

	%Hydrogen	%Methane	%VC (VCM)
Air	4.0–75.6	4.0–16.0	3.5–15.4
Oxygen	3.9–95.8	5.0–61.9	4.0–67
Chlorine	3.5–89	5.5–63	9.0–49.2

Table 9
Inerting requirements to prevent flame propagation in fuel–air with N_2, CO_2, Halon 1211 and 1301 at 25°C and 1 atm [20].

	Minimum inerting concentration (% vol.)			
	N_2	CO_2	Halon 1211	Halon 1301
Methane	36	23	4.0 (5.3)	2.0 (4.7)
Propane	42	28	5.9	6.5
Ethylene	48	39	9.6	11.0
Hydrogen	71	57	27	20.0

somewhat differently depending on the conditions, but the relative fuel ranking shown in Fig. 41 is expected to hold in most situations.

5.12. Other atmospheres than air

In process equipment or vessels, gas explosions may occur with other oxidisers than air. The oxidisers can be oxygen enriched air, pure oxygen, chlorine, NO or NO_2.

When the oxygen concentration increases from the 21% oxygen as in air, the explosion hazard will increase. The minimum ignition energy for methane is reduced from 0.3 mJ in air to 0.003 mJ in oxygen [20]. Chlorine is also a strong oxidiser and can lead to serious explosions. Some of the flammability limits in air, oxygen and chlorine are given in Table 8. In oxygen and chlorine, the flammable range is much wider than in air.

By adding inert gases, such as nitrogen, N_2, or carbon dioxide, CO_2, the explosion hazard can be reduced [129]. Fig. 42 shows the flammability for hydrogen and methane versus inert gas-flammable gas ratio. As we can see from this figure, the ratio inert gas-flammable gas has to be fairly large for the gas to be outside the flammable range. Table 9.

Halons are more effective than N_2 and CO_2 for inerting. However, since halon has a negative impact on the environment, its use will probably be limited in the future.

6. Deflagrations

A deflagration is the most common mode of flame propagation in accidental gas explosions. It is defined as an explosion where the combustion wave propagates at *subsonic* velocities relative to the unburnt gas immediately ahead of the flame (which itself is set in motion by the expanding combustion products). In the deflagrative mode the flame speed ranges from a few $m\,s^{-1}$ up to 500–1000 $m\,s^{-1}$. The explosion pressure will range from a few mbar to several bar, depending on the flame speed.

The flame speed and explosion pressure will strongly depend on the gas cloud and the geometrical conditions within the cloud (i.e. process equipment, piping etc.) or geometries confining the cloud (i.e. buildings etc.). To predict the flame speed and explosion pressure for a deflagration is not a simple task, even if scenario parameters such as cloud size, fuel concentration and ignition point are known. The phenomenon of

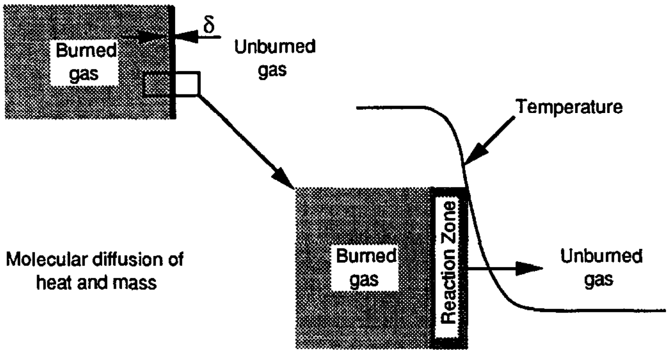


Fig. 43. Illustration of the structure of a laminar flame front in a premixed gas.

flame acceleration is a mathematically stiff problem, i.e. the result is very sensitive to variation of specific parameters.

The objectives of this chapter are:

- To describe the deflagration wave and its different combustion regimes.
- To describe the importance of venting and flame acceleration due to repeated obstacles.
- To describe some important findings from CMR experiments.
- To provide the basic fundamental understanding of deflagrations, so the information in Section 10,Section 11 and Section 12 is accessible.

6.1. Deflagration waves and explosion pressure

We have already defined a deflagration wave as a gas explosion where the flame front propagates at subsonic speed relative to the unburnt gas, immediately ahead of the wave. In a gas explosion the propagating velocity can span more than three orders of magnitude. The mechanism of flame propagation will be quite different in the different velocity regimes.

When the cloud is ignited by a weak ignition source (i.e. a spark or a hot surface) the flame starts as a laminar flame. For a laminar flame the basic mechanism of propagation is molecular diffusion of heat and mass. The laminar flame structure is illustrated in Fig. 43. This diffusion process of heat and mass into the unburnt gas is relatively slow and the laminar flame will propagate with a velocity of the order of 3–4 $m\,s^{-1}$.

The propagation velocity of the laminar flame depends on the type of fuel and the fuel concentration. Fig. 44 shows the laminar burning velocity (i.e. flame front velocity relative to the unburnt mixture just ahead of the flame) for methane–, ethylene– and hydrogen–air. Methane has a maximum burning velocity of about 0.4 $m\,s^{-1}$. Maximum laminar burning velocities of 0.4–0.5 $m\,s^{-1}$ are typical for hydrocarbons. Ethylene, acetylene and hydrogen have higher burning velocities due to fast chemical kinetics and high molecular diffusivity. As a result of variations in apparatus and measurement techniques different sources will state different values for laminar burning velocity.

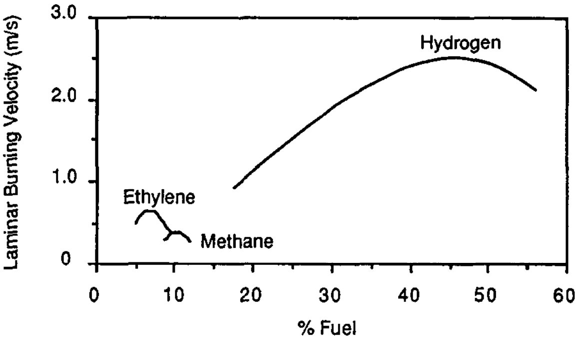


Fig. 44. Laminar burning velocity for methane–, ethylene– and hydrogen–air [30,31].

In most accidental explosions the laminar flame will accelerate and transit into a turbulent deflagration (i.e. turbulent flame), since the flow field ahead of the flame front becomes turbulent. The turbulence is caused by the interaction of the flow field with process equipment, piping, structures etc. The mechanisms generating turbulence ahead of the flame front will be discussed further in Section 6.2 "Flame acceleration in a channel caused by repeated obstacles". Here we will discuss how turbulence influences the structure of the front and thereby enhances the burning rate.

One of the mechanisms causing the increased burning rate in turbulent deflagrations is the wrinkling of the flame front by large turbulent eddies. Fig. 45 shows a wrinkled flame front. For this combustion regime the increased flame surface area is causing the burning rate to increase. This regime is characterized by the turbulent integral length scale, l_t, being significantly larger than the thickness of the flame front, δ.

When the turbulent integral length scale, l_t, is of the order of the thickness of the flame front δ or smaller, the flame becomes a thick turbulent flame brush. In this regime the turbulence is causing increased diffusion of heat and mass and thereby a high burning rate.

Further details about classification of combustion regimes can be found in Ref. [29].

When a flame propagates through a premixed gas cloud there are two mechanisms causing pressure build-up. These are:

(i) fast flame propagation

(ii) burning in a confined volume

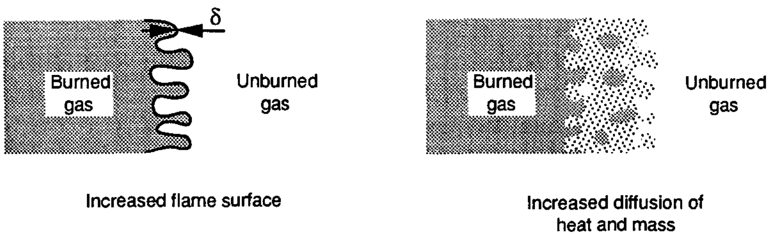


Fig. 45. Wrinkled flame front when $\delta <$ size of turbulent eddies. Turbulent flame brush when $\delta >$ size of turbulent eddies.

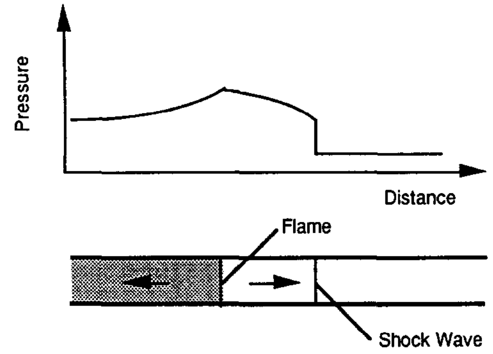


Fig. 46. Pressure–distance profile for a deflagration propagating in a tube.

In most accidental explosions a combination of these two effects causes the pressure build-up. Here we will use a flame propagating in a pipe and an explosion in a vessel as examples.

If we have a deflagration propagating in a pipe we can have situations as shown in Fig. 46. At the location of the flame front there will be a small pressure drop. This drop in pressure is required in order to satisfy the conservation equations across the flame front.

The pressure behind the flame (in the burnt gas) will gradually decay away from the flame. This pressure decay will mainly depend on the boundary conditions on the left end of the tube (i.e. open or closed tube) and on the flame velocity.

Since the flame front is a subsonic combustion wave, the burning will influence the flow ahead of the flame. In Fig. 46 this is illustrated by a decaying pressure and shock wave in the unburnt mixture. The pressure profile ahead of the flame will depend on the flame acceleration and speed. In order to obtain a shock wave ahead of the flame, a high flame speed is required.

Fig. 47 shows the maximum overpressure versus flame velocity in two modes of flame propagation; (i) planar mode, i.e. flame propagating in a tube and (ii) spherical mode, i.e. flame propagating in an unconfined cloud.

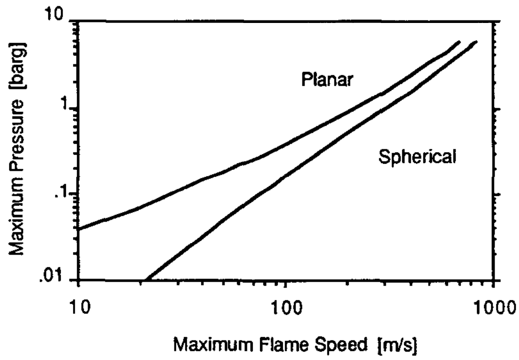


Fig. 47. Maximum overpressure vs. flame velocity for planar and spherical flames [34].

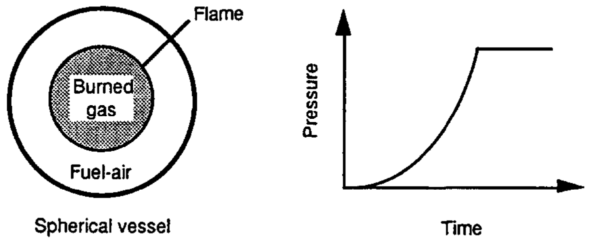


Fig. 48. Explosion in a closed vessel.

The spherical mode of flame propagation requires a higher flame velocity than the planar mode in order to obtain the same explosion pressure. This can be explained by the fact that gas can expand more freely in a spherical mode than in a planar mode.

From Fig. 47 one sees that a flame velocity of the order of $100\,\mathrm{m\,s^{-1}}$ is required to produce pressure waves of a significant strength (~ 0.1 barg). The pressure in a deflagration is strongly linked to the flame velocity and burning rate. Explosion pressures for constant velocity flames have been predicted by several researchers, among them Guirao et al. [32] and Strehlow et al. [33]. The results of such predictions are shown in Fig. 47.

If the explosion happens inside a closed vessel, fast flame propagation is not required to obtain high pressures. A vessel as shown in Fig. 48 will prevent the expansion of the gas when it burns and lead to pressure increase. As stated in Section 5.9, a Stoichiometric fuel–air cloud in a closed vessel will give up to 8 or 9 bar when exploding. By opening up part of the vessel wall, relief will be provided and the pressure will be reduced. The reduction will depend mainly on how fast the flame is burning in the vessel and the location and size of the vent area.

6.2. Flame acceleration in a channel caused by repeated obstacles

In a partly confined area with obstacles (i.e. process equipment, piping etc.) the flame may accelerate to several hundred meters per second during a gas explosion. The mechanisms causing the increased burning rate in turbulent deflagrations are the wrinkling of the flame front by large eddies and the turbulent transport of heat and mass at the reaction front. This turbulence is mainly caused by the interaction of the flow with structures, pipe racks, etc.

Fig. 49 shows how turbulence is generated in the wake of obstacles in a channel. When the flame consumes the unburnt gas, the products will expand. This expansion can

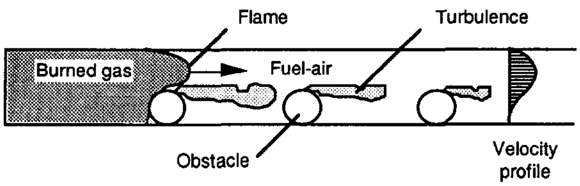


Fig. 49. Turbulence generation in a channel due to repeated obstacles during a gas explosion.

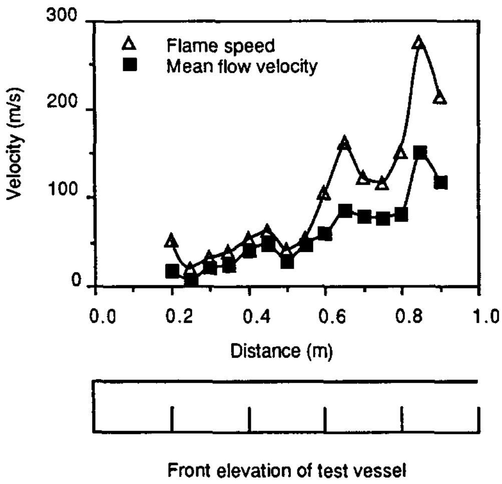


Fig. 50. Experimentally measured flame speed and flow velocity in a 1 m wedge-shaped explosion vessel with five obstacles [35].

be up to 8 or 9 times the initial volume. The unburnt gas is therefore pushed ahead of the flame and a turbulent flow field may be generated. When the flame propagates into a turbulent flow field, the burning rate will increase dramatically. This increased burning rate will further increase the flow velocity and turbulence ahead of the flame.

In Fig. 50 the flame speed and flow velocities are measured in a 1 m long wedge-shaped vessel. From this Figure we can see the velocities gradually increasing as the flame front propagates down the vessel. We can also see that the difference between the flame speed and the mean flow velocity, i.e. the burning velocity, also increases. The increased burning velocity will cause the explosion pressure to rise.

The mechanism of flame acceleration caused by repeated obstacles constitutes a strong positive feedback loop. This loop is shown in Fig. 51.

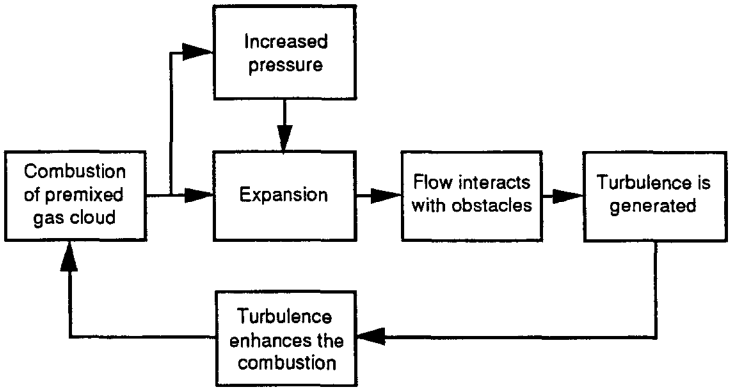


Fig. 51. Positive feedback loop causing flame acceleration due to turbulence.

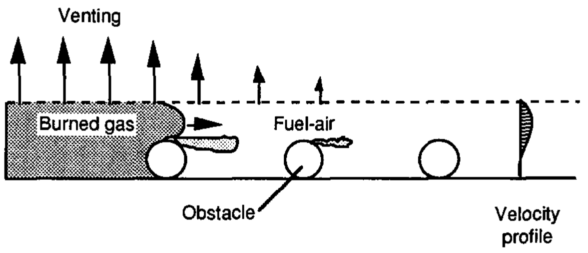


Fig. 52. Venting of hot combustion products will reduce turbulence generated by obstacles.

The flame acceleration can to some extent be avoided by venting the hot combustion products as shown in Fig. 52. The flow and turbulence in the unburnt mixture ahead of the flame will be reduced. Venting combustion products is a very effective way of minimising the acceleration effect of repeated obstacles.

Venting of unburnt gas ahead of the flame may also contribute to a lower explosion pressure, in particular when the venting directs the flow away from repeated obstacles. If venting unburnt gas leads it past repeated obstacles, flame acceleration will most likely occur.

When a deflagration propagates through a region of obstacles and then ends up in an unobstructed region the flame speed will normally drop and adjust to the new environment. Fig. 53 shows how a deflagration decelerates when it propagates from an obstructed into an unobstructed region. In this experiment, the flame speed drops from several hundred $m s^{-1}$ to a few tens $m s^{-1}$. The flame speed in the unobstructed region is so low that the pressure generated in this region is negligible (see Fig. 47).

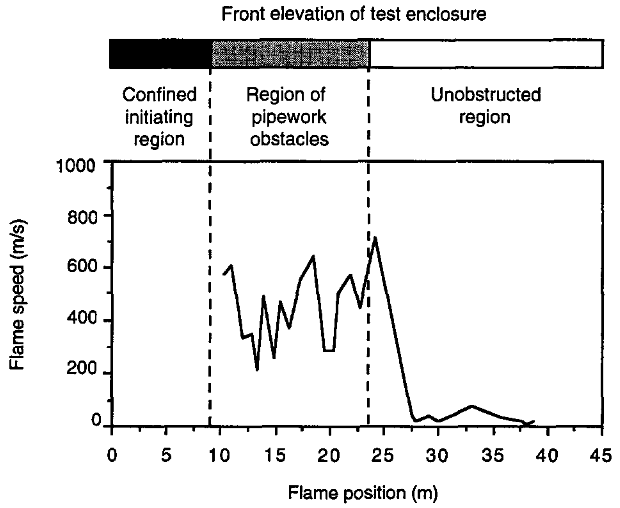


Fig. 53. Flame deceleration when exiting from a region containing repeated obstacles into an unobstructed region [43].

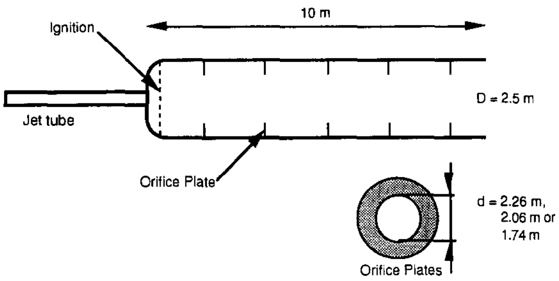


Fig. 54. CMR's 50 m^3 explosion tube. Inner diameter $d = 1.74$ m, 2.06 m and 2.26 m corresponds to blockage ratios of 50%, 30% and 16%.

This discussion shows that for a deflagration there are two mechanisms governing the pressure build-up in partly confined gas clouds, namely:

· Flame acceleration caused by enhanced burning resulting from turbulence generated by flow past obstacles.

· Venting providing pressure relief or reducing the effect of the feedback mechanism described previously in this chapter.

These mechanisms have competing effects. The flame acceleration due to turbulence will increase explosion pressure, while venting will reduce the pressure. It is the balance between these two that is governing the pressure build-up. When analysing gas explosions we have to take both of them into account. In the following section we will discuss some experiments involving both flame acceleration due to obstacles and venting.

6.3. Experiments in a 50 m^3 explosion tube

The 50 m^3 explosion tube is shown in Fig. 54. This experimental vessel was originally located at the Raufoss test site in the Eastern part of Norway. In 1983 it was moved to CMR's Sotra test site outside Bergen. Experiments conducted in this vessel have been reported in Refs. [36–42,126–128].

The tube is 10 m long and has a diameter of 2.5 m. The tube is closed in one end and open in the other. Inside the tube, orifice plates can be mounted. The number of rings and the inner diameter of the rings are variables. The ignition was either a matrix of electrically fired match-heads (i.e. plane ignition source) or a single match-head (i.e. point ignition source). In most of the experiments the tube was filled with a homogeneous fuel–air mixture, but in some tests the effect of nonhomogeneous fuel concentration was tested out.

Fig. 55 shows some of the results from tests with Stoichiometric propane–air and plane ignition. The peak explosion pressure is ranging from about 1 bar g to 14 bar g depending on the number and size of the orifice rings inside the tube.

When the inner diameter of the orifice plate, d, is 1.74 m, the orifice plate will block 50% of the free tube area. In case of d equal to 2.25 m, the blockage ratio (i.e. $B.R = (1 - (d/D)^2$ is 0.16% or 16%. We can see from the figure that the blockage ratio

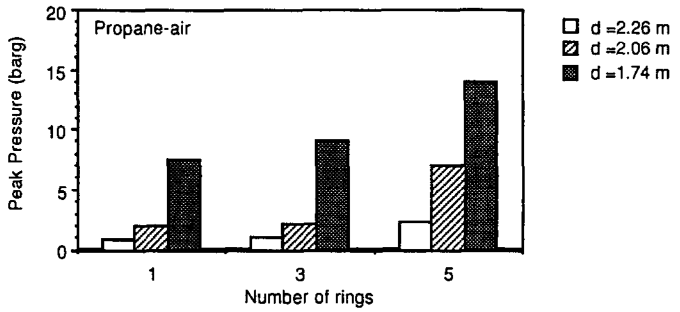


Fig. 55. Peak explosion pressure in a 50 m^3 explosion tube for various numbered and sized orifice rings [38].

is one parameter which has a significant influence on the explosion pressure. By increasing the blockage ratio, the vent area will be reduced and the velocity flow through the open part of the orifice plate will increase. The increased velocity enhances the turbulence generation in the shear layers behind the orifice plates. The number of rings is another important parameter. Each orifice plate will generate a turbulent shear layer that will accelerate the flame up to a certain level.

From these experimental results it should be noticed that the peak explosion pressure is much higher than the pressure based on constant volume combustion of Stoichiometric propane–air at 1 atm initial pressure (i.e. approx. 8–9 bar). The reason for this is pre-compression of the unburnt gas. Since the unburnt gas may be pre-compressed by the early phase of the explosion, the explosion in its later phase will start out at a higher than ambient pressure and the explosion pressure may therefore reach local values higher than 8–9 bar.

6.4. Experiments in a wedge-shaped explosion vessel

The wedge-shaped explosion vessel is shown in Fig. 56. The volume of the vessel is 18.5 m^3. The length is 10 m and the height is 1.25 m. Inside the vessel different types (i.e. round cylinders, flat plates and boxes) and numbers of obstacles can be mounted.

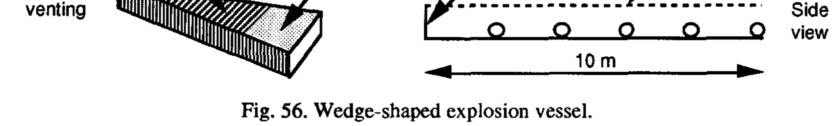


Fig. 56. Wedge-shaped explosion vessel.

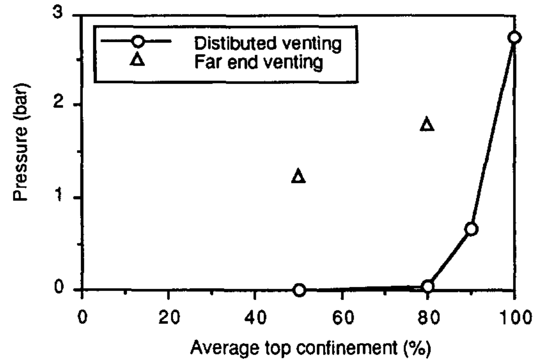


Fig. 57. Explosion pressure for propane–air as function of average vent top confinement (100% top confinement is a solid top plate) in a 10 m wedge-shaped vessel. With far end venting the entire vent area is located at the far end of the vessel with respect to the ignition point [35].

The top plate of the vessel can either be solid or perforated. Experiments carried out in this vessel have been reported in Refs. [35,44–49].

With the wedge-shaped explosion vessel it has been possible to study the effect of various types of vent arrangements in combination with repeated obstacles. The results in Fig. 57 show the effect of venting of gas through a perforated top plate. For 100% top confinement the top plate is solid and the only vent opening was at the end of the vessel with respect to ignition point. For the 80% top confinement case, 20% of the top plate area is open for venting.

The explosion pressure was strongly dependent on the top confinement. In the case of 50% evenly distributed top confinement, the explosion pressure was less than 0.05 bar. As the top confinement was increased from 80% to 100% the explosion pressure increased by nearly two orders of magnitude. This is typical for gas explosions [123]. Small changes in the geometry can lead to order of magnitude changes in explosion pressure.

In the 'far end venting tests' the vent area in the top plate was not evenly distributed, but located in the far end of the vessel with respect to the ignition point. In these tests, the explosion pressure was more than one bar. This shows that not only the size, but also the vent area location can be very important.

The explanation for the strong dependency of the explosion pressure on the top confinement and location of the vent area can be found in Section 6.2. Fig. 49 and Fig. 52 illustrate the same situations as the experiments in the present section. When there is sufficient venting close to the ignition point, the flame speed will be low and the turbulence generated behind the obstacles will be limited. Hence, the pressure will be low. However, when the venting is less effective in the early phase of the explosion the free unburnt gas will be pushed ahead of the flame and a strong turbulent flow field will be generated and the positive feedback mechanism will accelerate the flame and cause high pressure. From this we can conclude that to vent hot combustion products at an early stage of the explosion, is a very effective means of reducing flame acceleration.

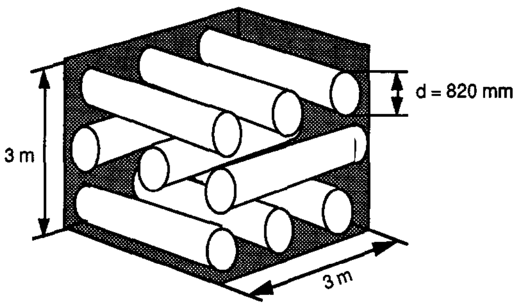


Fig. 58. Cubical explosion vessel with 3×3 pipes.

Most simple models for prediction of explosion pressure will not take the location of the vent area into account. They only use the size of the vent area as an input parameter. From the experimental results described above it is obvious that these types of simple models are inadequate and that they may in some cases generate overpressures that are wrong by orders of magnitude. The only models which can account for the combined effects of venting and equipment location on explosion overpressure are those based on solution of fluid dynamic equations (e.g. FLACS).

6.5. Experiments in a cubical explosion vessel

The cubical explosion vessel [52] is shown in Fig. 58. The vessel consists of a corner with a length dimension of 3 m. In this corner internal obstructions were mounted. The internal obstructions tested consisted of pipes with diameter of 164 mm, 410 mm and 820 mm. Three different porosities or volume blockage ratios (VBR) where tested. The diameters, VBR's and corresponding numbers of pipes are given in Table 10.

For Stoichiometric propane–air mixtures the flame speed ranged from 10 m s^{-1} without obstacles to approximately 1000 m s^{-1} in the most densely packed arrangements. The pressures produced ranged from a few tens mbar up to 4 bar. Fig. 59 shows the peak explosion pressure for various volume blockage ratios and obstacle diameters. For the same blockage ratio the smallest obstacle diameters give the highest pressure. As expected, increased blockage ratio will increase the explosion pressure.

From these results we can conclude that not only the volume blockage ratio is of importance, but also the size (and shape) of the obstacles. In the cubical explosion

Table 10
Diameter (d), volume blockage ratio (VBR) and number of pipes in cubical explosion vessel tests

	Volume blockage ratio		
d (mm)	0.1	0.2	0.5
164	6×6	9×9	15×15
410	3×3	4×4	6×6
820		2×2	3×3

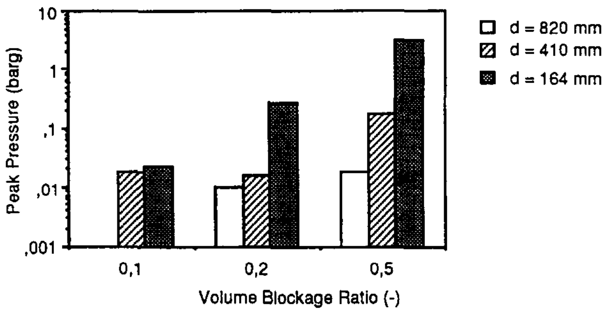


Fig. 59. Peak explosion pressure for Stoichiometric propane–air in a 27 m^3 cubical explosion vessel.

vessel, the smaller obstacles allow for a larger number of repeated shear layers, and thus the positive feedback loop described in Section 6.2 is traversed many times. Therefore, higher pressure is generated.

If we compare the results from the cubical vessel to similar tests (i.e. blockage ratio, number of obstacles and gas mixture) in the wedge-shaped vessel and the tube, we will find that the cubical vessel gives the lowest explosion pressure. This is shown in Fig. 60.

In the tube, the wedge-shaped and the cubical vessels, the respective modes of flame propagation will be planar, cylindrical and spherical. As shown in Fig. 47 a spherical mode of flame propagation requires higher flame velocity than a planar mode to generate the same explosion pressure. The pressure wave can expand more 'freely' in the spherical mode and the positive feedback mechanism is not as strong as in the planar mode.

A similar experience was reported by Van Wingerden et al. [53]. Experiments performed in a wedge-shaped vessel (sector) and a channel (respectively cylindrical and planar geometries) having the same length and similar obstacles showed that the terminal flame speeds were higher in the channel than in the sector. This effect decreased, however, when the degree of obstruction (blockage ratio) increased (Fig. 61).

This understanding has practical implications. As we will discuss further in Section 11, it is obvious that compartments and offshore modules should not be long and

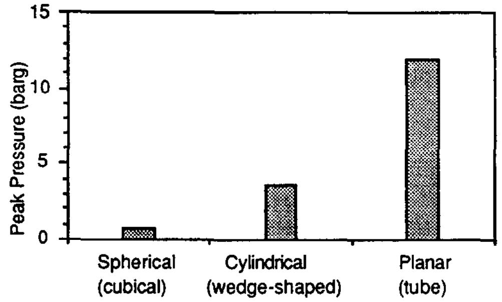


Fig. 60. Peak explosion pressure for Stoichiometric propane–air in cubical, wedge-shaped and tube vessels with blockage ratio of 0.5 and 5 obstacles. The spherical, cylindrical and planar geometries described are not directly comparable, but the results illustrate that $P_{spherical} < P_{cylindrical} < P_{planar}$.

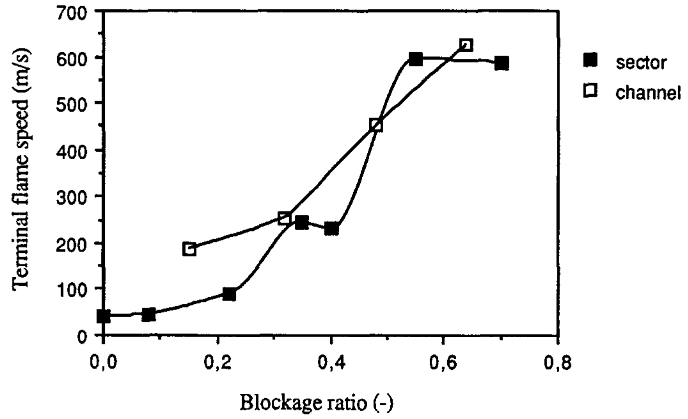


Fig. 61. Terminal flame speeds in ethylene–air mixtures as a function of blockage ratio for circular obstacles placed in a wedge-shaped vessel (sector) and a channel.

narrow. In elongated compartments the planar mode of flame propagation will be dominant and may therefore cause high explosion pressure.

6.6. Experiments in a 1:5 scale model of an offshore module

The 1:5 scale model of an offshore module is 8 m long, 2.5 m wide and 2.5 m high. The total volume is 50 m^3. The internal layout in the model is interchangeable. The standard internal layouts are a compressor module (i.e. M24) or a separator module (i.e. M25). These layouts consist of equipment located on two decks, the lower deck (LD) and the upper deck/mezzanine deck (UD). Fig. 62 shows the internal equipment in the separator module.

The module has been used for investigation of the effect of vent arrangements and ignition positions and testing of water deluge, blast panels, louver walls, relief panels etc. This work has been reported in [54–58].

In this section we will focus on the effect of venting with different wall arrangements. The different layouts that were tested are summarised in Table 11.

The peak pressures from the tests are given in Fig. 63. The peak pressure is plotted versus the dimensionless parameter $A_v/V^{2/3}$ where A_v is the free vent area and V the volume of the compartment. The different vent arrangements are given in Table 11.

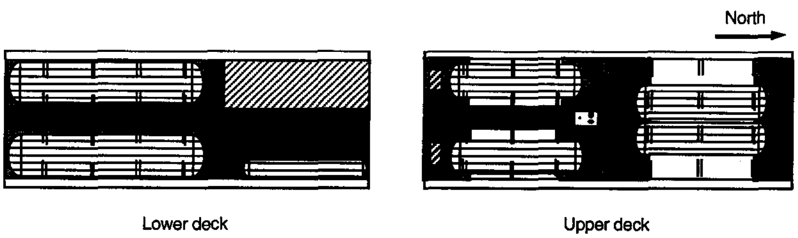


Fig. 62. Plan view of internal layout in 1:5 scale separator module.

Table 11
Vent arrangement for the 1.5 scale separator module

Layout	Closed areas	$A_v / V^{2/3}$	$A_v / V^{2/3}$ with louvers
	Roof deck	4.78	
	Roof, rear wall deck	2.85	1.48
	Roof, rear wall, 50% front wall deck	1.98	
	Roof, rear wall, front wall, deck	0.92	0.46

The results from the tests can be summarised as follows:

· The vent arrangement is extremely important for the explosion pressure. The peak pressure was about 0.01 bar g when all four side-walls were open. ($A_v/V^{2/3} = 4.8$). When the long side walls were closed and the end walls were louvered ($A_v/V^{2/3} = 0.46$) the peak pressure was 1.9 bar g. The conclusion is that explosion pressure in a compartment or building depends strongly on the vent arrangements.

· By removing the internal equipment (i.e. obstacles) the explosion pressure was reduced by a factor of 5–10. Equipment will enhance the turbulence generation during the explosion and accelerate the flame and thereby cause high pressure (see Section 6.2).

· Increasing the scale from 1:33 to 1:5 increases the explosion pressure by a factor of 5–10. This indicates that small scale data are irrelevant for large scenarios if not scaled properly.

· As a general trend propane tests gave about twice as high pressure as methane tests in a similar geometry. Explosion pressure will depend on the type of fuel.

6.7. Shape and arrangement of obstacles

The experiments in the tube, wedge-shaped vessel and cubical vessel demonstrated the importance of the degree of obstruction by obstacles. Area blockage ratio and

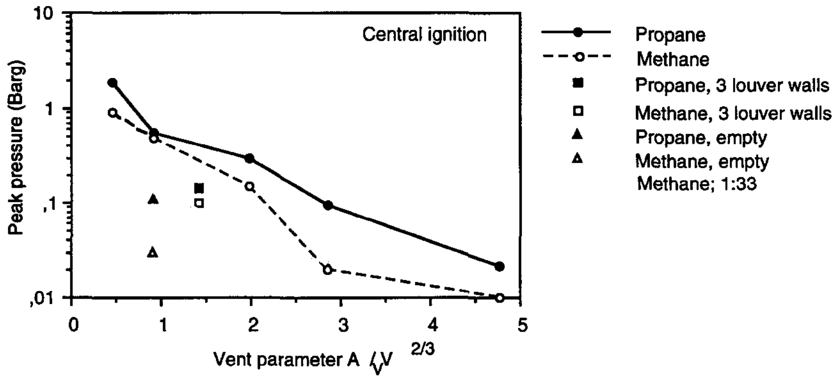


Fig. 63. Peak pressure as function of vent parameter for the centrally ignited explosion in the 1:5 scale separator module. A_v is the size of the vent area and V is the volume of confinement.

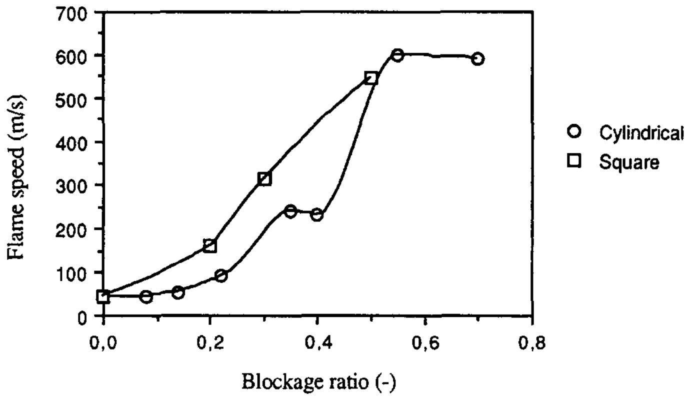


Fig. 64. Influence of obstacle shape on flame propagation in ethylene–air mixtures in a wedge-shaped vessel. Square and cylindrical obstacles were used.

volume blockage ratio are the parameters which are used to describe the degree of obstruction. Additional parameters which are important with respect to the effect of obstacles on explosion propagation are the shape of obstacles and their arrangement.

Experiments performed in a wedge-shaped vessel described by Bjørkhaug [35] showed the pressure development due to round obstacles was approximately half of the pressure development with similar (considering blockage ratio as a parameter) baffle-type obstacles. The main reason being the fact that the turbulence intensity in the shear layer produced by a sharp obstacle is larger than the turbulence intensity in the shear layer produced by a round obstacle.

Experiments performed by Van Wingerden et al. [53] demonstrate the effect of obstacle shape on flame speeds developed in a wedge-shape vessel (See Fig. 64). The effect of obstacle shape seems to be more important for low degrees of obstruction than for high degrees of obstruction.

The influence of obstacle arrangement was also studied by Van Wingerden et al. [53]. (Fig. 65) shows three different arrangements which were studied in a channel and the pressures that were obtained for these three arrangements.

The results of obstacle arrangements A and B demonstrate that staggering of obstacles leads to higher pressures something that cannot be described by using a parameter such as blockage ratio only. Only CFD-computer tools such as FLACS do take obstacle arrangement into account.

6.8. *Obstruction of vent openings*

Wilkins et al. [59] performed experiments to investigate the effect of an obstruction in front of a vent opening outside the vented structure. The experiments were performed in a 1:5 scale compressor module. A wall was placed outside the module in front of one of the vent openings at one of the short ends of the module. The distance of the wall to the vent opening was varied. Results of the situation where ignition is effected in the centre

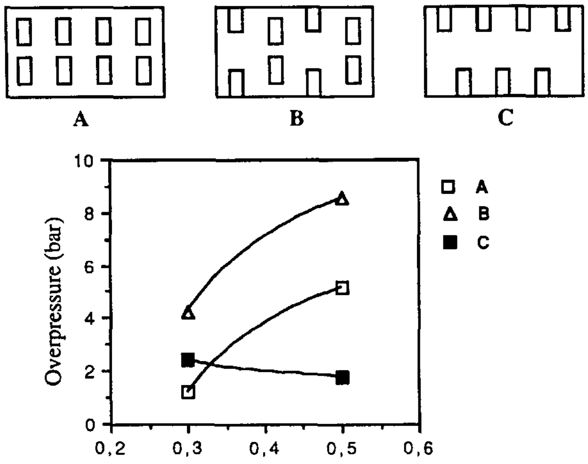


Fig. 65. Influence of obstacle arrangement on flame propagation in ethylene–air mixtures in a channel.

of the module and both short ends of the module are provided with vent openings are shown in Fig. 66.

The results show that the effect of the wall is limited to approximately 1 m from the vent opening. This coincides with a normalised vent area (the total vent area between the module and the wall) of twice the original vent area. Similar results were found for other ignition-vent configurations. The results clearly show that a partly obstruction of a vent opening can result in strong pressure increases. These results are important to consider when explosion venting occurs over a laydown area or when considering venting via intermodular gaps.

6.9. Jet flames

Eckhoff et al. [37] investigated explosions caused by jet flames emerging from a partly confined volume into another gas cloud. The test rig was the $50\,m^3$ tube described

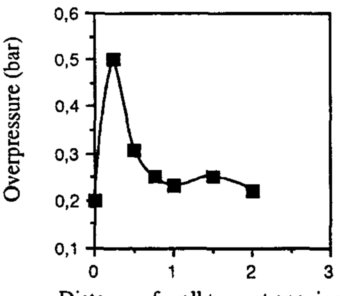


Fig. 66. Effect of the presence of a wall put in front of vent opening of a 1:5 scale compressor module. The figure shows the effect of the distance of the wall to the vent opening. Ignition was effected in the centre of the module. The module was open at both short ends.

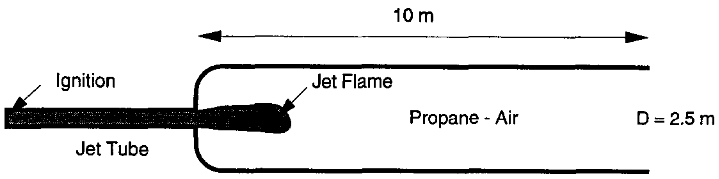


Fig. 67. Jet flame ignition tests in 50 m^3 tube.

in Section 6.3. In these tests the ignition was located at the closed end of the jet-tube. Both the jet-tube and the 2.5 m diameter tube was filled with Stoichiometric propane–air. The experimental set-up is shown in Fig. 67.

In these tests explosion pressures above 10 barg were recorded. The main conclusions from these tests were that a jet exiting from a partly confined volume acted as a very strong ignition source for the cloud inside the 2.5 m diameter tube, and the explosion pressure depended on the jet flame velocity. This type of jet flame ignition have experimentally been observed to cause very violent explosions in unconfined clouds. Even transition to detonation has been reported in sensitive fuel–air mixtures [60]. Experiments [61] show that deflagration velocities of at least of 500–700 m s^{-1} are required in order to observe transition to detonation in fuel–air (Fig. 68).

The small scale experiments by Wilkins and Alfert [62] indicate that 'ignition' by a jetted flame in a partly confined compartment enhances the pressure build-up more when the compartment is obstructed than when it is empty.

The effect of localised explosions (jet flames) may in some situations not only cause high pressures locally but also cause high velocity flames to propagate into less confined but obstructed regions, where the high velocity of the flame may be sustained. Some recently published data by Harris and Wickens [43] show examples of such an effect. They showed that if a flame entered the unconfined obstacle array at a high velocity, the flame was able to stabilise at a high velocity and associated high explosion pressure. However, if the flame had a low velocity in the beginning of the array, it was not able to accelerate to high velocities and the corresponding explosion pressure was low.

All the experiments referred to in this section show that a jet flame is a stronger ignition source than a spark. In consequence analyses jet flames should be considered

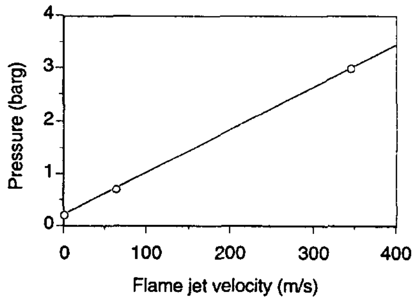


Fig. 68. Explosion pressure vs. flame jet velocity in a 50 m^3 tube [68].

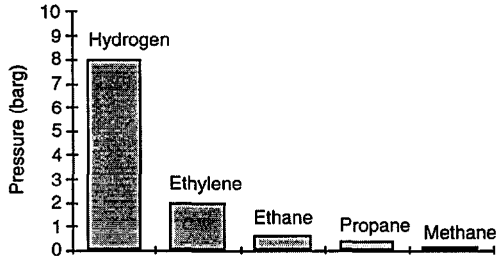


Fig. 69. Comparison of explosion pressure for various Stoichiometric fuel–air mixtures in the 10 m wedge-shaped vessel [28].

when explosions occur in channels, sewage systems, tunnels, motor noise shields or, more generally, when multi-compartment explosions can occur.

6.10. Type of fuel

The consequences and the probability of occurrence of gas explosions will to a large extent depend on fuel type. Under similar experimental conditions different fuel–air mixtures will generate different explosion pressures. At the present time there are no standard procedures for classifying the explosion hazard regarding pressure generation for different fuels. However, various experiments with turbulent deflagrations [63,28,48,49] and detonations [64] show that common fuels can be ranked, at least qualitatively.

Bjørkhaug [63,28] has carried out experiments with hydrogen–air and several hydrocarbon–air mixtures (acetylene–, ethylene–, propylene–, cyclohexane–, ethane–, propane–, and methane–air) in the 1 m and 10 m wedge-shaped vessels. Some results from the 10 m wedge-shaped vessel are shown in Fig. 69. Note that the results presented in this Figure are based on a specific experimental configuration and that the pressure levels will be different in other experimental situations. In particular higher pressures can be expected in more complex geometries, like partially confined, obstructed process areas.

Hydrogen gave the highest explosion pressure, 8 bar g. Hydrogen and acetylene are the two most reactive fuels that we normally handle. Ethylene is also very reactive. Propane and ethane are somewhat less reactive and seem to form an intermediate level of explosivity. Methane is the least reactive fuel shown in Fig. 69. Many other hydrocarbons (e.g. butane) fall into the same group as propane and ethane.

Experimental data for more complex fuels like cyclohexane and vinylchlorid monomer (i.e. VC, VCM) is limited. Bjorkhaug [63] performed experiments in small scale with cyclohexane which gave slightly higher pressures than methane. In larger scale cyclohexane behaved more like propane [43]. Mackay et al. [61] showed that VC was nearly as reactive as ethylene. It is still uncertain if more complex fuels can be ranked in the same way as the common hydrocarbons.

Other substances that we normally do not regard as fuels, like ammonia (NH_3), can also cause explosions. Ammonia burns very slowly, but in a confined situation, it can cause serious explosions (see Section 2.2).

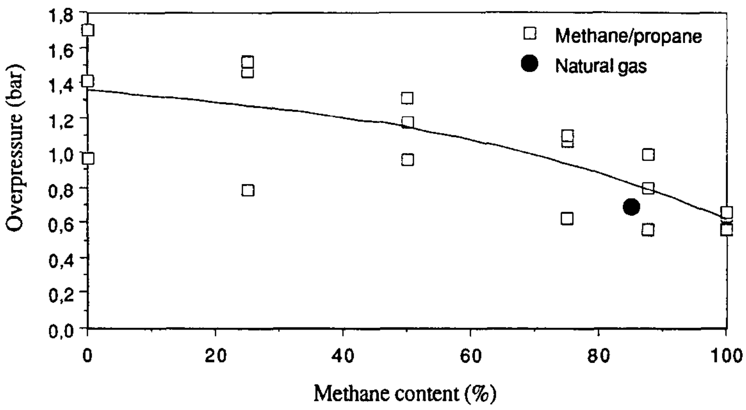


Fig. 70. Explosion pressure for natural gas, propane and methane in air [48].

For more heavy hydrocarbons such as heptane the fuel may be dispersed into the air as a mist. Experiments on mist–air mixtures is limited but experiments reported by Van Wingerden et al. [65] revealed that the reactivity of alkane mist–air mixtures is in the same order of magnitude as propane gas–air mixtures.

The amount of data describing turbulent explosion properties for fuel mixtures and mixtures of fuel and inert gases is limited. However, Kong and Alfert [66] showed that by adding CO_2 to methane the explosion pressure was reduced compared with pure methane. This feature was confirmed later by Pedersen and co-workers [67,48] but they also showed that relatively large quantities of CO_2 must be added before an effect can be noted.

Experiments with mixtures of various fuels have been reported in Refs. [47,66,48,49]. Fig. 70 shows some of the new results from the experiments in the 10 m wedge shaped vessel in Ref. [49]. As the Figure shows the reactivity of natural gas is comparable to that of equivalent methane–propane mixtures.

The reactivity of heptane mist–methane mixtures and heptane mist–propane mixtures lies between that of pure methane or propane and pure heptane mist depending on the mixture composition [65].

6.11. Fuel concentration

A premixed fuel–air cloud will only burn as long as the fuel concentration is within the lower and upper flammability limits (LFL, UFL). When the fuel concentration in a cloud is near the flammability limit the burning rate will be very low. In order to obtain high pressure for near flammability limit concentrations, a confined situation is required. At the flammability limits the final pressure for constant volume combustion of fuel–air is typically 4 times the initial pressure.

For single fuels the maximum explosion pressure is normally observed at Stoichiometric or slightly rich mixtures. Fig. 71 shows peak pressure measurements from experiments in a 1 m wedge-shaped vessel.

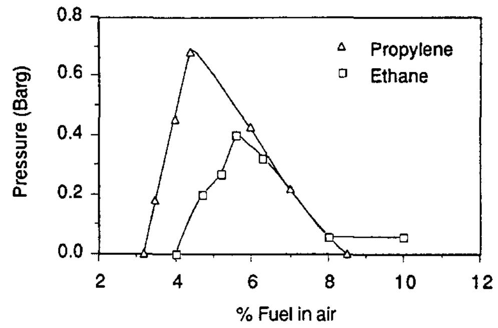


Fig. 71. Peak pressure vs. fuel concentration (% vol.) in air [57].

If we compare the results in Fig. 71 with the data in Table 12 we find that the concentration leading to maximum explosion pressure is close to the Stoichiometric composition. For this geometry, the concentration range where pressure is observed, is more narrow than the flammable range. The concentration range causing significant explosion pressures is dependent on the geometry where the explosion is occurring. The more confined and obstructed the geometry, the wider the concentration range. The limits for explosion pressure as shown in Fig. 71, must not be confused with explosion limits (or flammability limits) as defined in Section 5.1 and Section 5.2.

6.12. Inhomogeneities in the cloud

Hjertager et al. [41,56] have investigated the explosion propagation in methane–air clouds with concentration gradients inside a 50 m^3 tube and a 1:5 scale offshore module.

In the tube the nonhomogeneous cloud was generated by a high-pressure release of methane. It was observed that the explosion pressure in a realistically generated cloud may reach values as high as in the Stoichiometric homogeneous cloud, for which care has been taken in premixing the fuel–air. However, in general the results show a strong dependency on experimental parameters such as direction of the jet, mass of methane injected, and the ignition delay time.

Gas dispersion tests in the 1:5 scale offshore module [14] showed that for a high momentum release (i.e. high pressure reservoir) a relatively uniform gas cloud, the concentration of which would pass through the Stoichiometric value, was formed in large areas of the test module. This may explain why explosion pressures in real clouds may be as high as in premixed clouds. Hence it can be concluded that using a

Table 12
Flammability limits and Stoichiometric concentration (% volume) for ethane- and propylene–air [26].

	LFL (%)	UFL (%)	Stoichiometric (%)
Ethane	3.0	12.5	5.6
Propylene	2.4	10.3	4.4

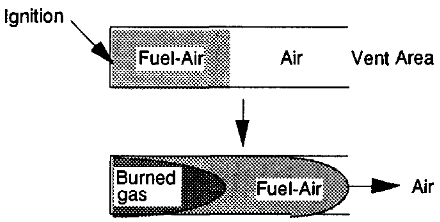


Fig. 72. During an explosion of a small cloud air can be pushed out through the vent area and thereby the whole volume can be filled with a combustible cloud.

homogeneous Stoichiometric fuel–air cloud in a gas explosion analysis is a conservative, but not unrealistic assumption.

6.13. Degree of filling by the cloud

In an accident situation the combustible gas cloud in an obstructed and/or partly confined volume may only fill a part of the volume at the time of ignition. The filling ratio is, of course, an important parameter. But in some situations 30–50% filling ratio may cause the same explosion pressure as a 100% filled compartment. The reason for this is that during an explosion the gas that burns will expand and push the unburnt gas ahead of the flame. Thereby air or fuel–air outside the flammable range is pushed out of the compartment. As discussed in Section 5.9 the expansion of the combustible cloud on burning can be up to 8 times the initial volume. Fig. 72 illustrates how a small cloud upon burning is pushing out air from a compartment and thereby fills the whole compartment with a combustible cloud.

Pappas (1983) [70] made some simple calculations on the effect of having only a part of the compartment filled with a gas cloud. It was assumed that the ignition point and the gas cloud are far from the vent opening. The results are shown in Fig. 73. The explosion pressure starts to drop at about 30% filling ratio.

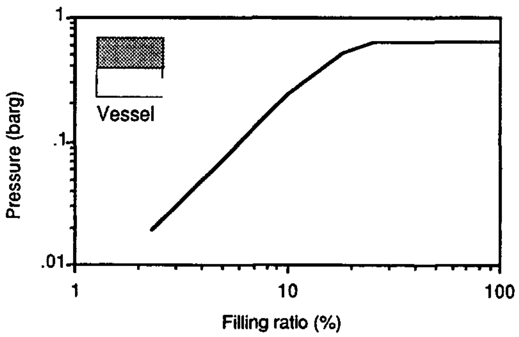


Fig. 73. Pressure reduction in a partly confined compartment as function of gas filling ratio. Gas cloud and ignition away from the vent opening [70].

An explosion in a partly filled compartment can in some instances cause the same explosion pressure as in a 100% filled compartment. It should be added that when the cloud is only filling a portion of the enclosure, the explosion pressure will be much more sensitive to the ignition location. If the ignition occurs at the edge of the smaller cloud and/or close to the vent area we can expect lower pressure for the partly filled than for the 100% filled case.

6.14. Ignition

Both the strength and the location of the ignition source can be important factors in determining the consequences of a gas explosion.

In Section 6.9 it was shown that jet flame ignition of a cloud can cause very strong explosions even for unconfined situations. If a cloud is ignited by detonating a high explosive charge within the cloud the gas may detonate directly.

Even though extreme ignition scenarios exist, the most likely ignition source is a weak ignition like a hot surface or a spark. In consequence analyses it is common to choose a weak ignition source as a probable scenario.

Various experiments and FLACS simulations have shown that explosion pressures can be very sensitive to the location of the ignition point. In many scenarios the peak explosion pressure can be changed by an order of magnitude if the ignition location is moved from 'worst case' to a more favourable place. In general the lowest pressure is obtained if the ignition point is:

(i) close to the vent area or

(ii) at the edge of the cloud

but as we will come back to in the end of this section, exceptions to this exist.

Fig. 43 and Fig. 46 show how repeated obstacles generate turbulence, while venting of combustion products reduces the turbulence generation. By igniting near the vent opening the combustion products will be vented and the flow velocity and the turbulence in the unburnt mixture will be low. Fig. 74 shows how different flow regimes will be generated in the same geometry with different ignition locations. In case (a) the flow velocity ahead of the flame will be low if the compartment is not too long. In case (b) a

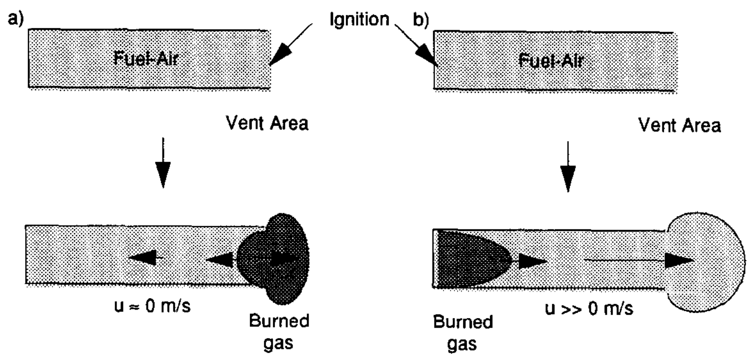


Fig. 74. The effect of different ignition locations in a compartment.

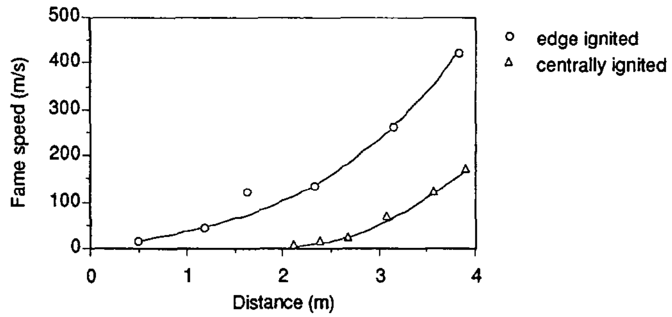


Fig. 75. Flame speed vs. distance for centrally and edge ignited explosions in a double configuration (i.e. solid top plate) with obstacles [73].

high flow velocity will be generated ahead of the flame which will generate turbulence by interaction with obstacles and hence support a high burning rate and cause high explosion pressure. For simplicity obstacles have been omitted from the figure.

However, if venting combustion products is not sufficient to keep the flame speed at a low level, edge ignition may cause higher explosion pressures than central ignition. Fig. 75 shows an example of this. In this case the flame propagation distance is a more important factor than the venting of combustion products. By increasing the length of the flame propagation, the flame will have the possibility to accelerate over a longer distance, by passing a greater number of obstacles. This effect will be most pronounced when one or more of the following apply: very reactive fuel, high density of obstructions, small vent areas or large obstructed volumes.

The practical implication of this is that one should try to locate potential ignition sources away from worst case locations.

6.15. Scale

The knowledge of gas explosion research made a great step forward in the end of the 1970s and the beginning of the 1980s. Before that time the research activity was mainly focusing on laboratory tests. However, laboratory scale was not appropriate in order to understand the nature of gas explosions in an industrial environment. Large scale tests in Norway ([37,36,55]) showed that explosion venting and turbulence were important factors governing the consequences of gas explosions. Today we know that simple scaling laws do not generally apply to industrial situations ([36,71]).

Bakke and Hjertager [72] have investigated scaling characteristics of explosions in vented obstructed channels by using an early version of the FLACS code. The channel was similar to the geometry shown in Fig. 52. The top plate was either a solid plate or a perforated plate. The results from the simulations are shown in Fig. 76. The legend gives the confinement of the top plate, i.e. conf. 1.0 is a solid plate and conf. 0.5 is a perforated plate with 50% blockage.

From this Figure we can see that the explosion pressure increases with increasing length scale until the pressure reaches 10–15 bar. The important finding in this investiga-

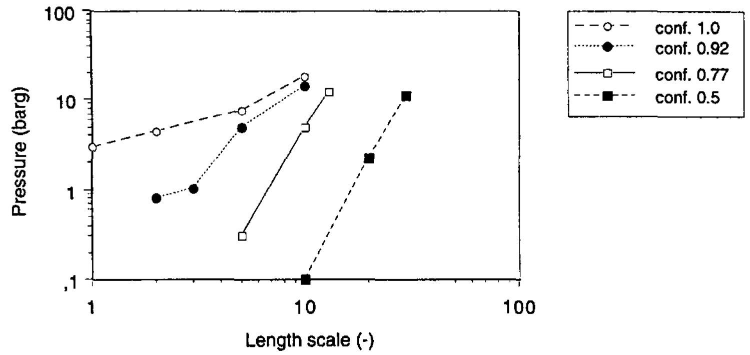


Fig. 76. Maximum overpressure vs. length scale in a channel with repeated obstacles and solid (conf. 1.0) or perforated top plate [121].

tion is that the venting through the top plate becomes less effective as the scale increases. For instance for a length scale equal to 2 there is nearly an order of magnitude difference between the solid plate (i.e. conf. 1.0) and 8% open top plate (i.e. conf. 0.92). For length scales of 5–10 this difference is 2 or less. This shows clearly the difficulties of gas explosion scaling. It is not only the venting and obstructions that are important, but also the dimensions.

6.16. Duration and impulse

So far we have only discussed the peak pressure as the characteristic parameter for gas explosions. Actually the dynamic response of walls, decks, etc. subjected to pressure from gas explosions will depend on the pressure time curve. In addition to the peak pressure, the rise time and duration of the positive phase are important. In some cases even the negative phase of the pressure pulse can be important.

One way of characterizing the pressure time curve is to use the time integral of the pressure, known as the impulse. The impulse is simpler to define than the duration of pulse and it contains more information (Fig. 77).

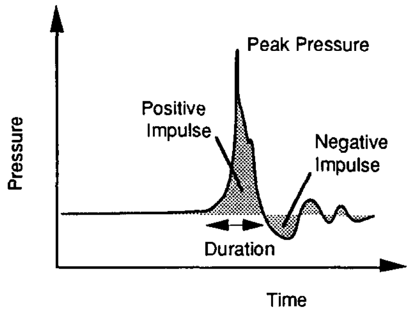


Fig. 77. Pressure–time curve.

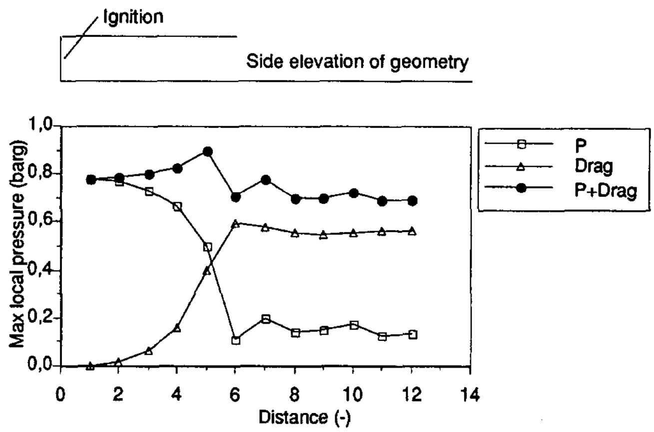


Fig. 78. Maximum static and dynamic pressures from a FLACS simulation.

The duration and the impulse depend on the size of the exploding cloud and the peak pressure. There are no simple methods of adequate accuracy for predicting the shape of pressure–time curves from gas explosions. Advanced numerical simulation tools like FLACS have to be applied.

6.17. Explosion wind

The wind force generated by the explosion will act as a drag load on smaller equipment such as piping. The dynamic pressure (or drag, $0.5\rho u^2$) is one of the parameters characterizing the explosion wind.

Fig. 78 shows the maximum static and dynamic pressures from a FLACS simulation. We can see that the maximum pressure is 0.7–0.8 up to a normalised distance of 4, but decreases out to the vent area at 5 or 6. At the vent area the flow velocity and the dynamic pressure are high. The stagnation pressure ($p + 0.5\rho u^2$) is fairly constant.

Experiments reported in Ref. [74] show that measured drag forces acting on a single pipe during an explosion appear to be very close to those predicted by FLACS.

6.18. Guidelines

The main factors determining the consequences of deflagrations are:

- Type of fuel
- Fuel concentration
- Size and location of the cloud
- Location and strength/type of the ignition source
- Obstacle number and size + orientation/location
- Confinement and venting (size and position of vent area)
- Scale

In order to evaluate the consequences of a deflagration all of these factors have to be taken into account. Otherwise order of magnitude prediction errors can be made!

Simple scaling rules have proven to be inadequate for most industrial environments. More advanced methods such as FLACS (Section 13) simulations have to be applied.

The consequences of a gas explosion depend strongly on the venting arrangements and the geometrical layout (i.e. arrangement of process equipment, piping, etc.). Small changes in the geometry can change the explosion pressure significantly. It is therefore important to understand the mechanisms of flame acceleration and pressure build-up. Based on this knowledge it is often possible to suggest changes in the layout that will affect the explosion behaviour significantly and hence improve overall safety.

In design it is important to start as early as possible to consider gas explosions. It is a common mistake to start too late, when the layout has been 'frozen'. Start at day one [9]. Apply the information in Sections 10–12.

A deflagration in a truly unconfined cloud will propagate slowly and only produce small overpressure. Deflagrations produce high pressures when they propagate in an obstructed, partly confined area or confined volume.

When evaluating the consequences of deflagrations, not only peak pressure should be considered, but also the rise time, the duration and the impulse.

7. Detonations

A detonation is the most devastating form of gas explosion. Unlike the deflagration, a detonation does not require confinement or obstructions in order to propagate at high velocity. Particularly in an unconfined situation, the behaviour of a detonation is quite different from a deflagration. A detonation is defined as a supersonic combustion wave (i.e. the detonation front propagates into unburnt gas at a velocity higher than the speed of sound in front of the wave). The gas ahead of a detonation is therefore undisturbed by the detonation wave. In fuel–air mixtures at atmospheric pressure, the detonation velocity is typically 1500–2000 $m\,s^{-1}$ and the peak pressure is 15–20 bar.

Transition to detonation, propagation and transmission of detonation waves, depend strongly on the reactivity of the gas cloud.

The objective of this chapter is:

· To describe the detonation, so that a detonation can be distinguished from a deflagration.

· To describe under which conditions detonation waves are likely to propagate.

· To describe how to calculate detonation velocities and pressures.

7.1. Detonation waves

Detonation waves were observed experimentally more than 100 years ago. Chapman and Jouguet were the first to present a theory describing this supersonic combustion wave, propagating at a unique velocity. The CJ (Chapman–Jouguet) theory [75], treats the detonation wave as a discontinuity with infinite reaction rate. The conservation equations for mass, momentum and energy across the one-dimensional wave give a unique solution for the detonation velocity (CJ-velocity) and the state of combustion products immediately behind the detonation wave. Based on the CJ-theory it is possible

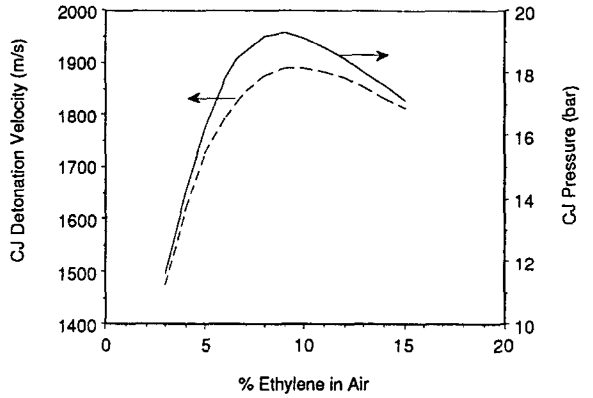


Fig. 79. CJ detonation velocity and pressure for ethylene–air.

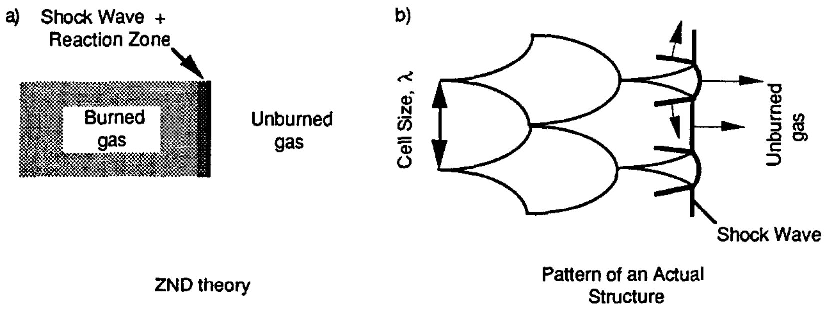


Fig. 80. ZND structure and pattern of an actual structure of a detonation front. The characteristic length scale of the cell pattern, the cell size, λ, is shown in the figure.

to calculate detonation velocity, detonation pressure etc. if the gas mixture is known. The CJ-theory does not require any information about the chemical reaction rate (i.e. chemical kinetics) (Fig. 79, Table 13).

During World War II, Zeldovich, Döring and von Neumann improved the CJ-model by taking the reaction rate into account. As shown in Fig. 80 the ZND-model describes the detonation wave as a shock wave, immediately followed by a reaction zone (i.e. flame). The thickness of this zone is given by the reaction rate. The ZND-theory gives the same detonation velocities and pressures as the CJ-theory, the only difference between the two models is the thickness of the wave.

Table 13

CJ-pressure and CJ-detonation velocity for some fuel–air mixtures. Initial conditions 25°C and 1.013 bar [25].

	Hydrogen	Ethylene	Propane	Methane
CJ-Pressure (bar)	15.8	18.6	18.6	17.4
CJ-Velocity ($m s^{-1}$)	1968	1822	1804	1802

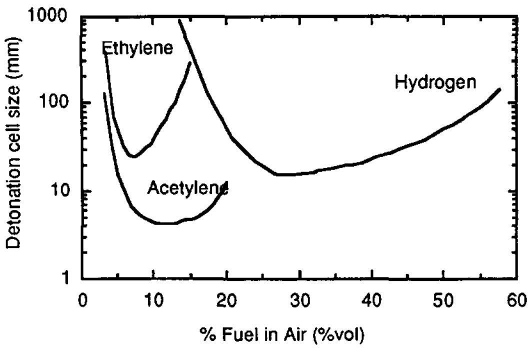


Fig. 81. Cell size vs. fuel concentration for acetylene, ethylene and hydrogen in air (25 °C and 1 atm) [13].

An actual detonation is a three-dimensional shock wave followed by a reaction zone. The leading shock consists of curved shock segments. At the detachment lines between these shock segments, the shock wave interacts in a Mach Stem configuration. A two-dimensional illustration of the actual structure is given in Fig. 80. The size of the fish shell pattern generated by the triple point (Mach stem) of the shock wave is a measure of the reactivity of the mixture representing a length scale characterizing the overall chemical reaction in the wave [76]. This length scale, λ, is often referred to as the cell size or the cell width. The more reactive the mixture, the smaller the cell size. Fig. 81 and Fig. 82 show the detonation cell size versus fuel concentration for several fuel–air mixtures.

The cell size is measured experimentally and there are some variations in the reported results. Variations of a factor of two is not uncommon.

The cell size, λ, is a parameter which is of practical importance. The transition from deflagration to detonation, propagation and transmission to detonation, can to some extent be evaluated based on the knowledge of the cell size of the mixture. This will be discussed in the following sections.

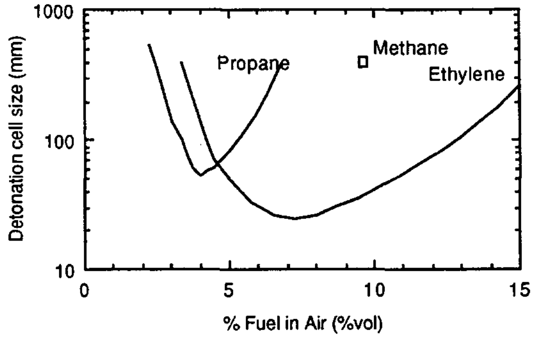


Fig. 82. Cell size vs. fuel concentration for ethylene, propane and methane in air (25 °C and 1 atm) [13].

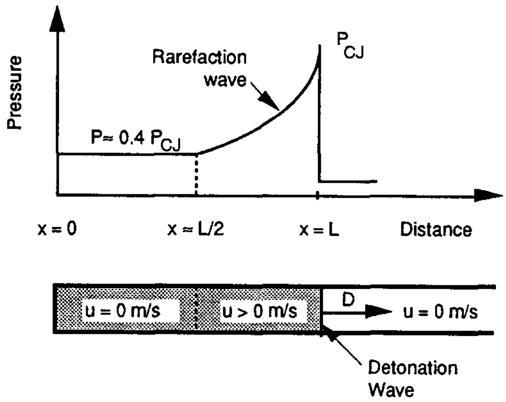


Fig. 83. Pressure–distance profile for a detonation propagation in a tube with a closed end (i.e. closed at $x = 0$).

7.2. *Rarefaction wave behind detonation front*

So far we have discussed the detonation pressure (i.e. CJ-pressure) of a detonation front. After the detonation front (CJ-plane) the combustion products will expand. This expansion will depend on the boundary condition.

The expansion of the combustion products forming a detonation wave propagating in a tube (i.e. one-dimensional propagation) is illustrated in Fig. 83. The tube is closed at $x = 0$ and propagates from left to right. When the detonation is at $x = L$, the tail of the expansion wave will be located at approximately $x = L/2$ which means that the tail of the expansion wave propagates at half of the detonation velocity for this boundary condition. The expansion process between the wave front (CJ-conditions) and tail of the expansion wave can be approximated as being isentropic.

In this case the pipe is closed at $x = 0$. The boundary condition at $x = 0$ is therefore gas velocity equal to zero ($u = 0\,\mathrm{m\,s^{-1}}$). For this boundary condition the pressure will expand to $P \approx 0.4\,P_{CJ}$. Note that this pressure is approximately the same as the constant volume combustion pressure. This pressure will be constant from $x = 0$ to the tail of the rarefaction wave (i.e. $x \approx L/2$).

For other boundary conditions, $u \neq 0\,\mathrm{m\,s^{-1}}$, the pressure will vary with the boundary conditions. The mode of propagation for the detonation, i.e. spherical or planar mode, will influence the expansion slope behind the wave.

7.3. *Deflagration to detonation transition (DDT)*

When a deflagration becomes sufficiently strong, a sudden transition from deflagration to detonation can occur. This has been observed in several experiments, especially in those involving very reactive mixtures, such as near-Stoichiometric acetylene–air, hydrogen–air or fuels with oxygen-enriched atmospheres.

There are also some examples of deflagration to detonation transition in fuel–air mixtures with moderate reactivity.

(i) In one CMR experiment [56] in the 10 m long wedge-shaped vessel with Stoichiometric propane–air, 100% top confinement and circular obstructions, transition to detonation was observed. This experiment shows that a propane–air explosion initiated with a weak ignition source, can accelerate to a detonation in less than 10 m, if sufficient confinement and obstructions are present.

(ii) Moen et al. [60,77] have observed transition to detonation caused by jet flames. In one test they reported transition to detonation in a lean mixture of acetylene–air (5% C_2H_2) in an essentially unconfined situation. The transition to detonation was caused by a jet-flame shooting into the unconfined cloud. These experiments demonstrated that detonations can be induced in an unconfined fuel–air cloud with moderate reaction rates as long as the size of the cloud is large.

(iii) British Gas experiments [78] in a pipe rack geometry also showed transition to detonation for propane–air. Transition to detonation occurred after 15 m. This experiment showed that in relatively 'open' situations, such as a pipe bridge, the geometry can support flame acceleration to detonation.

These experiments show that transition to detonation can be obtained by flame acceleration caused by obstacles and confinement or if a jet flame is shot out from an opening in a confined volume into an unconfined cloud [132].

The mechanism of transition to detonation is not fully understood. Presently there is no theory which can predict conditions for deflagration to detonation transition. We have only a qualitative understanding of the phenomenon; it is likely that local explosions within explosions cause transition to detonation. The size of these localised explosions must be of the order of 10 times the cell size.

From a practical point of view, it is important to recognise that transition to detonation will cause extremely high pressures in the area where the transition takes place.

Fig. 84 shows a pressure–time profile from an experiment where transition to detonation occurred. The first pressure rise at $t = 2510\,\mu s$. is the shock wave which compresses the unburnt gas. The pressure continues to rise after the shock wave, and subsequently a transition to detonation occurs. As a direct result of this pre-compression,

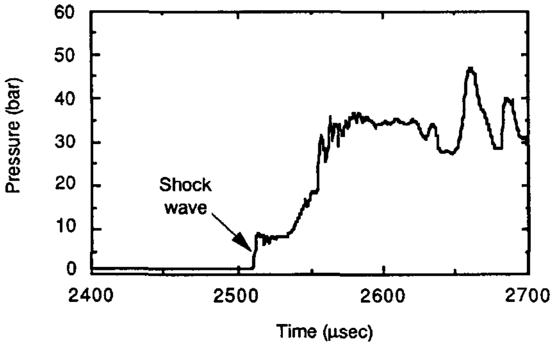


Fig. 84. Pressure–time profile from a pressure transducer located close to an area of transition to detonation [79].

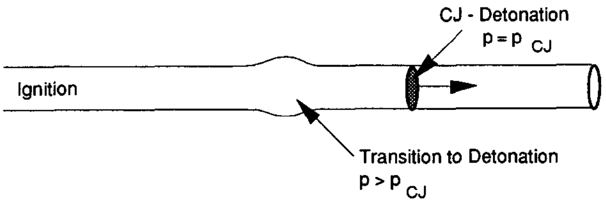


Fig. 85. Transition to detonation in a pipe. A case history.

the detonation pressure in the transition process is much higher than the pressure in a stabilised detonation wave (i.e. CJ-pressure).

In an accident situation, where transition to detonation has occurred, localised damage can be observed. One example is an accidental explosion inside a pipe. At one particular position the pipe was expanded radially, as shown in Fig. 85.

In this case the pipe was able to withstand CJ-pressure, but the pressure at the location where the transition to detonation took place represented a force exceeding the strength of the pipe.

7.4. Propagation and transmission of detonation wave

From the CJ-theory, the detonation velocity and pressure can be predicted independently of the geometrical conditions. However, the propagation and transmission of a detonation are limited by geometrical conditions [134]. The limited conditions are controlled by the sensitivity of gas mixtures and length scale of the geometry. As discussed in Section 7.1, the cell size is a length scale characterizing the reactivity of the mixture. By using these two length scales, the conditions for successful propagation and transmission can be evaluated.

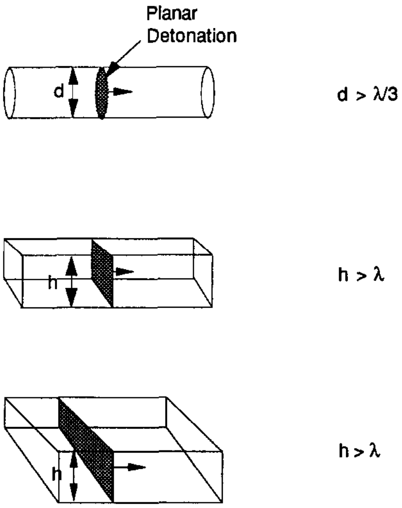


Fig. 86. Requirements for successful propagation of a planar detonation in pipes and channels.

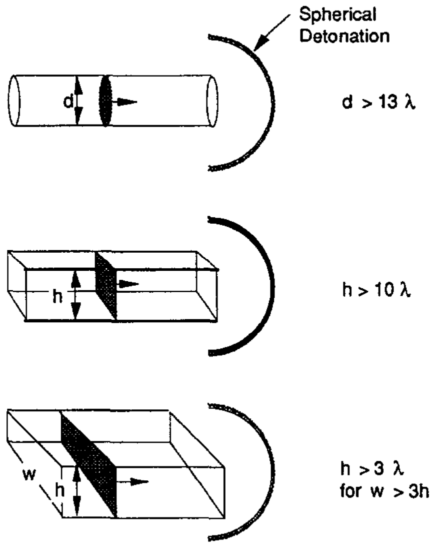


Fig. 87. Requirements for successful transmission of a planar detonation into an unconfined three-dimensional spherical detonation wave.

Fig. 86 shows detonation propagation limits within pipes and channels. We see that a pipe is more supportive of detonation propagation than a channel.

Fig. 87 shows requirements for a successful planar detonation transmission from a pipe or channel into an unconfined situation (i.e. three-dimensional spherical detonation wave). In order to make a successful transmission, there is a need for more cells than for the planar propagation mode. The information in Fig. 87 is useful in evaluating the possibility for transmission of a detonation from a confined area, like a building, ventilation duct, culvert etc. into an unconfined situation.

The requirement for propagation in an unconfined cloud is shown in Fig. 88.

7.5. Estimating detonation loads

To estimate the CJ-values for gas mixtures the STANJAN program can be used. This may be acquired from Professor W.C. Reynolds at Stanford University (see Ref. [80]).

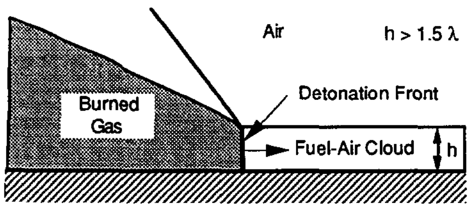


Fig. 88. Limit for propagation of detonation waves in an unconfined fuel–air cloud.

7.6. Guidelines on detonations

The probability of occurrence of a detonation in fuel–air mixtures depends strongly upon the type of fuel. Very reactive fuels, such as hydrogen, acetylene or ethylene, may detonate in an accidental situation. For accidental situations involving such fuels, detonations should be regarded as a possible scenario.

Other fuels are less likely to detonate. In particular no data exist on detonations involving pure methane–air. Generally, however, in large gas clouds with a high degree of confinement and/or with a high density of obstructions, detonations cannot be ruled out.

Presently the most effective way of mitigating the occurrence of a detonation is to avoid situations where the deflagration can accelerate to a condition where transition from deflagration is possible, i.e. high pressure deflagrations.

The CJ-detonation pressure can be calculated by codes like STANJAN. Such data can be used for stable detonation waves. However, in the event of transition from deflagration to detonation, pressure spikes much higher than the CJ-values (see Fig. 84) appear.

Propagation and transmission of detonation waves depend mainly on the cell size (i.e. type of fuel and fuel concentration) and geometrical conditions. By operating with geometrical dimensions (d, w, h) smaller than the limits indicated in Figs. 86–88, it is very unlikely that a stable detonation will occur.

The cell size as a measure of detonability is not an exact number. In the literature a variation of a factor of two is often found. When using cell sizes for estimation of limiting conditions for successful propagation or transmission, they should be regarded as approximate values. Hence safety factors should be used.

8. Blast waves

If a strong gas explosion occurs inside a process area or in a compartment, the surrounding area will be subjected to blast waves. The magnitude of the blast wave will depend on:

- The source, i.e. pressure and duration of the explosion.
- The distance from the explosion (Fig. 89).

Fig. 90 shows maximum explosion overpressures from various CMR experiments in a 50 m^3 tube, a wedge-shaped vessel (results scaled to 50 m^3) and a 50 m^3 offshore

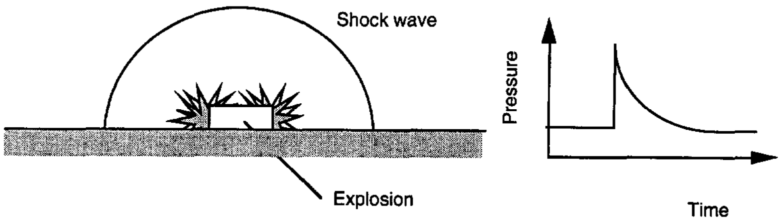


Fig. 89. Free field blast wave.

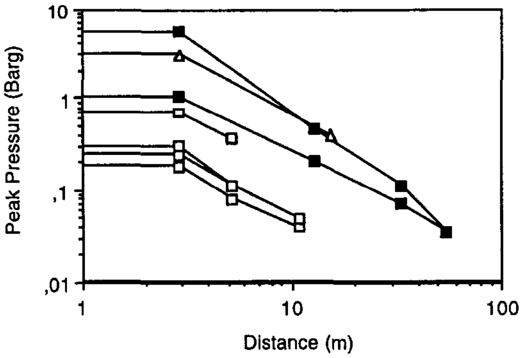


Fig. 90. Peak pressure from free field blast for CMR experiments in 50 m^3 test vessels [38,39].

module, together with the associated blast wave overpressure variation with distance. The horizontal part of the curves indicate the extent of the gas clouds before the explosions (actually the radius of a hemispherical cloud of the same volume as the experiment). No legend discriminating between the explosion vessels is given, since the gas volume and explosion overpressure are the important parameters here.

The results show that the blast wave from a gas explosion can cause high pressures far away from the area where the explosion actually takes place. In safety evaluation, free field blast must therefore be considered. In accidental investigations evaluation of the free field blast from recorded damage is often used for evaluation of the source strength of the explosion.

The objective of this chapter is:

(i) To describe the nature of a blast wave from a gas explosion.

(ii) To present methods to estimate the blast waves from a gas explosion.

8.1. Scaling

The blasts from detonation of high explosive charges, such as TNT, are fairly well documented [25]. The peak explosion pressure for blast waves from TNT explosions with charges ranging from 1 kg to 1000 kg, as function of distance R (from the centre of the charge) is shown in Fig. 91.

These data can be scaled through a normalised length scale (Hopkinson scaling) R^*

$$R^* = R/W^{1/3} \qquad (8.1)$$

where R m is the distance from the centre of the explosive source and W kg is the mass of the explosive source. Fig. 92 shows the same set of data as shown in Fig. 91, but plotted versus the normalised length scale R^*.

Similar diagrams as Fig. 92 also exist for duration, impulse and other blast parameters. These curves can be found in Ref. [25].

8.2. TNT method

The diagram for TNT detonations have been used for estimations of blast from gas explosions, even though there are differences between the blasts from a gas explosion

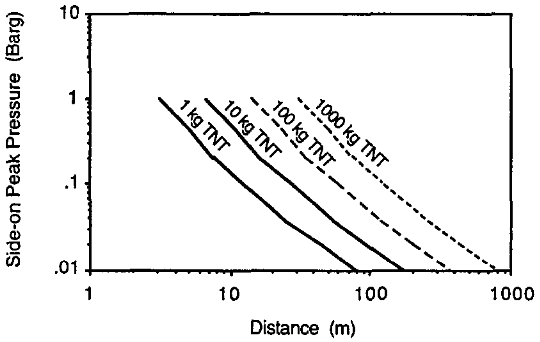


Fig. 91. Peak explosion pressure (side-on) vs. distance for TNT ground burst.

and a TNT detonation [13,81]. In a gas explosion the local pressure may reach values as high as a few bars. The blast pressure for TNT explosions is much higher close to the charge. Such near-field data are therefore irrelevant for gas explosions and it is recommended not to use TNT data indicating pressures higher than 1 bar to estimate gas explosion blasts.

The so-called TNT equivalence method has been widely used for gas explosions. The TNT equivalence method applies pressure-distance curves for TNT explosions to gas explosions and the equivalent TNT charge is estimated from the energy content in the exploding gas cloud.

For typical hydrocarbons, such as methane, propane, butane etc., the heat of combustion is 10 times higher than the heat of reaction of TNT.

The relation between the mass of hydrocarbons W_{HC} and the equivalent TNT charge W_{TNT} is then

$$W_{TNT} \approx 10 \cdot \eta \cdot W_{HC} \tag{8.3}$$

where η is a yield factor ($\eta = 3$–5%), based on experience, see Ref. [82].

In the original TNT equivalence method, the mass of hydrocarbon W_{HC} was based on the total mass released and the yield factor η. In order to estimate consequences of gas

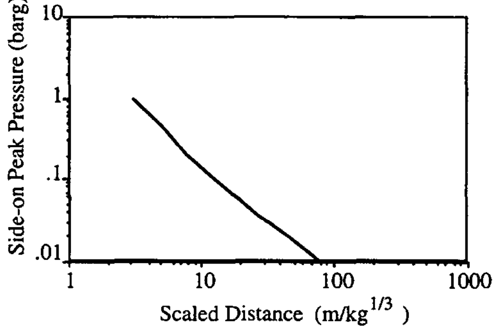


Fig. 92. Peak explosion pressure (side-on) vs. scaled distance, R*, for TNT ground burst.

explosions, the geometrical conditions (i.e. confinement and obstructions) have to be taken into account. In the original TNT equivalence method, the geometrical conditions are not taken into account. The results from this type of analysis, have therefore hardly any relevance and should in general not be used.

The drawbacks of the TNT equivalence method can be listed as follows:

· a non-unique yield factor is necessary
· representation of weak gas explosions a problem
· positive phase duration only
· gas explosion processes are not represented well
· choice of 'blast centre' is problematic (no well-defined and sensible method exists)

In order to take the geometrical effects into account in the TNT equivalence method, Harris and Wickens [43] proposed to use a yield factor of 20% ($\eta = 0.2$) and the mass of hydrocarbon, W_{HC}, contained in Stoichiometric proportions in any severely congested region of the plant. For natural gas the equivalent mass of TNT can be estimated from (assuming atmospheric pressure initially)

$$W_{TNT} \approx 0.16V \text{ kg} \tag{8.4}$$

where V m^3 is the smaller of either the total volume of the congested region or the volume of the gas cloud. Eq. (8.4) will also hold for most hydrocarbons, since the energy content per volume Stoichiometric mixture is approximately the same ($\sim$ 3.5 MJ m^{-3}).

Fig. 93 shows the results from a TNT equivalent analysis, as suggested by Harris and Wickens, in comparison with CMR's experimental results from 50 m^3 tests.

As we can see from this figure there is a fairly good agreement between the predicted values and the experimental values as long as the explosion pressure in the cloud is in a few bars range. Weak gas explosions (less than 0.5 bar) are not represented satisfactorily. This indicates that the TNT equivalence method can be useful as a rough approximation if one uses a yield factor of 20% and appropriate values for W_{HC} or V. However, for explosion pressures below 1 bar, the TNT equivalence method will

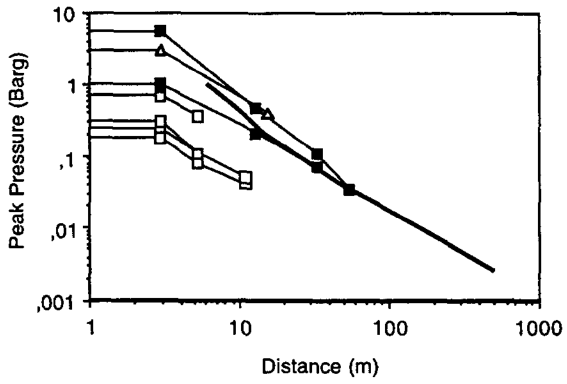


Fig. 93. Peak explosion pressure (side-on) vs. distance for TNT equivalence method [43] and CMR experiments from 50 m^3 tests.

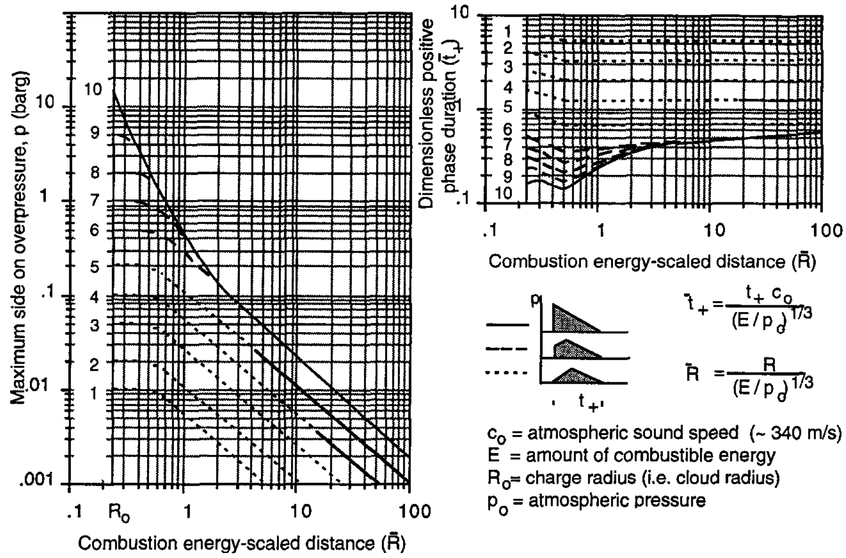


Fig. 94. Hemispherical fuel–air charge blast for the multi-energy.

overestimate the blast. More sophisticated methods must therefore be applied for such cases.

8.3. The multi-energy method

The multi-energy method [81] is a more sophisticated method than the TNT equivalence method. It can estimate the blast from gas explosions with variable strength. The method is based on numerical simulation of a blast wave from a centrally ignited spherical cloud with constant velocity flames. By varying the flame velocity, a set of curves for different explosion strengths (i.e. explosion pressure inside the cloud) have been produced. Fig. 94 shows the dimensionless curves that are used in the multi-energy method.

Fig. 94 is in principle the same figure as the previous blast curves for TNT. For a detonating cloud, curve 10 can be used. For a deflagration (curves 1–9) we see that the pressure profile inside the cloud is not a shock wave followed by an expansion wave, but it can either be a shock wave followed by increasing pressure that drops off after the passage of the flame front or a sonic wave (i.e. gradually increasing pressure) that drops after the flame front.

However, as a blast propagates away from the centre of the explosion, the gradient at the front will steepen and eventually become a shock wave, like the blast from a TNT charge.

The difficult part of a multi-energy method analysis is to choose:

(i) The explosion pressure within the exploding gas cloud (i.e. the charge strength).

(ii) The combustion energy, E, given the size of the gas cloud contributing to the blast (i.e. the charge size).

The multi-energy method does not give any information about which explosion pressure (charge strength) to choose in a blast analyses. That information has to be found separately by using numerical simulations, experimental data or make a conservative assumption. The combustion energy, E, is also a parameter that is not straight forward to estimate.

For a Stoichiometric hydrocarbon–air mixture of volume V, the combustion energy E can be estimated from

$$E \approx 3.5(\mathrm{MJm}^3) \cdot V \tag{8.5}$$

In an accidental explosion (deflagration), only the confined and/or congested areas will contribute to blast generation. Therefore only portions of the total cloud volume should be included in Eq. (8.5). Van den Berg [81] indicates that the total volume of a confined and/or congested area should be used in Eq. (8.5). However, even such an approach can lead to conservative numbers and overestimate the blast in some situations. For instance in an explosion in a partly confined volume, the total volume will give conservative data, particularly in low pressure cases. During the explosion as the gas cloud burns the gas will expand and push the unburnt gas outside the confinement. The gas that is pushed outside the confinement, will often not contribute significantly to the generation of the blast.

Before we leave the multi-energy method there is one aspect of gas explosions that is discussed by van den Berg [81] which should be mentioned. In a process area for instance, one large gas cloud can cause multiple blast waves. To illustrate this we include Fig. 95. In this Figure we can see that the gas cloud covers two obstructed areas. Between these areas there is open space. If we assume that the cloud ignites in area A, we will first get an explosion in area A. If no transition to detonations occurs in area A, the flame velocity will drop when the flame propagates outside area A. In an open area, the flame velocity will be so slow that the pressure generation will be negligible. When the flame reaches area B, the flame will accelerate again and a new blast wave will be generated. If one monitors the pressure at location C, one will observe two blast waves passing.

This feature was also confirmed experimentally. Explosion propagation from one obstructed area into a second nearby obstructed area at various intervening distances

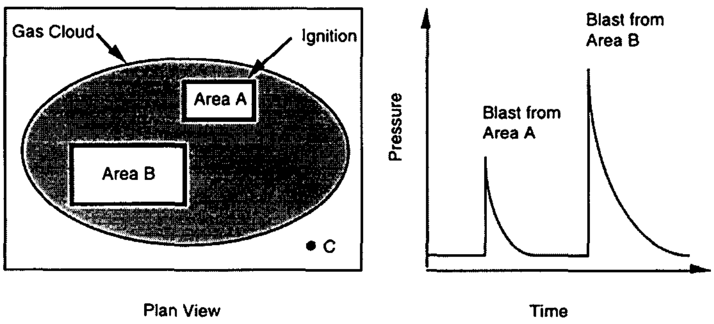


Fig. 95. One gas cloud may cause more than one blast wave.

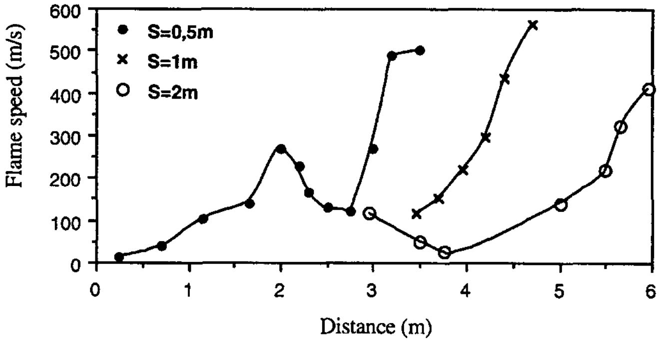


Fig. 96. Explosion propagation in two obstructed areas with an intervening area filled with gas in between them. Both obstructed areas have a length of 2 m. The length of the intervening area (S) was varied between 0.5 m and 2 m [83].

shows deceleration of the flame upon propagating outside the first obstructed area and a re-acceleration within the second obstructed area (Fig. 96, [83]).

8.4. Scaling of experiments

An alternative to the TNT equivalence method and the multi-energy method is to scale experimental results. In Fig. 90 some data from CMR experiments were presented. Based on these data and by applying scaling with dimensionless length scale, a set of curves for explosions with different strengths, for a 1000 m^3 compartment, have been developed. The curves are shown in Fig. 97.

For an explosion in a confinement of volume, V, the blast wave can be found simply by scaling the actual distance from the explosion centre R to an equivalent distance R_{Eq1000} and use that distance in Fig. 97.

$$R_{Eq1000} = R \cdot \left[\frac{1000m^3}{V} \right]^{1/3} \tag{8.6}$$

Results from such scaling are shown in Fig. 98.

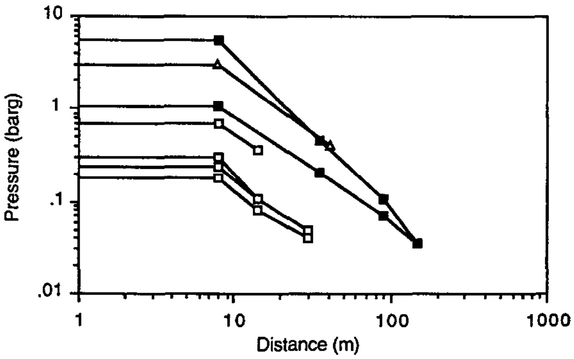


Fig. 97. Peak explosion pressure for blast waves from explosions in a 1000 m^3 confinement.

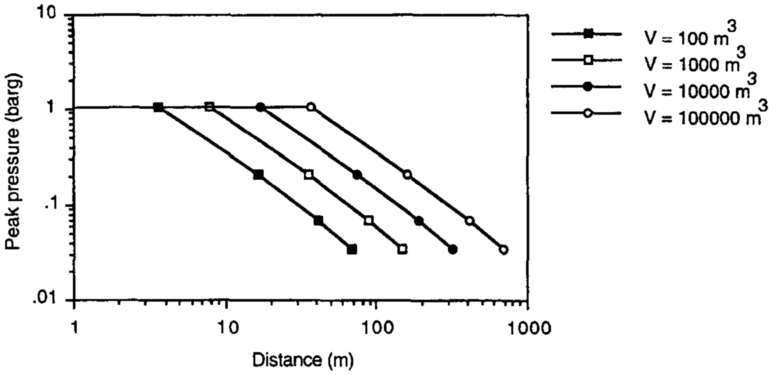


Fig. 98. Peak explosion pressure for blast waves from 1 barg explosions in a 100, 1000, 10000 and 100000 m^3 confinement.

8.5. Numerical methods

Several advanced numerical codes for blast prediction exist. However, all these types of codes have limitations. They need either a predefined flame speed or explosion pressure (i.e. cannot estimate source term) or they require computers of an order of magnitude larger than we have today to handle both flame propagation and blast propagation.

Savvides and Tam [84] have compared FLACS results with results from TNT equivalence and multi-energy methods. It was found that in the test cases used, the high overpressure was created in localised pockets within the plant, where the density of equipment was high. They observed that the overpressure decayed rapidly in open space. The conclusions were that a numerical simulation model like FLACS, provides much more information than the simpler models, but the requirement for computer time is high for process plants. They foresee that such simulations will become a routine task in assessing explosion hazards.

At CMR the FLACS 3-D code has been used for combined explosion and blast simulations even though the main use of FLACS is in simulating gas explosions only. The main difference between the two applications is that blast simulations are usually performed on a large calculation domain, where the explosion takes place in a smaller part of this domain. As a result of limitations in the computer capacity larger control volumes must be used, which may not be compatible with the fact that in onshore plants localised explosions can be very important. To handle localised explosion in the simulations, small control volumes are needed. However, for local explosions of a given source strength, FLACS is still suited to predict blast decay in congested or semi-confined surroundings of the exploding gas cloud.

Figs. 99 and 100 compare examples of blast decay simulations using FLACS in local explosions in a process plant with scaled experimental results (using Eq. (8.6)) for two clouds of 20 m^3 and 600 m^3, respectively. The scaled experimental results are based on one test in CMR's 50 m^3 model of an offshore module (Fig. 100 only, see Section 6.6)

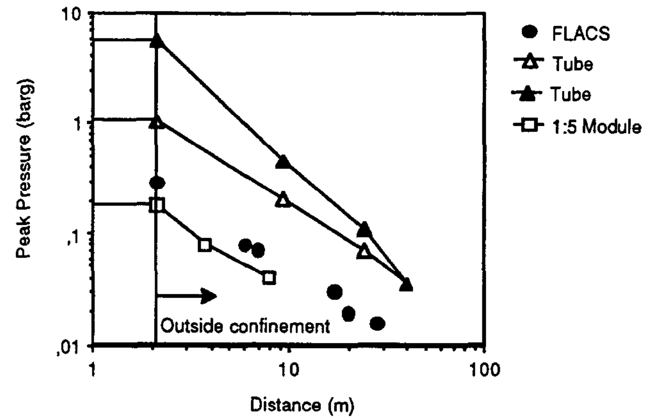


Fig. 99. Blast decay for a 20 m^3 gas cloud. FLACS simulations vs. scaled experiments.

and on two tests in the 10 m long tube (see Section 6.3), producing maximum pressures inside the gas cloud of 0.2, 1 and 6 bar g, respectively. The FLACS simulations generate 0.3 bar overpressure in the 20 m^3 cloud and 5–6 bar overpressure in the 600 m^3 cloud. The simulated pressure decay outside the gas clouds show a behaviour very similar to the experimental results. The observed deviations may be due to differences in congestion outside the exploding gas cloud.

The vertical lines in Fig. 99 and Fig. 100 show the radius of equivalent, hemispherical gas clouds of volumes 20 m^3 and 600 m^3, respectively.

8.6. *Reflection of free field blast waves*

The loading on a construction hit by a blast wave is a rather complex phenomenon [25].

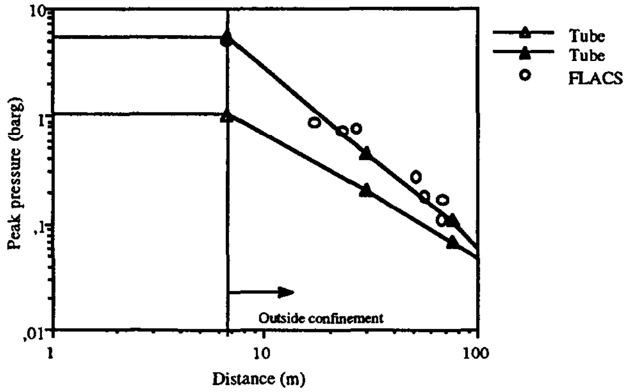


Fig. 100. Blast decay for a 600 m^3 gas cloud. FLACS simulations vs. scaled experiments.

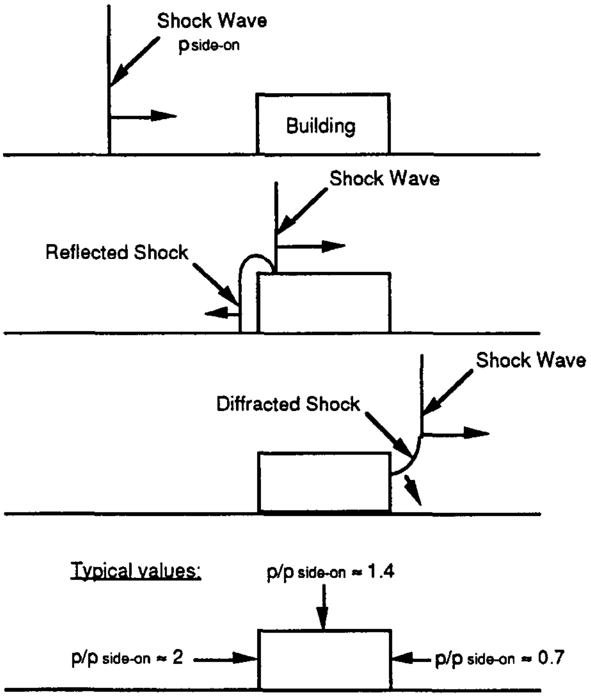


Fig. 101. Blast reflection off a building.

When a free field blast wave runs into an object like a building, the wave will be reflected. Fig. 101 shows how a shock wave is reflected off a building. As a result of reflection and diffraction, the wave loading on the walls and the roof will differ. The maximum loading will be on the wall facing the explosion. At this wall the shock wave will be reflected and the pressure will typically increase by a factor of 2 (depending on shock strength.).

When the shock wave propagates in a free field, the gas behind the shock wave will have a velocity in the same direction as the wave propagates. When the shock wave hits the wall, the gas must stop and the dynamic pressure (i.e. $0.5\,\rho u^2$) is transformed to pressure. This is in principle why the pressure increases because of blast wave reflection.

On the opposite wall (see Fig. 101) the shock wave will be diffracted and that will reduce the pressure load on the building.

8.7. Guidelines for blast waves

- Do not spend a lot of time and effort estimating free field blast waves from gas explosion in scenarios where the gas explosion scenario itself has not been analysed. You need to know the source strength in order to estimate free field blast.

· Do not use the original TNT method assuming an energy yield factor of 3–5% for the released substance.

· The first step in calculating the far field blast from gas explosions is to evaluate the explosion pressure and cloud size. (i.e. pressure-time history inside the exploding cloud).

· As a rough estimate of pressure in the far field the following approaches are adequate:

(a) Use scaled experimental results as described in Section 8.4.

(b) TNT method as described by [43]. (Beware of over-estimation for weak explosions as described in see Section 8.2).

(c) Multi-energy method. (Beware of limitations as discussed in Section 8.3).

(d) μFlacs has the capability of predicting far field blast.

· For more accurate predictions numerical codes have to be applied.

9. Response of structures

To predict explosion pressure is one step in a consequence analysis. The next step is to estimate the response of the structures subjected to the load from the gas explosion. Knowledge about structural response is therefore also important in accident investigations. (See Section 15).

Structural response is not a research activity which CMR has been heavily involved in. However, the area of loads acting on structures is under investigation. In our opinion there is little information available on loads and structural response from gas explosions. Today, the main source of information in this field is in blast effects from military weapon tests. These data are not always directly applicable for accidental gas explosions.

The objectives of this chapter are to:

(i) Describe the difference between a static load and a dynamic load acting on a structure.

(ii) Explain how the load from a gas explosion acts upon a structure.

(iii) Describe the typical damage and response of equipment and buildings when subjected to explosion pressure loads.

9.1. Dynamic response

A gas explosion is a very rapid event. In a large gas explosion, the overpressure duration will typically be 100–200 ms. The load from a gas explosion is therefore a dynamic load.

To illustrate the difference between a static load and a dynamic load we will use a single-degree-of-freedom system as an example. A house subjected to a blast wave can be reduced to a single-degree-of-freedom system. This is shown in Fig. 102.

The pitched roof is reduced to a rigid beam and the walls are treated as vertical cantilevers. This can further be reduced to a simple mass spring system. The load, i.e. pressure-time area, is simplified to a triangular pulse. The response, x, i.e. the displacement of mass, m, will depend on the maximum force, the natural frequency of the system, $T = 2\pi(m/k)^{1/2}$, and the mass, m. The displacement can be predicted by

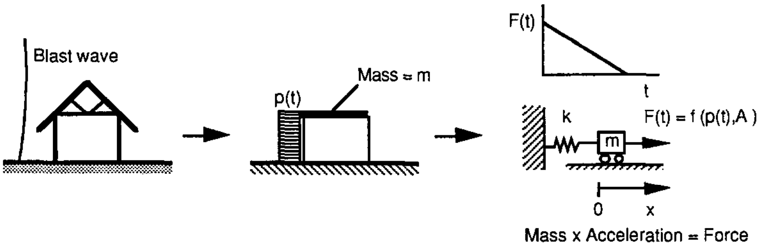


Fig. 102. A house subjected to a blast wave can be reduced to a single-degree-of-freedom system.

Newton's second law: mass · acceleration = force. The result of such a calculation is shown in Fig. 103.

In this system there is no damping. The mass therefore continues to oscillate. In real situations there will always be some damping and the mass will come to a rest after a while. However, it is important to recognise that the maximum displacement of the mass, $X_{\text{max dynamic}}$, will depend on the ratio of the duration of load, t_L, and the natural frequency of the system, T. For low t_L/T ratio, the $X_{\text{max dynamic}}$ is smaller than the displacement for the static load ($X_{\text{static}} = F/K$). For larger t_L/T-ratios, $X_{\text{max dynamic}}$ can be larger than the displacement for static loads. Fig. 104 shows the ratio of $X_{\text{max dynamic}}/X_{\text{static}}$ [also called the dynamic load factor (DLF)] versus t_L/T for two different types of triangular loads.

Actual structures may have many degrees of freedom and prediction of their behaviour needs detailed analysis. A single-degree-of-freedom system is very simplified, but it illustrates the basic behaviour of structures subjected to a dynamic load [133].

The structural response and damage level will depend on the load (i.e. pressure or/and drag) as a function of time and the structure's own characteristics.

9.2. Loads from gas explosions

A gas explosion will generate high pressures and also often high flow velocities. It is the pressure and flow that cause the dynamic load on structures and consequently cause the damage.

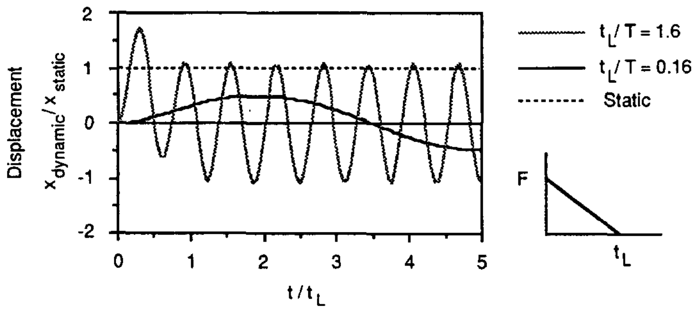


Fig. 103. Displacement of a single-degree-of-freedom as function of time, t, when subjected to a triangular pulse.

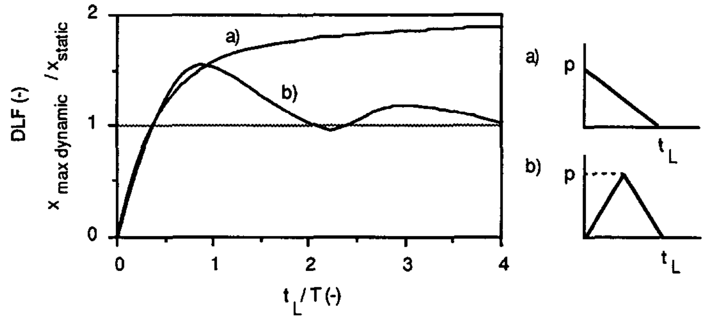


Fig. 104. Dynamic Load Factor (DLF).

Inside an exploding gas cloud the type of load as generated by a gas explosion simulation will depend on the size of the structure. A wall can be spatially resolved by the simulation code. The main load from the explosion, the pressure, will therefore be calculated directly by the code. A small pipe standing in the explosion, however, will not be resolved by the code and the pressure differential can not be directly calculated. The load will have to be calculated by reference to the flow conditions (velocity and density) using a drag formula.

A pressure–time curve for a gas explosion in a compartment is shown in Fig. 105. The pressure will be close to zero in the initial phase of the explosion when the burning rate is low. When the flame starts to accelerate the pressure rises rapidly and the maximum pressure will be reached. The pressure will then drop as the burning rate decreases and the gas is relieved through the vent openings. As a result of the inertia of the flow the pressure of the burnt gas will drop below the ambient pressure. The main parameters that will influence structural response are: maximum pressure, the pressure rise time (dp/dt), the positive impulse and the negative impulse. The impulse is the time integral of pressure which takes both the pressure and the duration of the pulse into account.

The importance of the negative impulse will depend very much on the natural frequency of the structure. If the negative pressure is in phase with the vibration of the

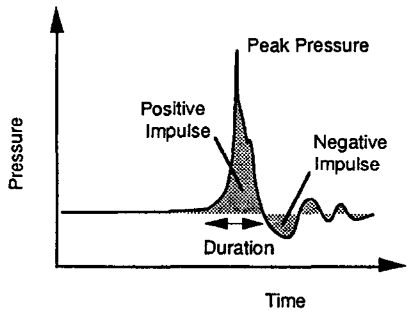


Fig. 105. Pressure–time curve.

structure, the negative phase can have significant contribution. The negative impulse can be about 1/3 of the positive impulse phase, but this ratio depends on the layout of the geometry where the explosion occurs.

The results from gas explosion analyses or experimental results are often reported as maximum pressure. The maximum pressure is a very important parameter, but rise time, impulse and duration can also be important. It should also be noted that accurate values for maximum pressure are not always easy to read from a record because of the often spiky nature of the pressure signal.

The high spikes that are observed both in experiments and FLACS-simulations may be of importance in estimating structural response. The topology of the pressure load (the distribution in time and space) may also be important. These areas are still under investigation. It is presently not clear what level of information is required to perform detailed analyses.

As explained above, smaller objects like piping which are inside an exploding gas cloud, will be subjected to drag force. In fluid dynamics drag force is often estimated from the formula:

$$F_{Drag} = C_D A \cdot 0.5 \rho u^2$$

C_D is the drag coefficient, A m^2 is the projected area of the object normal to the flow direction and $0.5 \rho u^2$ is the dynamic pressure. For objects large enough to be resolved by the simulation code used to predict the gas explosion, the pressure differential is calculated directly.

For non-stationary loads from gas explosions there are still uncertainties with regard to estimating drag load. The drag coefficient will probably be dependent on several factors such as turbulence level, time, pressure rise time etc.

CMR has lately performed some pilot tests with a 0.168 m diameter pipe in the exit of a wedge shaped vessel [74]. The explosion pressure and load are shown in Fig. 106.

As discussed in Section 8, an explosion will cause the blast wave to propagate away from the explosion area. We call this blast wave, which is outside the explosion area, the free field blast (see Fig. 89). When the wave hits a building or another object, the wave and the object will interact. One effect of this is that the shock wave (i.e. front of a strong blast wave) will be reflected, as shown in Fig. 107.

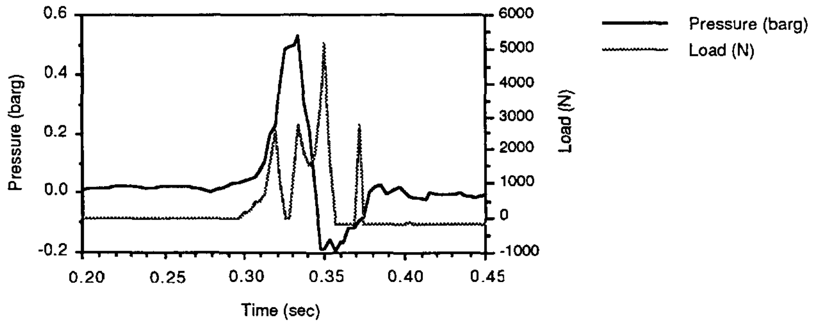


Fig. 106. Experimental results from test with loading of a pipe.

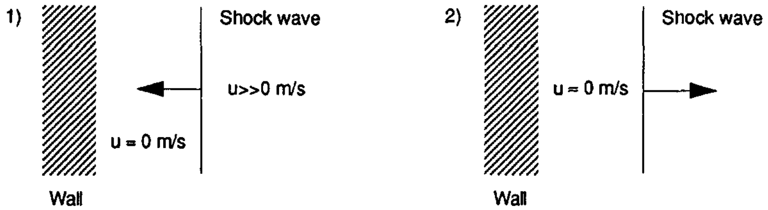


Fig. 107. Reflection of a shock wave when it hits a wall head-on.

When the shock wave hits the wall, the gas behind the shock wave has to come to a rest (i.e. $u = 0\,\mathrm{m\,s^{-1}}$) to satisfy the boundary conditions. The actual (reflected) pressure will then consist of the sum of the incident blast pressure and the dynamic pressure (i.e. $0.5\rho u^2$). For a shock wave with incident pressure of 1 barg, the reflected pressure will be approximately 2.7 bar g. For incident pressure of a few hundred millibars, the reflected pressure is approximately twice the incident pressure (in this paragraph pressure means overpressure).

If a small object is subjected to a free field blast with a shock front, the first phase of the loading will be caused by the reflected pressure. The duration of this phase is the time the shock wave takes to pass the object (i.e. object dimension/shock velocity). When the shock wave has passed the object, the object will feel the wind load (i.e. drag) from the blast wave (see Fig. 108).

Further details about shock reflection and drag from blast waves can be found in Ref. [25].

9.3. Damage level

The objective of this section is to list some available data on damage levels for typical process equipment. The data included here are general and should not be used as exact values, but as indications of damage level. A lot of the available data comes from military sources and are based on experience from blast waves for high explosives and nuclear explosions. To our knowledge there are limited data available on structure response to actual gas explosions. However, we expect that the future will bring more exact data. Data including both impulse and pressure are needed.

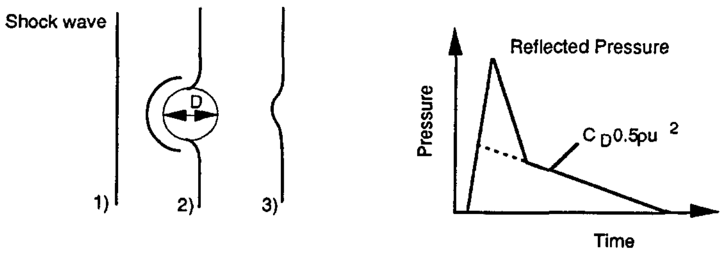
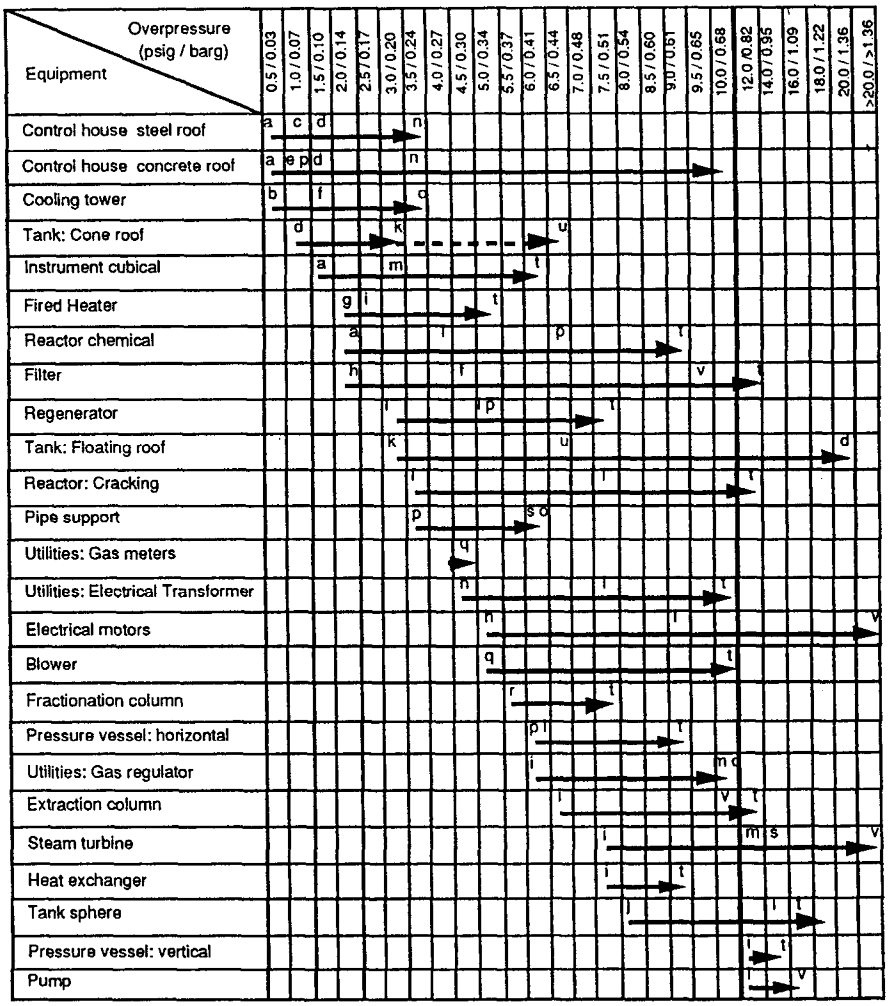


Fig. 108. Interaction of blast wave with a small object. Load–time history consists of a reflected phase and a drag phase [25].

Stephens [85] has presented damage level to vulnerable refinery parts. These data are given in Table 14. From this figure we see that the damage starts around 100 mbar g and the damage becomes very serious from 0.5–1.0 bar g.

Table 14

Blast overpressure effects on vulnerable refinery parts [85]. Code: (a) Windows and gauges break; (b) Louvers fall at 0.3–0.5 psi; (c) Switchgear is damaged from roof collapse; (d) Roof collapses; (e) Instruments are damaged; (f) Inner parts are damaged; (g) Brick cracks; (h) Debris-missile damage occurs; (i) Unit moves and pipes break; (j) Bracing fails; (k) Unit uplifts (half-filled); (l) Power lines are severed; (m) Controls are damaged; (n) Block walls fail; (o) Frame collapses; (p) Frame deforms; (q) Case is damaged; (r) Frame cracks; (s) Piping breaks; (t) Unit overturns or is destroyed; (u) Unit uplifts (0.9 filled); (v) Unit moves on foundation.



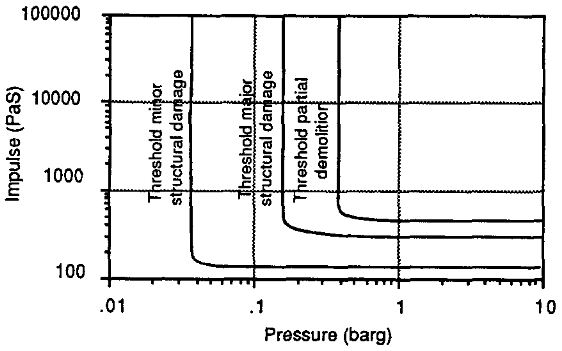


Fig. 109. Iso-damage curves [25].

9.4. Damage to buildings

Fig. 109 shows damage levels to brick buildings versus peak pressure and impulse of the blast wave from high explosives. These data were obtained from the London area at the end of World War II. Baker et al. [25] claim that this diagram also can be used for other homes, small office buildings and light frame industrial buildings.

An important aspect of damage to buildings is whether the integrity of buildings survives. Damage to a building in case of an accidental gas explosion is not a serious problem as long as the building is not collapsing or dangerous fragments are generated within or from the building. This is equally important for buildings subjected to blast loads from the outside as well as buildings with possibilities of internal explosions. Fig. 110 shows design of a building where an internal explosion will cause the building to collapse. Buildings made of pre-fabricated walls and roof will often collapse when subjected to explosion loads. As shown in Table 15 ordinary brick walls are also weak. In case of an internal explosion the brick wall will disintegrate and cause dangerous fragments.

Ordinary window glass will typically fail at 20–70 mbar g and cause dangerous flying fragments. As shown by Harris [26,125], glass fragments can fly more than 20 m when the breaking pressure is about 0.25 barg. The velocity of these fragments will be up to

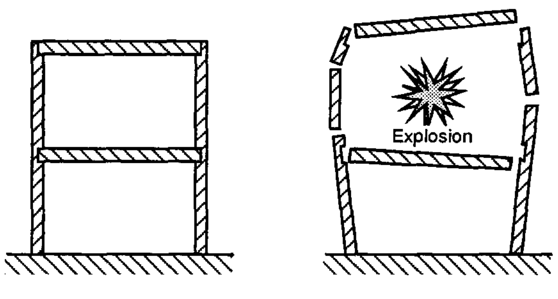


Fig. 110. Overpressures due to an internal explosion will cause the building to collapse [68].

Table 15
Typical failure pressures of some structural building elements under gas explosion conditions [26].

Structural element	Typical failure pressure (mbarg)
Glass windows	20–70
Room doors	20–30
Light partitionwalls	20–50
50nm thick breezeblock walls	40–50
Unrestrained brickwalls	70–150

30 or 40 $\mathrm{m\,s^{-1}}$ (approx. 100 $\mathrm{km\,h^{-1}}$). To use ordinary window glass in areas where there is an explosion hazard is not recommended. Use blast resistant glass [131] and make the windows as small as possible. The window frames must be as strong as the window itself. If ordinary windows are replaced by blast resistant windows, the frame also has to be changed. If the frame is weaker than the window, the window will fly out as one piece. Some design criteria for buildings can be found in Fig. 109.

Guidelines for building design:

· Buildings possibly subjected to external blast waves, should be made of reinforced concrete. The windows should be small and made of blast resistant glass with a strong frame. Air intakes should not be placed at ground level, to prevent combustible dense gas from entering into buildings.

· Buildings subjected to possible internal explosions should have a strong frame structure supporting roof and intermediate floors. The 'walls' should be open, if possible. If a solid wall is needed, use low weight wall panels to facilitate early explosion venting.

9.5. Domino effects

As a result of a violent gas explosion walls or decks may start to move or even break down and fragment. Pipes that are suspended on a moving wall may be sheared off (i.e. guillotine break) as a result of the relative movement of the points of suspension. Piping from one module to another module may have to respond to relative movements of the structure. Cables and control lines may also be damaged by this type of relative movement. Fig. 111 illustrates how deflection and movement caused by explosions may cause damage to piping.

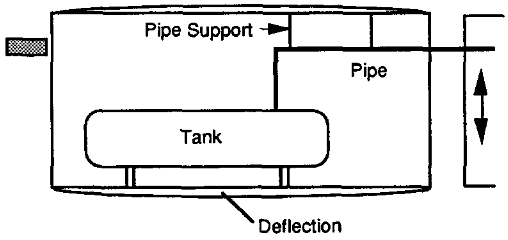


Fig. 111. Deformations or movements due to explosions may cause new releases and fire.

9.6. Effect on people

People can survive fairly strong blast waves. Lung damage data [25], show 1% survival for shock pressures of approximately 3.5 bar g and 99% survival for shock pressures of about 2 bar g for long duration blast. The threshold limit is about 0.7 bar g. Eardrum rupture data show 10% rupture for peak pressures of about 0.25 bar g.

In accidental gas explosions there are very few cases where the blast has killed people directly. The Sarnia incident [86], where two people were killed because of a detonating hydrogen–air cloud is one of these cases. When people are killed or injured in gas explosions the injuries are typically caused by:

- burning;
- fragments hitting the people;
- buildings or other structure falling down or being disintegrated;
- people falling or 'flying' and subsequently hitting a solid object.

Protecting people from injuries is therefore linked to designing structures. Structures should be designed to withstand loads without creating dangerous fragments or falling down.

10. Gas explosions in vessels, pipes, channels and tunnels

When we analyse an internal explosion, we will find that the gas cloud size is the main parameter determining pressure build-up. The geometrical conditions nearly always support flame acceleration and pressure build-up. So, if a large cloud is formed within equipment it is likely that there will be a severe explosion if it ignites.

An internal explosion may result in loss of containment. The subsequent event can then be strong blast waves from high pressure reservoirs, fires or toxic releases.

In the chemical and hydrocarbon process industries, we will find a large variety of cases where internal gas explosions may occur. Such explosions can be caused by uncontrolled leaks, or simply by accidental purging with air (and thereby formation of fuel–air mixtures). There is limited information available in the open literature about these aspects of gas explosions. It is beyond the scope of this chapter to present detailed methods for analysing gas explosions in such systems.

The objective of this chapter is:

- To present the basic physics of internal gas explosions.
- To point out which phenomena can occur during an internal gas explosion.
- To indicate worst case scenarios.

10.1. Closed vessels

A closed vessel often has very small openings, such as connected pipes, rupture disks or relief valves through which pressure can be relieved during a gas explosion. In this case, the relief process is often too slow to relieve the pressure fast enough, and the vessel may behave like a fully closed vessel with regard to pressure build-up. The pressure build-up will mainly depend on type and concentration of fuel, the initial pressure, the filling ratio in the vessel, the burning rate, the venting and the oxidiser.

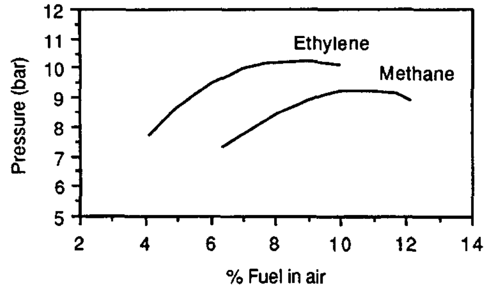


Fig. 112. Explosion pressure predicted by STANJAN for constant volume combustion of ethylene– and methane–air at 1 bar and 25°C [88].

In the first part of this discussion we will assume that the flame is a slow deflagration with a velocity of less than 20% of the initial speed of sound (i.e. in fuel–air at 1 atm. and 25°C less than $70\,m\,s^{-1}$), hence local high pressures due to high burning rate is neglected. For a slow deflagration in a homogeneous gas mixture, the pressure in the vessel will gradually increase as the flame consumes the gas mixture. As shown in Fig. 48 the maximum pressure will be reached when the combustion has been completed. For most hydrocarbon fuels, a Stoichiometric fuel–air cloud with initial pressure of 1 atm. will give 8–10 bar pressure (See Table 6), when burning under constant volume conditions. Fig. 112 shows the pressure for a constant volume combustion as function of percentage fuel in air for homogeneous methane– and ethylene–air mixtures. The highest pressure is found for slightly rich mixtures, i.e. slightly higher concentration than the Stoichiometric mixture which is 9.5% for methane and 6.54% for ethylene. When the fuel concentration approaches the flammability limits, the explosion pressure will be reduced, but even close to the flammability limits, the theoretical values for constant volume combustion will be in the 4–5 bar range. Even a cloud near the flammability limit can, in an explosion, cause significant pressure build-up in a closed vessel.

The initial pressure is a parameter which influences the explosion pressure at constant volume conditions. By increasing the initial pressure, the energy content, i.e. heat of combustion, per unit volume will increase. Bartknecht [87] has given some measurements of explosion pressure for slow deflagration for propane in a 7 litre spherical

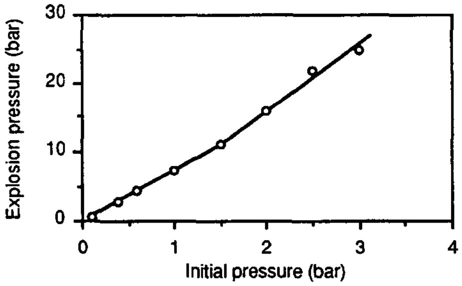


Fig. 113. Explosion pressure vs. initial pressure for Stoichiometric propane–air in a 7 l vessel [87].

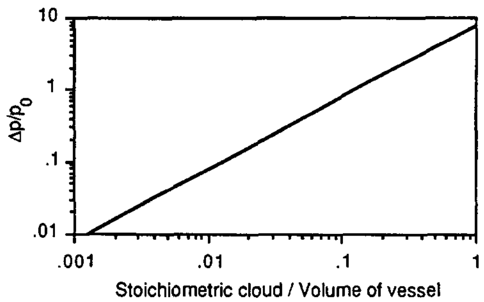


Fig. 114. Approximate values for pressure increase vs. filling ratio in a closed vessel.

vessel. These results are shown in Fig. 113. There is a nearly linear relation between initial pressure and explosion pressure. For Stoichiometric fuel–air the pressure increase at constant volume will be approximately 8 times the initial pressure. For other oxidisers than air, such as pure oxygen, oxygen enriched air or chlorine, higher constant volume explosion pressures can be expected. To estimate constant volume explosion pressure for specific fuel–air or fuel–oxidiser mixtures at given initial conditions, programs like STANJAN can again be used.

In many situations only a portion of the vessel will be filled with combustible gas. The explosion pressure for a partly filled vessel is shown in Fig. 114. Note that in this figure, it is assumed that the cloud has a Stoichiometric composition even though it occupies only part of the vessel. If about 15% of the closed vessel is filled with a Stoichiometric cloud and this cloud burns, the pressure in the vessel will be doubled. Even 1–2% filling ratio may cause problems for large vessels or tanks operating at atmospheric conditions. They are often very weak and may rupture at a few hundred mbar overpressure. This shows that even low filling ratio can cause significant increase of pressure in closed vessels. To avoid this problem, controlled venting is recommended as a mitigation device.

Lees [89] states that detonations occur in pipelines, but are very improbable in vessels. In an empty vessel there are no obstructions causing turbulence and flame acceleration. Transition to detonation is therefore not likely in vessels, unless the gas is very detonable (small cell size), the gas cloud is large, the cloud is jet ignited or the vessel contains obstacles.

10.2. Pipes

In addition to closed vessels, pipes (including channels and tunnels) are also typical simple geometries where internal explosions can occur. In pipes, the pressure generated by the flame has the possibility to propagate away from the combustion front. For long pipes or open ended pipes, a high flame speed is required to generate high explosion pressure. Fig. 47 shows the relation between flame speed and explosion pressure. The planar case is applicable for pipes. The main mechanism causing the flame to accelerate in pipes, is turbulence. When the gas burns, it expands and pushes unburnt gas ahead of

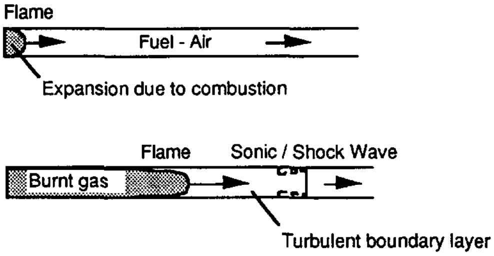


Fig. 115. Flame acceleration in a pipe, channel or tunnel.

the flame front. The flow ahead of the flame will cause a turbulent boundary layer to grow and the turbulence will enhance the burning rate. This is illustrated in Fig. 115.

Bartknecht [90] has measured flame velocities in a 1.4 m diameter pipe with methane–air at 1 atm. The pipe was 40 m long and the end was either closed or open. The results are shown in Fig. 116. The highest flame speed was observed when the gas was ignited in the closed end and the other end was open. In that case the gas ahead of the flame was pushed through the pipe and a lot of turbulence was generated. When the pipe was closed in both ends, the flame accelerated fast in the beginning, but after 15–20 m the flame started to decelerate, because the flow ahead of the flame is obstructed by the closed end. Since the pipe is closed in both ends, the pressure will increase like in a closed vessel. In the third case the ignition is at the open end and the other end is closed. Here, the flow velocity and the turbulence level ahead of the flame are very low and the flame propagates at low velocities through the pipe. These experiments show the importance of boundary conditions for the flame acceleration in a pipe. The boundary conditions in a pipe will be similar to ignition at the closed end of a pipe if the gas cloud is ignited in the centre of the cloud. In that case the flame will propagate in both directions and there will be zero flow velocity where the ignition took place (i.e. symmetry plane).

In a pipe the flame can continue to accelerate until it becomes a detonation (a supersonic combustion wave propagating at 1500–2000 m s^{-1} in fuel–air). As discussed in Section 7 we have only a qualitative understanding of the mechanism of transition

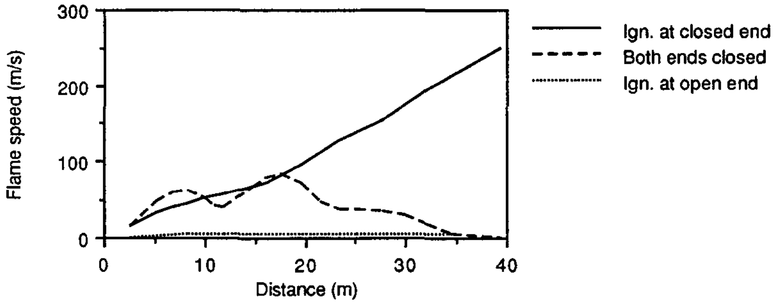


Fig. 116. Flame speed in a 1.4 m diameter pipe with methane–air [90].

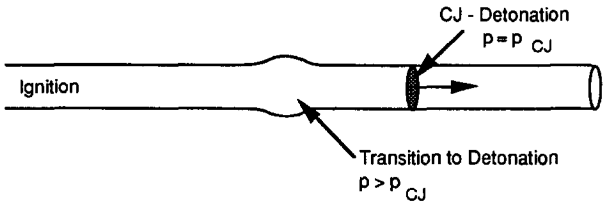


Fig. 117. A case history. Transition to detonation deformed the pipe.

from deflagration to detonation. We are therefore not capable of predicting this phenomenon. Experimental data is all that is available. The transition phenomenon is characterized by very high local pressures, pressures of 50 times the initial pressure have been measured when transition to detonation has occurred. In accidental situations, very strong damage can be observed at the location of transition to detonation. A case history from a gas explosion in a pipe is illustrated in Fig. 117. At one particular location the pipe was expanded radially. That was the place where the transition to detonation took place. When the detonation propagated further down it stabilised at a so-called CJ-condition, which gives lower pressure. In the case history, the pipe did not rupture. If the pipe had ruptured, a high pressure reservoir would have been released. This shows that transition to detonation in pipes, channels and tunnels is a hazardous phenomenon which should be recognised as being possible.

The run-up distance, i.e. the distance from ignition to transition to detonation in pipes is an experimental value giving some indication of the likelihood of transition to detonation. Steen and Schampel [91] have reviewed experimental investigations of the run-up distance of gaseous detonations in large pipes. The experimental conditions, i.e. pressure, temperature and gas mixture, are limited compared with the actual conditions in the industry. The data presented by Steen and Schampel are mainly for 1 atm. and fuel–air mixtures. Fig. 118 shows the run-up distance for Stoichiometric ethylene– and propane–air vs. pipe diameter. The run-up distance increases with increasing pipe diameter. The turbulent boundary-layer ahead of the flame is filling a relatively larger portion of the tube in small pipes than in large pipes. The fuel concentration is also an important factor for the run-up distance. This can be seen in Fig. 119.

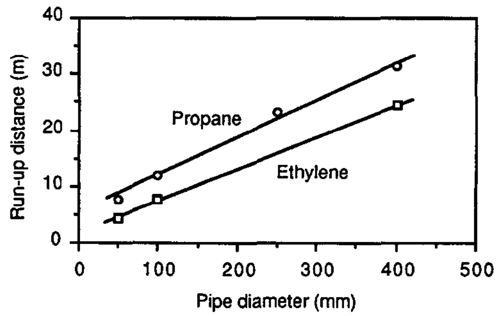


Fig. 118. Run-up distance to detonation vs. pipe diameter [91].

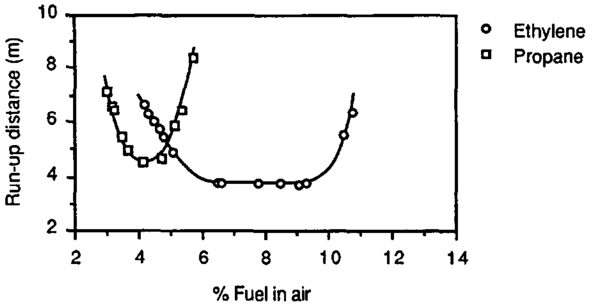


Fig. 119. Run-up distance for ethylene– and propane–air. Pipe diameter 50 mm [91].

Several other factors also influence the run-up distance. Experiments show that it decreases with:

(i) increasing initial pressure;

(ii) decreasing initial temperature; and

(iii) increasing turbulence in the pipe (i.e. obstructions in the pipe) [130].

In general we can say that the run-up distance depends on the reactivity and cell size. The smaller the cell size, and the more reactive the mixture (burning velocity), the shorter is the run-up distance.

10.3. Pressure piling

In a process unit or an underground system, we will find that large volumes (i.e. tanks, unit operations and rooms) are interconnected by pipes and channels. In case of an internal explosion, these interconnections can cause very strong pressure build-up. This phenomenon is often referred to as precompression or pressure piling. Pressure piling is a local dynamic effect which can cause high local explosion pressures.

Fig. 120 illustrates such a situation. Volumes 1 and 2 are interconnected by a pipe. Heinrich [92] performed some laboratory tests with the geometry shown in Fig. 120. The volume of the tanks was 12 l and the pipe was 50 cm long. When the cloud is ignited in Volume 1, the pressure will gradually increase and some unburnt gas from Volume 1 will flow into Volume 2. When the flame enters Volume 2, the gas is pre-compressed. The flame will now be a jet flame shooting into Volume 2. As discussed in Section 6.9 such jet flames will cause fast pressure build-up. If the pressure relief back into Volume 1 through the pipeline is not sufficient, the pressure in Volume 2 will become much higher than in Volume 1, because of the pressure piling and the jet flame. In this experiment the maximum pressure was 30% higher than that predicted from the constant volume conditions.

10.4. Guidelines

- Avoid combustible mixtures that can cause internal explosions. It is bad practice to rely solely on elimination of sources of ignition.

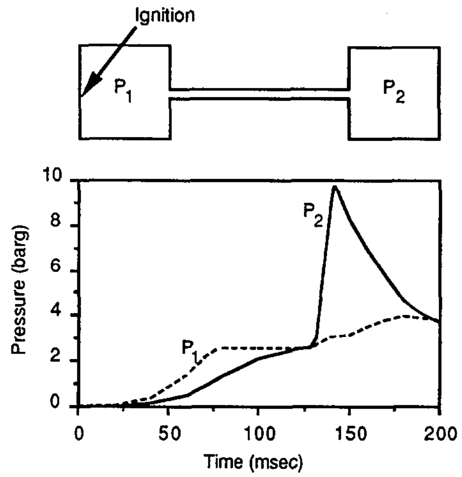


Fig. 120. Experiments with pressure piling [92].

- To calculate constant volume conditions and detonation pressure, tools like STANJAN can be used.
- For reactive mixtures take the possibility of transition to detonation into account.
- Do not design atmospheric vessels too strong. If they rupture, they should rupture at low pressure, not at several bars.
- Design vessels with relief valves and/or rupture disks.

11. Gas explosions in compartments, buildings and offshore modules

If fuel is accidentally released inside a partly confined area or if combustible gas is drifting into such an area, serious explosions may occur. The consequences of such explosions will depend on several parameters, such as type of fuel, size and concentration of the gas cloud, ignition and geometrical layout, i.e. confinement and obstructing objects. In consequence analyses all these factors have to be taken into account. Variations of these parameters may result in large changes in peak explosion pressure.

As discussed in Section 6, confinement and obstructing objects are key factors for the development of high explosion pressures in accidents. In buildings, offshore modules and partly confined areas containing process equipment, there will be confinement and obstacles. Walls, roofs, floors and decks will confine the gas cloud. The process equipment and piping engulfed by the cloud will act as obstructing objects during an explosion. By following simple guidelines while designing or modifying compartments, one can reduce the hazard potential significantly.

In this chapter we will mainly focus on simple guidelines for improving gas explosion safety and discuss methods for predicting gas explosions in compartments. The objectives of this chapter are to:

- Describe how a gas explosion behaves in a compartment and explain which factors are important for the pressure build-up.

- Present and discuss simple guidelines and possible methods for mitigating gas explosions in compartments.
- Discuss why it is difficult to predict the consequences of gas explosions.
- Present a review of FLACS results as a database for evaluation of expected explosion pressure in compartments.

11.1. Gas explosions and venting

The objective of this section is to illustrate how geometrical

· 989conditions such as confinement, obstacles and venting influence explosion pressure in accidental explosions.

Gas explosions are a result of liberation of chemical energy due to flame propagation (i.e. combustion) through premixed fuel–air clouds. As discussed in Section 6 and Section 7, in a premixed cloud the flame can propagate in two distinct modes; the deflagration and the detonation. The flame speeds of deflagrations range from a few $m\,s^{-1}$ up to 500–1000 $m\,s^{-1}$, resulting in overpressures from close to zero up to several bar (see Fig. 47). The detonation is a supersonic combustion wave causing explosion pressure in the 20 bar range. When discussing gas explosions and flame propagation in this chapter we refer to the deflagrative mode of flame propagation if nothing else is stated.

The pressure build-up during a gas explosion is governed by the balance between pressure generation by the flame, and relief of the pressure through venting. In an unconfined situation or in a compartment with large explosion vent areas, a flame speed in excess of 100 $m\,s^{-1}$ is required in order to obtain damaging pressure waves (see Fig. 47). However, if a fuel–air cloud explodes within a compartment with no or very little venting, even slow burning can cause pressure build-up. In extreme cases, a slow flame can in a closed compartment cause pressures up to 8 bar, if the compartment does not disintegrate.

In an accidental gas explosion the flame will normally start out as a slow laminar flame with a velocity of the order of a few $m\,s^{-1}$. If the cloud is truly unconfined and unobstructed (i.e. no equipment or other structures are engulfed by the cloud) the flame is not likely to accelerate to velocities of more than 20–25 $m\,s^{-1}$, and the overpressure will be negligible.

In a partly confined area with obstacles as shown in Fig. 121, the flame may accelerate to several hundred meters per second. The main mechanism of flame acceleration under such conditions is turbulent mixing caused by the generation of turbulent flow fields ahead of the flame.

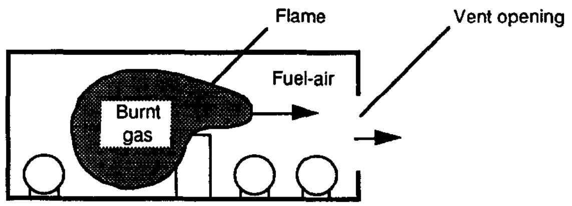


Fig. 121. Gas explosion in a partly confined area containing process equipment.

Fig. 121 shows a compartment filled with a premixed combustible fuel–air cloud. The cloud is ignited in the centre of the compartment. When the flame consumes the fuel–air cloud, the gas expands. This expansion can be up to 8–9 times the initial volume. As a result of expansion, unburnt gas is pushed ahead of the flame, and a flow is generated in the compartment. Some of the unburnt gas will in the early phase of the explosion be pushed outside the compartment through the vent openings (i.e. open parts of the compartment). Inside the compartment the gas has to flow through and around process equipment, piping etc. The process equipment and piping will obstruct the flow and generate turbulence ahead of the flame.

In Fig. 121 the explosion starts in the centre of a compartment. Since the vent area is located only on the right hand side of the compartment, the dominant direction of the flow and flame propagation will be towards the vent area. The flow in this area will be turbulent because of the obstructing effect of process equipment etc. and this turbulence will support the flame acceleration. The location of the ignition point relative to the vent opening is a key factor for how the flow field or turbulent flame acceleration develops during a gas explosion.

A consequence of the above statement is that the ignition point location relative to the location of the vent opening is also very important for the effectiveness of the venting. When the flame front reaches the vent opening, combustion products will start to flow out from the vent opening. Since the hot combustion products have a much higher sound speed (approx. $900\,\mathrm{m\,s^{-1}}$) than the unburnt fuel–air mixture (approx. $340\,\mathrm{m\,s^{-1}}$), the flow velocity through the vent will increase when the hot combustion products start to vent. In experiments and FLACS simulations we have often seen that the pressure starts to drop immediately after the combustion products have reached a major vent area. In addition to the enhanced venting, the venting of hot combustion products may also influence turbulence generation and flame acceleration. If hot combustion products are vented out of a compartment, the flow and the turbulence can be reduced since the driving pressure is relieved and less gas is pushed ahead of the flame. Venting of combustion products as a way of minimising the positive feedback mechanism that causes flame acceleration is illustrated in Fig. 49 and Fig. 51. However, in some cases we will find that pressure will continue to rise even if the combustion products are vented. This is typical for compartments with small vent areas, high density of process equipment, piping etc., or when the gas explosion reach high pressures before the combustion products start to vent. For very high-speed deflagrations venting may not be effective at all.

Many studies have aimed at identifying the necessary vent area to relieve overpressures for a confined volume. Unfortunately there is a wide spread between simple model predictions and experimental results. Harrison and Eyre [93] claim that the models do not properly take account of:

(i) turbulence inside the enclosure;
(ii) acoustic resonance inside the enclosure;
(iii) combustion of gas outside the enclosure.

In Fig. 122 a comparison is shown between the maximum overpressure from CMR experiments [36] and the commonly used Bradley and Mitcheson safe recommended vent area [94]. The CMR experiments were performed in a $50\,\mathrm{m^3}$ vessel (a tube 2.5 m in

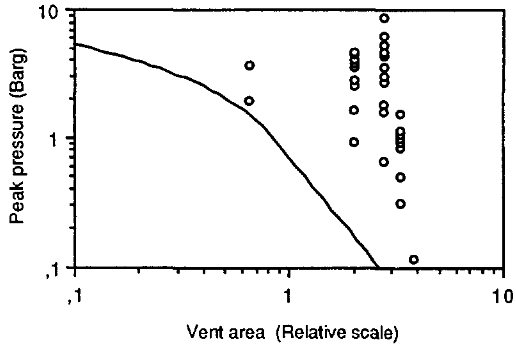


Fig. 122. Maximum overpressure observed in a 50 m^3 tube [36] compared with the upper pressure bound (solid curve) based on vent areas for central ignition in near-spherical vessels as proposed by [94].

diameter and 10 m long, open at one end) with regularly spaced obstacles in the form of orifice plates. The gas mixture was methane–air. The variation in the experimental results for a constant vent area corresponds to different internal geometries in the tube. More details from these experiments can be found in Section 6.3. The experimental results show that simple models are inadequate for such conditions. This has further been confirmed in the review report by British Gas for the Department of Energy (1990) Review of the Applicability of Predictive Methods to Gas Explosions in Offshore Modules [71].

A gas explosion in a compartment is a very complex process strongly depending on several parameters. In the following sections we will discuss these parameters separately.

11.2. Shape of compartment

The objective of this section is to discuss the influence of the shape of the compartment on flame acceleration and pressure build-up, and to point out what is the optimum compartment shape to keep the explosion pressure as low as possible. The shape of the compartment and location of vent areas are closely linked and will therefore depend on each other.

There are mainly three principles to apply when optimising the shape of a compartment.

(i) From the ignition point the flame should be able to propagate in a spherical mode for as long as possible (see Fig. 47).

(ii) An ignition point anywhere in the compartment should be as close as possible to the major vent areas, so hot combustion products can be vented out in an early phase of the explosion.

(iii) Avoid strong turbulence in the unburnt gas ahead of the flame and long flame travel distances.

For a compartment with explosion venting on two end walls the ideal shape is a cubical box. In such a configuration a relatively low explosion pressure can be expected (Fig. 123).

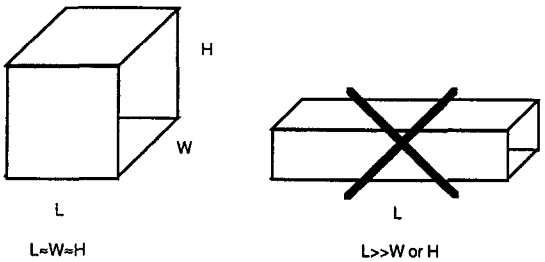


Fig. 123. For a given volume a cubical compartment gives the best explosion venting in the case of vent areas on the two end walls.

If the module is elongated and vent openings are only located on the two ends most explosion scenarios will give high pressures. The situation in an elongated module is in principle the same as the channel in Fig. 49. The flame can travel over a long distance and the conditions, i.e. limited venting, will support the flame acceleration. The flame will propagate in a planar propagation mode (one-dimensional propagation) in the main part of the module.

For the cubical module the flame will propagate in a spherical mode. A spherical propagation mode requires higher flame velocity than a planar mode to generate the same explosion pressure. The pressure wave can expand more 'freely' in the spherical mode (three-dimensional propagation). (See Fig. 60).

If the compartment has a vent opening only in one of the side-walls, it is even more important to avoid an elongated shape. In case of ignition at a closed end wall, the flame can accelerate over a long distance and venting has no beneficial effect since it only leads to flow past obstacles and thereby turbulence generation.

We have seen in our work that the height of the compartment is often important, as illustrated in Fig. 124. By increasing the height of the module the explosion pressure can in some cases be reduced. However, the advantage of increasing the height of a compartment or the smallest side of the compartment, depends also on how densely packed the compartment is with obstructing objects (i.e., process equipment and piping). In compartments with a lot of obstructing objects, there may be little or no advantage in increasing the height. In such situations, the obstructing objects are controlling the flame propagation and the shape of the compartment is less important.

In compartments with low density of obstructing objects it may be beneficial to replace solid decks with grated decks and thereby create a more cubical shape of

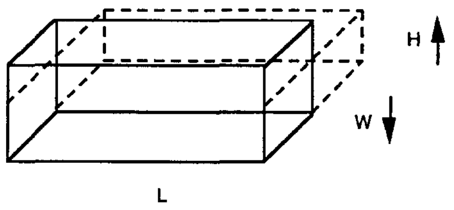


Fig. 124. The height of the module can be important.

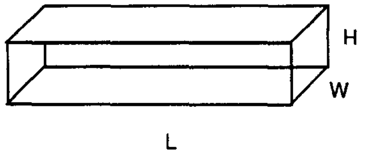


Fig. 125. Elongated module with explosion venting on three sides.

confinement. Such an action should be viewed in relation to gas dispersion and fire hazards.

For an elongated compartment it is necessary to open up at least one of the long sides for venting if we want to have venting close to a randomly chosen ignition point. In a building the possibility may exist of venting through the roof. In discussing flame acceleration in Section 6, it was pointed out that ignition close to a vent area will cause venting of hot combustion products in the early phase of an explosion. This is an effective way of minimising flame acceleration and high explosion pressures. This effect can be utilised by venting through three walls of the module as shown in Fig. 125.

In some FLACS simulations and experiments we observed a factor of 10 reduction in explosion pressure by opening one of the long side walls in a module. The roof, deck or a side wall should be considered as possible venting areas.

Unfortunately we have also seen examples of flames that have been able to accelerate and cause high explosion pressures even with venting on three sides. These are cases where the compartment is large and contains many obstructing objects. One way of mitigating the consequences of gas explosions in such cases may be to introduce a solid blast wall in the central part of the compartment as shown in Fig. 126.

The solid wall will prohibit a strong turbulent flow ahead of the flame and guide the flow out of the compartment. The length of flame travel will be reduced. The disadvantage of introducing a solid wall is the reduced natural ventilation. Build-up of large homogeneous gas clouds is therefore more likely with a solid wall. This concept will be investigated further.

11.3. Types of vent areas

With vent openings we mean areas where gas can be relieved from the compartment during a gas explosion (pressure relief). The important factors for effective venting are:

(i) Size of the vent area.

(ii) How the vent area is distributed.

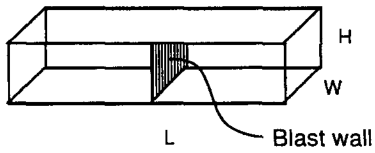


Fig. 126. Elongated module with venting on three sides and a solid wall in the central part of the compartment.

(iii) Direction of explosion relief.

(iv) For explosion relief panels: how quickly are they activated?

It is very simple to make guidelines for the size of the vent area. The vent area should simply be as large as possible.

In Section 6.4 and Fig. 57 some experimental results from CMR's 10 m long wedge-shaped vessel are presented. For distributed venting in the top plate (i.e. along the long side-wall) the explosion pressure was low when the top plate was 50% and 80% open. However, the explosion pressure increased from a few mbar to more than 1 bar when the same vent area was located in the far end of the vessel with respect to the ignition point. The consequences of a gas explosion are strongly linked to both the size and the distribution of the vent area. Since we normally do not know where the ignition point is located, the general recommendation for locating vent areas is to distribute the vent areas around the side-walls of the compartment. It is important that vent areas guide the flow ahead of the flame away from obstacles!

As a general principle, the gas explosion venting should be directed into open areas with a minimum of obstructions. If one is venting into another compartment or a congested area, combustible gas clouds may be pushed into this area and a violent multi-compartment explosion may occur. This can be investigated by using the FLACS code.

In many situations it is not practical to have open walls. Weather conditions, noise reduction and fire protection may require closed walls or partly closed walls. If these initially closed walls shall act as vent openings during an explosion, they must be lightweight and designed to open quickly.

Fig. 127 shows the displacement versus distance for wall elements from 10 kg m^{-2} to 300 kg m^{-2} when subjected to a triangular pressure pulse with a duration of 100 ms and a peak pressure of 1 bar g.

The 100 kg m^{-2} and the 300 kg m^{-2} walls will move very short distances within the duration of the pressure pulse. Walls in this weight range will not act effectively as vent panels. They start to move after the explosion and their only contribution will be to act as dangerous projectiles. The 10 kg m^{-2} panel is moving away fairly quickly. Panels of this weight or lighter, will normally be effective vent panels if the opening mechanism is carefully constructed. Our experience is that panels of 30–50 kg m^{-2} are too heavy to

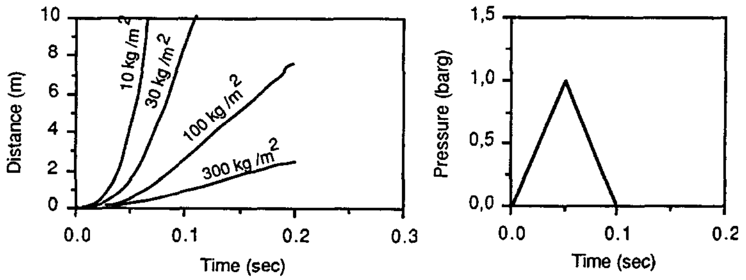


Fig. 127. Displacement distance for wall elements subjected to a triangular pulse of 1 bar g peak pressure and 100 ms duration.

have a significant effect on peak pressure. But, some reduction in the duration of the explosion pressure may be expected. The vent areas that are initially closed should not be heavier than $10\,kg\,m^{-2}$, preferably lighter to be effective.

In the last part of this section, we will discuss the different types of explosion vents commonly used. They can be listed as follows:

(i) open walls;

(ii) louvered walls;

(iii) solid wall/cladding;

(iv) relief walls (also called wind walls or weather cladding) opening during an explosion;

(v) glass windows (not recommended).

The open wall is normally the best solution from an explosion point of view. If a large part of the module is open, the natural ventilation will be good and explosive cloud formation will be less likely. If an explosion should occur, the open wall will relieve the explosion pressure as well as is possible. However, because of the weather conditions, fire protection and noise reduction requirements, fully open walls are often impractical or unacceptable.

A louver wall will also act as a vent area, but the effective vent area will be about half that of the open wall. Louver walls for offshore applications weigh typically $40–50\,kg\,m^{-2}$. Even though these walls may be designed to open up during an explosion, i.e. break loose at low static overpressure, they will normally not open up fast enough to improve venting. Bjørkhaug [28] tested experimentally the behaviour of louver panels. FLACS simulations of explosions in offshore modules of approximately $10\,000\,m^3$ with louvers on three sides indicate that the opening of the louver wall does not reduce the peak pressure, but may reduce the duration of the positive pressure phase.

A relief wall, also called wind wall or weather cladding, is an alternative combining the requirements for acceptable working environment and gas explosion safety. A relief wall is mainly a frame with a thin metal plate covering the frame. If an explosion should occur, the metal plate will break loose on the rim and collapse. The principle of a relief wall is shown in Fig. 128. This panel opens at 50 mbar overpressure and is fully open after about 40 ms.

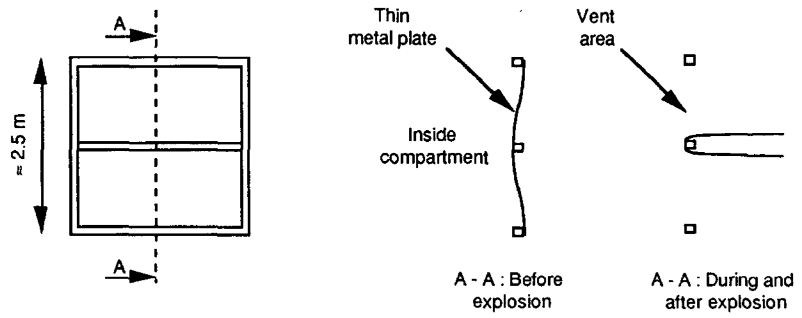


Fig. 128. Relief panel type Stord Industrier AS.

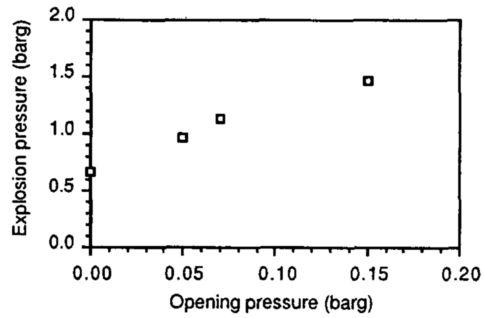


Fig. 129. Explosion pressure vs. opening pressure of relief walls from FLACS simulations. (Note: Different results will be obtained with different geometries).

Critical parameters for selecting relief walls should be:

- acceptable natural ventilation must be ensured;
- the opening mechanism must allow for fast release;
- the weight of the panel ($kg\,m^{-2}$) must be low;
- dangerous fragments (projectiles) should be avoided.

The use of relief walls (wind walls) should be limited so that acceptable natural ventilation is obtained under normal operation. Without natural ventilation even a small gas leak can build up a hazardous gas cloud (unless sufficient forced ventilation is available).

A relief wall should open as early as possible during an explosion, but not open because of wind. Our experience is that the design of the opening mechanism is not straightforward. Experimental testing with dynamic loads (i.e. explosion testing) appears to be required. Static testing of the opening mechanism may not produce relevant information. A panel that has a static opening pressure of 50 mbar, may not open before the pressure reaches 100–200 mbar if the load is a dynamic load from a gas explosion.

Fig. 129 shows some results from FLACS simulations in an offshore module with relief walls on three sides. The simulations were performed with different opening pressures of the relief walls. In this geometry the explosion pressure increases with a factor of two when the relief wall opening pressure goes from 0 (i.e. open wall) to 150 mbar.

The weight of the panel ($kg\,m^{-2}$) will indicate how fast the panel will move after it has started to open. One should select relief walls with low panel weight. Relief walls with a weight of 5–10 $kg\,m^{-2}$ are commercially available today.

When the panels are blown open by an explosion they should be designed so that no dangerous fragments are generated. Flying fragments or even the flame jet can cause damage to piping or equipment and also hurt personnel.

The FLACS code is capable of handling explosion relief walls with different opening pressures and weights. In addition to that FLACS can discriminate between hinged panels and 'pop-out' panels.

In existing facilities, such as old process plants, buildings etc. we may find large window areas that were intended for, or will act as vent areas during an explosion.

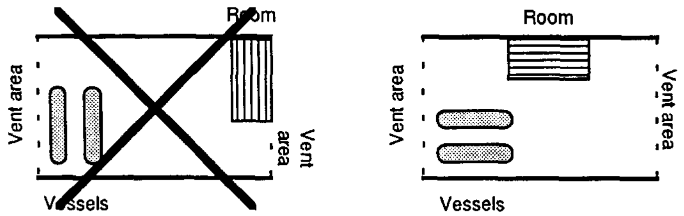


Fig. 130. Top view of two compartments. In the layout on the left side the room blocking the vent area and the vessels are generating turbulence by acting as repeated obstacles. The right side show an improved layout.

Ordinary glass windows will break when exposed to explosion pressures of 20–70 mbar [26,125]. But the dangerous fragments generated when glass windows break, is a very serious problem. Accidents, such as in Flixborough in 1974 and in Pernis in 1968 show that fragments from windows can cause both serious injuries and a large number of injuries [89]. It is not recommended to have ordinary glass windows in areas where gas explosions can occur. Therefore apply the information given above to determine how to replace windows intended for explosion relief with more proper relief walls.

11.4. The effect of congestion and obstructions

A compartment will contain process equipment, pipework, rooms etc. During a gas explosion these objects will obstruct the flow and thereby cause turbulence. These objects will also interfere with the explosion venting. As discussed in Section 6, turbulence and venting are very important for the flame acceleration and pressure build-up in gas explosions. In this section we will discuss how to arrange obstructing objects in order to keep the explosion pressure at a minimum. The main principle is to arrange the obstructing objects so that:

(i) minimum turbulence is generated;

(ii) explosion venting is not blocked.

Fig. 130 shows the top view of two different layout arrangements in a compartment. The compartment has venting on the two end walls. The obstructing objects consist of two vessels and a room.

In the first layout, the room will block the main parts of the vent area on the right hand side and the vessels in the left part of the compartment will cause reduced venting and flame acceleration, respectively. In Section 6 the effect of repeated obstacles is discussed. The vessels arranged on the left side in Fig. 130 will act as repeated obstacles for a centrally ignited explosion. In an explosion turbulence will be generated in the wake of the obstacles, as shown in Fig. 49. In the turbulent wake the flame will burn very fast and the positive feedback mechanism for flame acceleration will be activated. The result may be high explosion pressure.

The flame acceleration caused by turbulence depends on the arrangement of the equipment and on the turbulence level in the flow field. It is very important to arrange the equipment in such a way that a minimum of turbulence is generated during an explosion. This is normally obtained when the longest side/dimension of the equipment

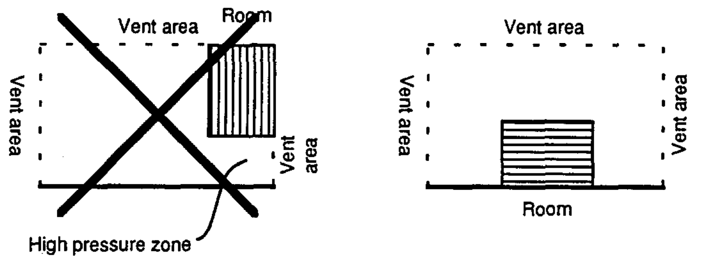


Fig. 131. Top view of two compartment layouts. In the layout on the left side the room blocks the vent area.

is parallel with the flow direction during an explosion, i.e. pointing in the direction of the vent area. In Fig. 130, the right side shows the vessels pointing in the direction of the vent area. This is a better arrangement than the layout on the left hand side.

Layout of different types of equipment should not be viewed in isolation. We may find situations where relocating major equipment will add to piping, hence pressure may rise to a higher level with the new equipment layout, even though the situation for the major equipment appears to be improved. It is important to avoid sub-optimisation.

In Fig. 130 the room blocks the vent area on the right side. In this case, a much better solution would be to rotate the room 90° and if possible move it to the central part of the compartment. The vent area on the right hand side will then become more effective.

Even in a compartment with venting on three sides, the location of rooms can be very important. Fig. 131 shows a bad and a good example of how to arrange a room in a compartment. In the bad example the solid wall and the room will form a compartment. In FLACS simulations of similar geometries we have seen high pressures predicted in the area confined by the solid wall and the room. The passage between the room and the solid wall will act as a funnel, the flow is forced through this passage and high pressure is generated.

The layout to the right in Fig. 131 is a much better solution. In this case ignition anywhere in the compartment will be fairly close to the vent areas and confinement is at a minimum.

Venting can also be hindered when obstructions are placed outside the protected room. An example is obstructions placed on a laydown area in front of a vent opening. Hence the presence of a laydown area in front of a vent opening should be avoided. Intermodular gaps should be as wide as possible (see also Section 6.8).

11.5. Ignition

Both the strength and the location of the ignition source can be important factors for the consequences of the gas explosion.

In Section 6.9 it was shown that jet flame ignition of the cloud could cause very strong explosions even for unconfined situations. If a cloud is ignited by detonating a high explosive charge within the cloud a detonation could be initiated directly.

Even though extreme ignition scenarios exist, the most likely scenario is a weak

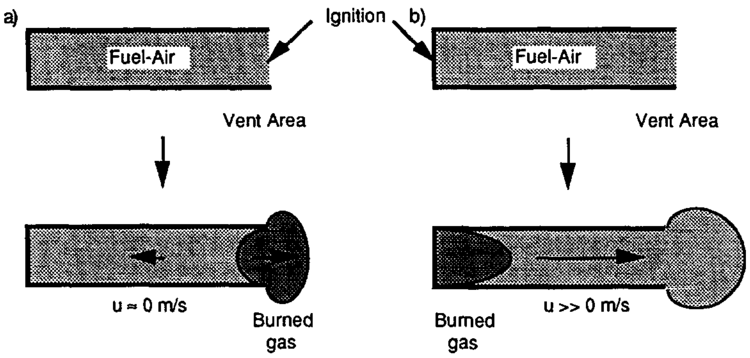


Fig. 132. Differently located ignition points in a compartment. In case a) the flow velocity ahead of the flame will be low, and low explosion pressure can be expected. Case b) is a "worst case" scenario since the flow ahead of the flame will be turbulent and therefore cause rapid burning and high pressure.

ignition source like a hot surface or a spark. In consequence analyses it is common to assume a weak ignition source.

Various experiments and FLACS simulations have shown that explosion pressures can be very sensitive to the location of the ignition point. In many scenarios the peak explosion pressure can be changed by an order of magnitude if the ignition is moved from a worst case location to a more favourable place. In general the lowest pressure is obtained if the ignition point is:

(i) close to the vent area or;

(ii) at the edge of the cloud

but as we will come back to in the end of this section, there are exceptions to this.

Fig. 49 and Fig. 52 show how repeated obstacles generate turbulence, while venting of combustion products reduces the turbulence generation. By igniting near the vent opening the combustion products will be vented and the flow velocity and the turbulence in the unburnt mixture will be low. Fig. 132 shows how different flow regimes will be generated in the same geometry with different ignition locations. In case (a) the flow velocity ahead of the flame will be low if the compartment is not too long. In case (b) a high flow velocity will be generated ahead of the flame which will support a high burning rate and cause high explosion pressure. For simplicity obstacles have been omitted from the figure.

However, if the venting of combustion products is not sufficient to keep the flame speed at a low level, ignition at the edge may cause higher explosion pressures than central ignition. Fig. 133 shows an example of this. In this case the length of flame travel is a more important factor than the venting of the combustion products. By increasing the length of flame travel, the flame will have the possibility to accelerate over a longer distance, by passing a greater number of obstacles. This effect will be most pronounced for reactive fuels, high density of obstructions, small vent areas and large scale.

The practical implication of this is that one should try to locate potential ignition sources away from worst-case locations.

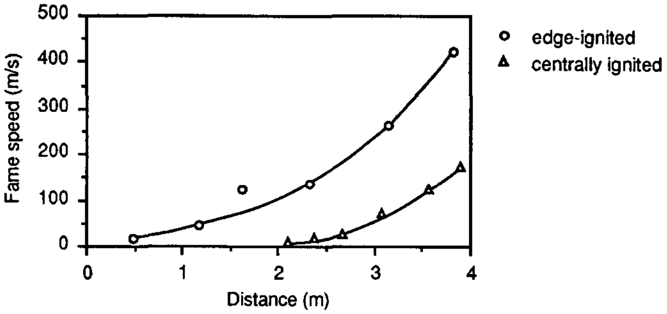


Fig. 133. Flame speed vs. distance for centrally and edge ignited explosions in a double configuration (i.e. solid top plate) with obstacles [73].

11.6. Gas cloud

In an accidental situation the combustible gas cloud in an obstructed and/or partly confined area may only fill a part of the volume at the time of ignition. The filling ratio is, of course, an important parameter. But in some situations 30–50% filling ratio may cause the same explosion pressure as a 100% filled compartment. The reason for this is that during an explosion the gas that burns will expand and push the unburnt gas ahead of the flame. Thereby air or fuel–air is pushed out of the compartment. As discussed in Section 5.9 the expansion of the combustible cloud on burning can be up to 8 or 9 times the initial volume. Fig. 134 illustrates how a small cloud upon burning is pushing out air from a compartment and thereby fills the whole compartment with a combustible cloud.

Pappas [70] made some simple calculations on the effect of having only a part of the compartment filled with a gas cloud. He is assuming that the ignition point and the gas cloud are far from the vent opening. His results are shown in Fig. 135. The explosion pressure starts to drop at about 30% filling ratio.

An explosion in a partly filled compartment can in some instances cause the same explosion pressure as in a 100% filled compartment. It should be added that when the cloud is only filling a portion of the enclosure, the ignition point location will be a much more sensitive parameter. If the ignition occurs at the edge of the cloud and/or close to

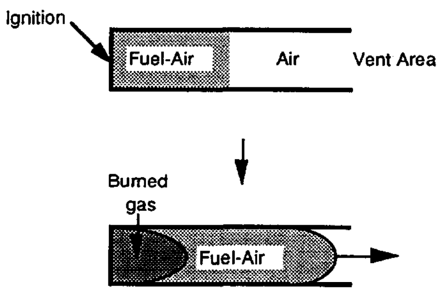


Fig. 134. During an explosion of a small cloud air can be pushed out through the vent area and thereby the whole volume can be filled with a combustible cloud.

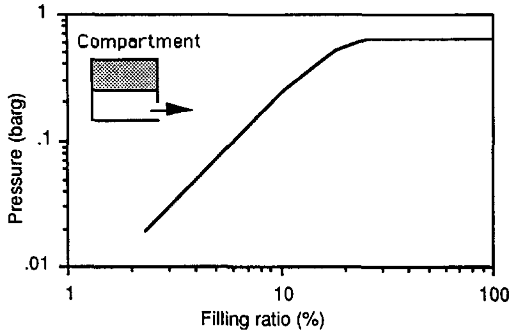


Fig. 135. Pressure reduction in a partly confined compartment as function of gas filling ratio. Gas cloud and ignition away from the vent opening [70].

the vent area we can expect lower pressure for the partly filled, than for the 100% filled case.

11.7. Deflagration to detonation transition

As discussed in Section 6 and Section 7, there are two distinct modes of flame propagation in premixed gas clouds, namely deflagrations and detonations.

A deflagration is a sub-sonic combustion wave with respect to the unburnt gas ahead of the flame, and is a common mode of flame propagation in an accidental gas explosion. The deflagration pressure goes from zero to several bars depending on confinement and flame speed. A detonation is a supersonic combustion wave propagating at 1500–2000 $m\,s^{-1}$ in fuel–air and the pressure is 15–20 bar. In an accidental explosion the ignition is normally a weak ignition source, e.g. a hot surface or a spark. In this situation the explosion will start out as a slow burning deflagration. As a result of obstructing objects and confinement, the deflagration can accelerate and become a fast burning deflagration. When a deflagration becomes sufficiently rapid, a sudden transition from deflagration to detonation can occur. Presently there is no theory which can predict transition from deflagration to detonation. There are therefore great uncertainties related to the transition process and in practical situations it can be hard to evaluate the possibility of deflagration to detonation transition.

However, it is very important to know if transition to detonation can occur. If it occurs, very high pressure loads, in the order of 50 bar, can be reached locally and severe damage can be expected within the compartment. If a detonation has been established in the compartment it may also propagate into the unconfined cloud outside. The existing criteria for propagation and transmission of detonations are described in Section 7.4.

A deflagration propagating into a large truly unconfined and unobstructed cloud will slow down and the pressure generation will normally be negligible. A detonation, however, will propagate through the entire cloud at a high velocity and cause severe blast waves.

The possibilities of transition to detonation will mainly depend on (i) type of fuel, (ii) size of cloud and (iii) geometrical conditions, such as obstructing objects and confinement.

As shown in Fig. 69 the flame acceleration will depend strongly on the type of fuel. Fuels like hydrogen, acetylene, ethylene–oxide and ethylene, are the most likely fuels to detonate. There are several examples of accidental explosions where hydrogen has detonated.

Fuels like propane and butane may also detonate, but a strong deflagration is required to initiate the detonation.

In methane it is difficult to initiate detonations. It is still uncertain whether it is possible to get a detonation in an accidental explosion with methane. Full scale tests in large volumes, like an offshore module, would be required to test this out.

For natural gas which mainly contains methane and various amounts of higher hydrocarbons, the content of higher hydrocarbons is important. Bull [64] has shown that even small quantities of higher hydrocarbons increase the sensitivity and thereby the likelihood for transition to detonation considerably.

In a practical situation, presently the most effective way of mitigating the occurrence of detonations is to avoid situations where a deflagration can accelerate to a condition where transition from deflagration is possible, i.e. a high pressure deflagration.

11.8. Explosion outside a compartment

An explosion inside a compartment may lead to strong turbulent jets of fuel–air shooting out from the compartment's vent openings. In some situations the explosion in the jet can have significant strength and it may cause pressures as high as, or even higher than inside the compartment. Explosion in such jet flames is discussed in Section 6.9. In this section it is shown that a jet from a long pipe can cause a strong explosion outside. This has also been shown in FLACS simulations [60]. Our experience from experiments with a 1:5 scale offshore module and FLACS simulations is that an explosion outside a compartment is not dominant as long as the compartment is filled with obstructing objects, or if the compartment is not very long and narrow (tunnel-like).

In our consequence analyses we however, never neglect the contribution from the external explosion. External explosions may, e.g. contribute to the blast wave outside the compartment. As discussed in Section 8, a strong explosion inside a compartment may result in strong blast waves propagating a long distance away from the explosion compartment.

11.9. Mechanical ventilation system

There is no doubt that mechanical ventilation systems can counteract the formation of explosive gas clouds, if the release rates are small. However, for a massive release, a ventilation system may transport gas from one area to another. Further, if ignition occurs and the explosion propagates into the ventilation channels, a violent explosion may occur within the ventilation system.

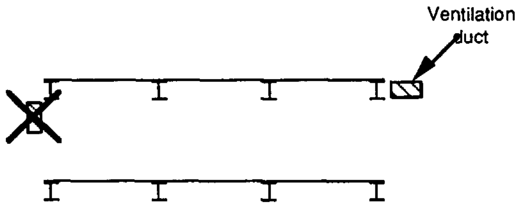


Fig. 136. Front elevation of a compartment. Ventilation ducts should not block the vent areas. Placing them behind the I-beams will be more beneficial.

The emerging flame jet from an explosion in a ventilation channel can act as a very strong ignition source. If such a flame ignites a cloud in a module very high explosion pressure can be expected. This flame jet ignition has been experimentally observed to cause very violent explosions, and even transition to detonation for sensitive fuels.

To avoid this type of hazard the reliability and response time of shut down systems for the ventilation systems are critical.

In design of offshore modules we have seen that ventilation ducts have been implemented in the later phase of the detailed engineering and that these ducts have blocked significant parts of the vent areas.

Fig. 136 shows a bad and a good location of a ventilation duct in an offshore module or another building. By locating the ventilation ducts behind the I-beams they will not lead to additional blocking of the vent openings of the module.

In design one should try to locate ventilation ducts in such a way that they do not block the vent openings. They should also be taken into account as early as possible in the design.

11.10. Fire, a common event after a gas explosion

A gas explosion in a compartment will often be followed by serious fires.

The source of the fire can either be

(i) the initial leak source that caused the formation of the explosive cloud, or

(ii) new release source(s) caused by equipment or piping being damaged by the initial explosion.

To avoid new releases, it is important that piping, equipment and their supporting structures are designed to take the loading from the explosion.

As a result of a violent gas explosion, walls or decks may start to move or even break down and fragment. Pipes that are suspended on a moving wall may be sheared off (i.e. guillotine break) as a result of the relative movement of points of suspension. Piping from one module to another module may have to respond to relative structure movements. Cables and control lines may also be damaged because of this type of relative movement.

To illustrate this phenomenon a case history from a gas explosion in an onshore petrochemical process plant is included. The events are shown in Fig. 137. It started with a violent explosion inside a building. On the roof of this building there was a pipe bridge with a 0.3 m diameter pipe crossing over to a pressurised vessel containing

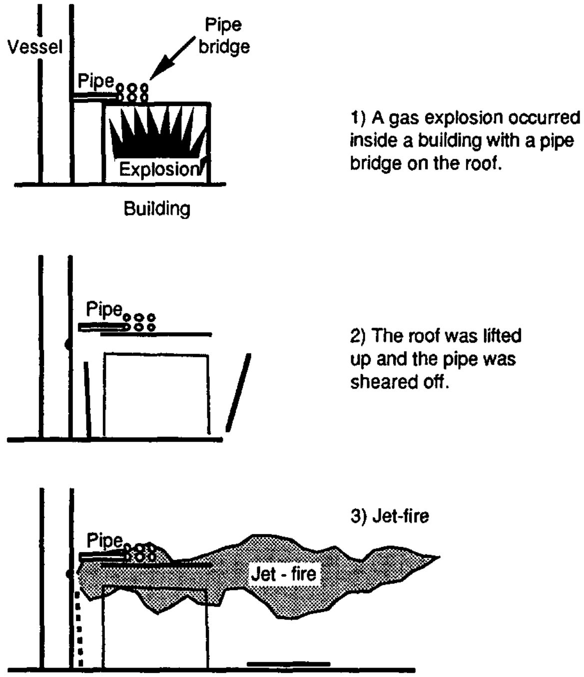


Fig. 137. A case history: Jet-fire as a consequence of a gas explosion inside a building.

hydrogen. As a result of the explosion the roof was lifted about 1 m and the hydrogen pipe was sheared off.

The result was that large quantities of hydrogen leaked out from the vessel. The hydrogen caught fire and a very intense jet flame burned until the reservoir was empty. The length of the jet flame was about 50 m.

Other phenomena that may cause deformation or damage to the piping system are:
(i) drag forces caused by the explosion wind;
(ii) flying fragments that may cut or break weak connections like instrument lines.

11.11. Water deluge

Some recent experimental results [78,58,95,69,96] have shown that ordinary water deluge for fire fighting can have a mitigating effect on gas explosions.

By request from the Department of Energy (D.En.), UK, the Chr. Michelsen Institute [58] undertook a pilot experimental investigation addressing the effect of water sprays on gas explosions. The objective of this test programme was to identify any beneficial effect of deluge water sprays on overpressures generated by gas explosions.

The 1:5 scale model of an offshore module was used in the tests. The gas mixture was either methane in air (8.5–10 vol%) or propane in air (4.25 vol%).

In the tests the deluge system was activated prior to the ignition, i.e. the water spray droplets were inside the gas cloud at the time of ignition. A deluge density of

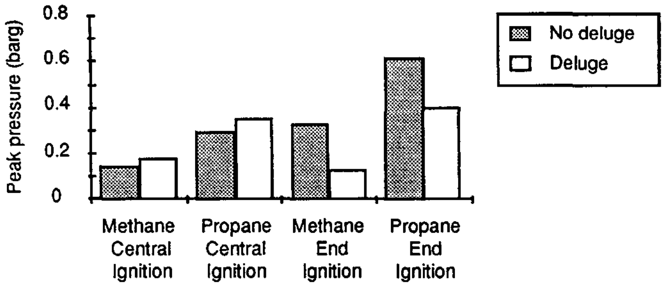


Fig. 138. D.En./CMR results.

121 $min^{-1} m^{-2}$ was used as base case in the tests. This value is recommended in the Department of Energy Guidance Notes on Fire fighting Equipment on Offshore Installations.

The recorded explosion overpressures ranged from 100–700 mbar. The propane–air tests gave about twice as high pressure as the methane–air tests. Some of the tests were performed without the deluge system activated (i.e., dry tests) as reference tests. In tests with central ignition no beneficial effect of the water deluge was observed, actually there was a slight increase in peak pressure. In tests with end ignition and louver walls close to the ignition point, a significant reduction of the explosion pressure was observed when the water deluge was activated. This reduction was as large as up to a factor of three. Fig. 138 summarises the results.

Fig. 139 shows pressure records from two identical tests with and without water deluge activated. These are tests using end ignition. Here we can clearly see a positive effect of the water deluge.

British Gas have also reported results from water spray tests [78] (see Fig. 140). In these experiments the pressure in the dry tests (i.e. no deluge) was in the range of several bar. For the offshore module Case 2, no pressure for the dry tests was reported. It was only stated that the explosion pressure was several bar. Test performed in a geometry consisting of piperacks pressures of 3.5 bar were noticed for natural gas. Also

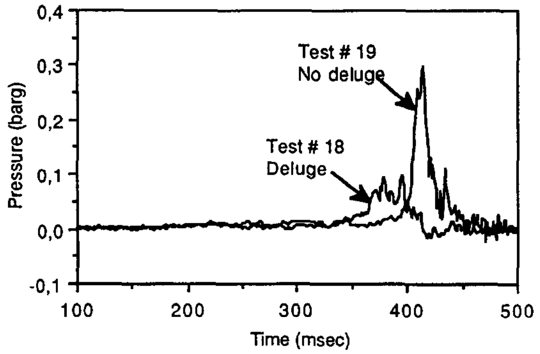


Fig. 139. Pressure records from deluge tests.

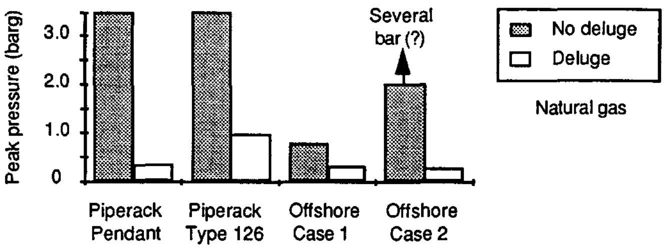


Fig. 140. British Gas results.

for these tests the deluge had a positive effect on the explosion pressure. With the deluge activated, the explosion pressure was about 0.25 bar except for the pipe-rack tests with nozzle type 126, where pressures of I bar were noticed.

Recent experiments on waterspray were reported by Catlin et al. [96]. They were performed in two rig geometries, closed on all sides except for one side. On this side either a small or large vent area could be installed. In the experiments with the large vent opening the sprays substantially reduced the overpressures. But the experiments with a small vent opening resulted in higher pressures than those that would have been produced had the sprays not been activated.

From all these experimental programmes it was concluded that the effects of water spray on gas explosions seem to be twofold and competing:

(i) The water spray interferes with the low velocity flame in the initial phase of the gas explosion or in situations where the flame cannot accelerate sufficiently, i.e. in compartments with little venting. This causes increased flame acceleration and faster pressure build-up.

(ii) It is likely that mist is generated in the unburnt gas mixture by droplet break-up and stripping in the later phase of the gas explosion. The evaporation of the mist in the flame will result in water vapour diluting the mixture and thereby reducing the reaction rate or even stopping the reaction completely. As a result an important reduction of the explosion pressure will occur.

Further, the experiments showed that the beneficial effect of waterspray systems increased when:

(i) a larger number of nozzles was used;

(ii) higher nozzle pressures.990 were used;

(iii) a more uniform spray distribution was used.

Experiments reported by Wilkins and Van Wingerden [97] showed that the overpressure increasing effect of waterspray systems in more confined geometries and during the initial stages of flame propagation increased when

(i) higher nozzle pressure were used;

(ii) using nozzles generating higher water velocities;

(iii) the water application rate increased.

From simple calculations we know that the droplets from standard deluge nozzles (> 100 μm) will not evaporate in the flame front, because they are too large. In order to evaporate in the flame front the droplet diameter has to be 1–50 μm or less. Therefore

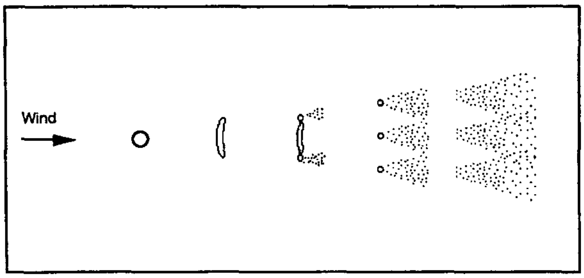


Fig. 141. One mode of droplet break-up due to wind.

in order to be effective the large droplets have to break up due to the wind in the unburnt mixture ahead of the flame front. This is illustrated in Fig. 141.

For break-up there must be a velocity difference between the gas flow and the droplet. This critical velocity difference increases with reduction of the droplet size, i.e. big droplets will break up easier than small droplets.

Experiments with very reactive fuels, such as hydrogen and ethylene, have shown that the flame acceleration caused by droplets in the initial phase of the gas explosion, can be significant. It is likely that very reactive fuels are more sensitive to this effect. It may therefore be true that the water spray has the most positive effect on the least reactive fuels. No conclusive evidence, however, exists to support this statement.

For a detonation in acetylene–air, Jenssen [98] has shown that ordinary deluge has no influence on a detonation wave. The time available for break-up within the detonation front is probably too short. Thomas et al. [99] have shown that small droplets are required to get any quenching effect on detonations.

Unfortunately there are disadvantages related to the use of water deluge also. Since the activation time for an ordinary deluge system is much longer than the duration of the explosion, the deluge system has to be activated on gas detection. Accidents have been reported where the probable ignition source was a discharge in electrical equipment due to moisture from the deluge system. Water sprays and deluge should therefore be activated in compartments with waterproof electrical equipment.

Our general opinion about water sprays is that such systems seem to increase the likelihood of ignition, but they can reduce the pressure build-up, particularly in the high pressure cases.

The tests have given promising results, which indicate that water spray may be a future mitigating device for accidental gas explosions. However, further research is required in order to quantify and relate all the effects of water sprays in an explosion event.

11.12. How to estimate the loads from gas explosions in compartments

The quality of predictions of gas explosions depends on:

(i) the quality and approximations of the physical models and codes that have been used;

(ii) the representation of the geometry and the scenario parameters by the user.

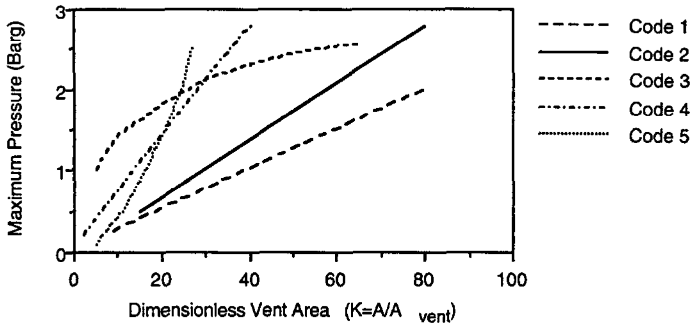


Fig. 142. Comparison of predicted maximum pressure from different formulas (venting guidelines) for prediction of explosion pressures in a compartment [6].

Back in the 1960s and the 1970s there were several attempts to make simple correlations, formulas or venting guidelines relating maximum explosion pressure and vent area. Fig. 142 shows a comparison of results of these types of formulas.

As we can see there is a wide spread between these formulas. If we compare these results with experimental results we will find order of magnitude differences. The typical weakness with such formulas is that they do not take into account the location of the ignition point and vent areas, and they do not handle the generation of turbulence and flame acceleration. Most of these formulas are also based on small-scale and empty compartment experiments. In the report Review of the Applicability of Predictive Methods for Gas Explosions in Offshore Modules (British Gas for the Department of Energy, 1990) [71], it is concluded that the use of these simple formulas with any degree of confidence, must be limited to situations involving empty single-chamber vessels up to volumes of the order of 200–300 m^3 and with an aspect ratio of less than 3. Our view is that these simple formulas in almost all industrial situations (accidental releases) are not applicable and should not be used. They should only be used within their stated range of validity.

A much better way to estimate loads from gas explosions inside a compartment is to use numerical fluid dynamic codes such as the FLACS code, which is described in detail in Section 13.

11.13. Guidelines

Guidelines for equipment location can be given as follows:

- Do not locate large pieces of equipment or rooms near the module vent areas.
- Avoid laydown areas outside explosion vent areas. Containers etc. will block the venting.
- The longest side/dimensions of equipment should normally be parallel with the flow direction during an explosion, i.e. pointing in the direction of the explosion vent areas.
- Locate piping in low drag (i.e. explosion wind) zones.

Guidelines for module shape and explosion venting are:
- Approach a cubical module shape when explosion vents are placed on the two end walls.
- An elongated module needs venting on three walls.
- The two smallest module (confinement) dimensions should be of the same length.

Guidelines for venting:
- Make the vent area as large as possible.
- Distribute the vent area, or make it large close to the potential ignition source.
- Vent into open areas.
- Relief walls should be able to open up quickly and be light-weight.
- Relief walls should not cause any dangerous fragments (projectiles).
- Do not use windows (ordinary window glass) for venting.

To avoid fires as consequences of explosions one should:
- Design the piping and the supporting structure so that deformation of the module(s) will not cause strong deformation of the piping system.
- Locate piping in low drag (i.e. explosion wind) zones.
- Avoid constructions that during an explosion will cause flying fragments.

Guidelines for use of water deluge.
- The use of water spray should be made part of a hazard evaluation. Each case should be viewed individually, and both the positive and possibly negative effects of water spray should be addressed.
- Electrical equipment must be waterproof if water deluge is to be activated based on gas alarm.
- The design of the water spray system will depend on the layout of the compartment.

Guidelines for estimating the loads from a gas explosion in a compartment (see Section 13 and Section 14):
- Simple formulas are not recommended, unless the use is strictly within the applicability range. Almost all scenarios in industrial environments are outside the applicability of the simple formulas.
- The best way to estimate loads from gas explosions is to use advanced numerical codes, like FLACS.
- Use μFlacs as a screening/layout tool. Note that this code is not intended for design purposes, hence main conclusions based on μFlacs use should be verified by additional FLACS simulations.
- Applying such tools correctly provides good results but is time-consuming and requires planning and expertise.

12. Gas explosions in process areas and unconfined areas

In Flixborough in 1974, 60 tons of cyclohexane were released inside the process plant. A large dense flammable cloud was formed and when this cloud exploded the

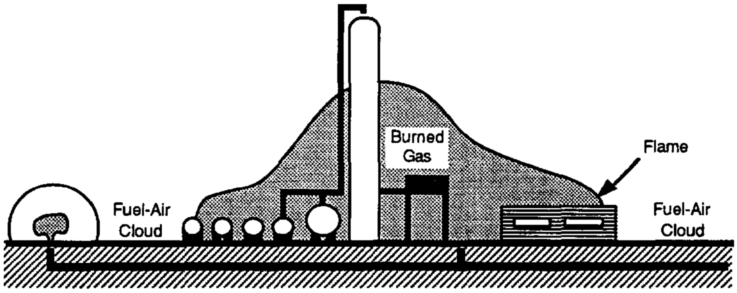


Fig. 143. Illustration of a process plant. A deflagration will only cause high explosion pressures in confined areas or areas packed with equipment.

plant was totally demolished. The blast from the explosion was estimated to be equivalent to 15 tons of TNT. 29 people were killed in this accident. In the Port Hudson event, propane was released from an underground pipeline. The release filled up a valley with propane–air mixture. The explosion started as an internal explosion in a pump-house and this triggered the unconfined cloud to detonate. These two cases are examples of large gas explosions in process areas and unconfined situations. Other accidents may be caused by much smaller releases of combustible gas, like the Sarnia incident. In Sarnia [86] 10–20 kg of hydrogen leaked out. The cloud detonated and killed two people.

The objective of this chapter is:

- To describe what is typical for gas explosions in process areas and unconfined areas and which factors are governing the explosion pressure.
- To describe in which areas a gas explosion will cause high pressure and how to avoid this situation.
- To describe how to estimate explosion pressure under these conditions.

12.1. Confinement

Fig. 143 shows an illustration of a process plant explosion where the flame propagates through a fuel–air cloud. If the explosion is a deflagration, as described in Section 6, high explosion pressures will only be generated when the gas cloud is inside confined or partly confined areas or engulfs obstructing objects, such as pipework and process equipment. In a process plant the areas where high pressures can be generated by a deflagration, are mainly inside buildings, pipe bridges, in open process area where pipework and process equipment is densely packed and in tunnels and culverts. However, if the cloud detonates as a result of a strong flame acceleration, the detonation will be able to propagate through the cloud without any confinement or obstructing objects (see Section 7).

12.2. Fuel

When a fuel is accidentally released, the density of the fuel is an important parameter for the formation of the combustible cloud. When the gas is lighter than air, like

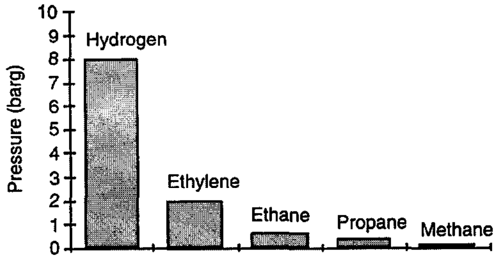


Fig. 144. Comparison of explosion pressure for various stoichiometric fuel–air mixtures in a 10 m wedge-shaped vessel [28].

hydrogen, buoyancy will make the cloud rise. In an open situation, the gas will rise and be dispersed relatively quickly. A dense gas will drift along the ground, and will not disperse as fast as a light gas. The dense gas may drift into buildings, tunnels, culverts or other confined areas. A release of a dense gas therefore has a higher potential of forming larger fuel air clouds than a release of a light gas.

In Section 6 and Section 7 we discussed flame acceleration and detonability of different types of fuels. For otherwise equal conditions, the different fuels mixed with air will generate different explosion pressures. Fig. 144 shows some experimental results with different fuel–air mixtures in a specific apparatus. Even though the pressure will be different in other situations, the relative fuel ranking, as shown in Fig. 144, seems to constitute a general trend. In an accidental situation, we can therefore expect that hydrogen and ethylene will give higher explosion pressures than fuels like propane and methane for the same size of gas cloud and with other conditions being similar as well.

Hydrogen is a fuel that is lighter than air, disperses relatively fast, and causes high explosion pressures. If we review loss experience with hydrogen, we will find that the sizes of the explosions are fairly limited. The larger hydrogen explosions are typically equivalent to a few hundred kg of TNT, which is significantly less than accidents like Flixborough, which was equivalent to 15 tons of TNT. Even though the size of the hydrogen explosion is limited, the local damage in the area where the explosion takes place is very severe. Hydrogen is very reactive and a deflagration may accelerate very fast and easily transit into a detonation. Several accidents have been reported where hydrogen clouds are likely to have detonated. Sarnia was definitely a detonation in a free hydrogen cloud. In records from accidental releases of heavier-than-air fuels, you will find large varieties of accidents. In this section we have discussed fuel type as an important parameter characterizing the consequences of a gas explosion.

12.3. Flash fires

The term 'flash fire' is often used for a deflagration producing negligible overpressure.

Various large scale tests [100–103] have demonstrated that a truly unconfined, unobstructed gas cloud ignited by a weak ignition source will produce only small overpressures while burning. There are no mechanisms that can accelerate the flame (i.e.

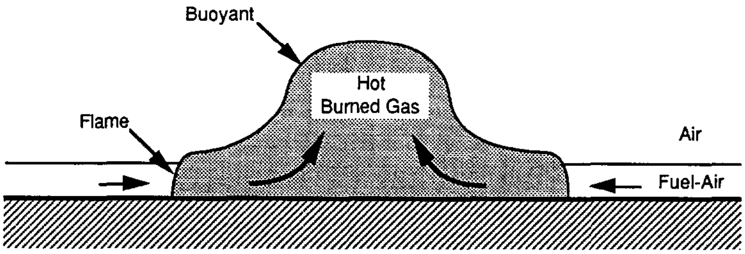


Fig. 145. Buoyancy can generate strong wind.

a deflagration) to more than a few tens of meters per second under these conditions. The combustion is so slow that burned gas will expand before any significant pressure can build up. The thermal effect is the main hazard from a truly unconfined deflagrating cloud.

However, if the same free cloud detonates due to transition to detonation in a confined neighbouring area, the result will be a very strong blast wave. Detonations are discussed in Section 7.

When a fuel–air cloud burns, the hot combustion products will rise due to buoyancy. For a large cloud this buoyancy can be very strong and the flow ahead of the flame can even be reversed, as indicated in Fig. 145. In the accident in Ufa in 1988 where a train ignited a large gas cloud from an LPG pipeline, the wind forces caused by the buoyancy were so strong that the trees tilted [104]. This Ufa event is an extreme case, since the cloud was extremely large.

12.4. Buildings and other partly confined areas

In the previous chapter gas explosions in compartments and offshore modules were discussed. The information in Section 11 is directly relevant for evaluation of explosions in buildings in process plants.

In a process plant combustible gas may be formed as a result of a leak inside the building or gas drifting into the building. The consequences of a gas explosion inside the building will mainly depend on the type of fuel, size and concentration of the gas cloud, ignition and geometrical layout, i.e. confinement, venting and obstructing objects. In a building with no or little explosion venting, the building will confine the explosion and high explosion pressures may be generated. Vent openings are of major importance in keeping the explosion pressure down.

In the period 1965–1975 there were a large number of gas explosions in buildings, particularly in compressor buildings [17]. One reason for this large number of explosions was the design of the buildings. As a result of weather conditions as well as noise the buildings were closed. In a closed building a release of a few kilograms of fuel can cause a serious explosion. Even with forced ventilation, a flammable gas cloud can easily be generated. Again referring to Kletz [17] is pertinent: "The best building has no walls".

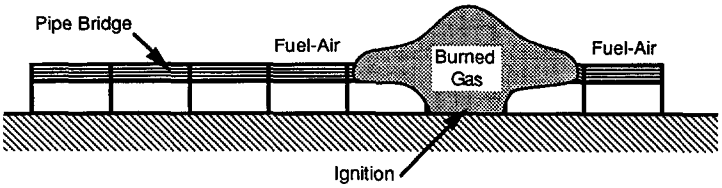


Fig. 146. Gas explosion in a pipe bridge.

12.5. Pipe bridges

In a process plant a pipe bridge can be fairly congested and can therefore support flame acceleration and cause high explosion pressures. Fig. 146 illustrates flame propagation through a pipe bridge [105]. In the FLACS simulations described in Ref. [105] the fuel–air cloud was ignited at ground level. The flame was therefore propagating in a spherical mode until it reached the pipe bridge. In the pipe bridge, the flow ahead of the flame was turbulent and the flame was therefore accelerating. In Fig. 146 we can see that the flame has propagated a longer distance at a higher velocity in the pipe bridge than at ground level. In the numerical simulation, the explosion pressure was predicted to be approx. 200 mbar. This value was of course only valid for this particular geometry.

In British Gas experiments, in a 1:5 scale pipe bridge geometry with propane–air, even transition to detonation was observed when the ignition source was a strong jet flame.

12.6. Open process areas

An open process area can also be very congested. Pipework, process equipment, tanks etc. will contribute to turbulence generation during an explosion. The experimental results presented in Section 6.5 (from CMR's cubical vessel), show that a spherical gas explosion in a very obstructed area only needs a few meters of flame travel before the explosion pressure reaches levels that can cause severe damage. To avoid damaging overpressures it is therefore important to keep congestion to a minimum and not make congested areas too large. It should be noted that extensive obstructedness also may act as confinement!

Tanks and process vessels should not be located too close to each other. Fig. 147 shows a row of tanks. During a gas explosion, the flame will propagate under the tanks

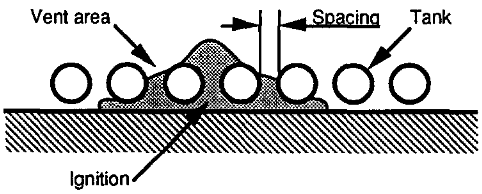


Fig. 147. Side view of a row of tanks.

and the tanks will act as repeated obstacles and accelerate the flame. (See Fig. 49). The venting area is, in this case, mainly dependent on the space between the tanks and their length. The longer the spacing, the better is the venting. To avoid strong flame acceleration it is therefore important to ensure that satisfactory equipment spacing exists. Van Wingerden and Zeeuwen [73] have performed tests in relevant geometries, the results of which support this statement. The optimum equipment spacing is scenario dependent and can be estimated by performing gas explosion simulations with FLACS.

12.7. Tunnels and culverts

In an accidental release in a process area or an open area, dense gas clouds have a tendency to flow into underground systems like sewers, culverts, tunnels etc. If a gas cloud manages to enter such areas and ignite, the explosion will be an internal explosion, as discussed in Section 10.

Another event (or phenomenon) that can cause high explosion pressures and possibly transition to detonation is jet ignition [60]. Fig. 143 shows an example of jet ignition of an unconfined cloud, caused by a confined explosion in a sewer system. Such a jet flame shooting out from a confined region is a very strong ignition source that may cause high pressure explosions.

12.8. Multiple explosions and blast waves

A large release may form a large explosive cloud that may cover many confined and/or congested areas. We have illustrated the situation in Fig. 148. If we assume ignition close to Area A, we will get a flame acceleration, i.e. explosion within this area. If the explosion does not transit into a detonation in Area A, the flame speed will decay as it propagates into the open area between Areas A and B. Results from experiments showing deceleration on flame exiting from an area containing repeated obstacles into an unobstructed area are presented in Fig. 53. In the open area, between Areas A and B, the flame may propagate at a few tens of m s^{-1}. The time for propagation from Area A to Area B will be fairly long compared with the time to burn the clouds within these areas. When the flame reaches Area B there may be a new explosion. At the location C we

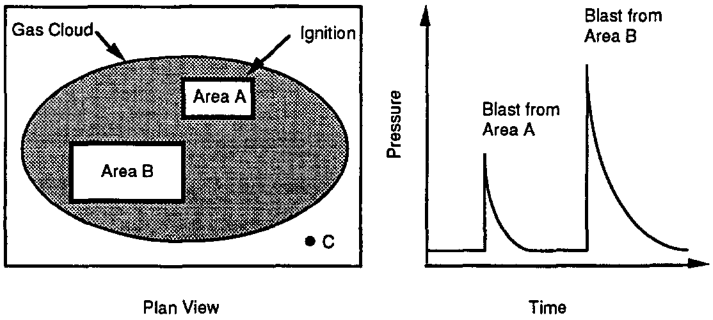


Fig. 148. Multiple explosions in a process area.

may get two blast waves as shown in the figure. This shows that one gas cloud may cause several local explosions.

The effect of localised explosions may in some situations not only cause high pressures locally but also cause high velocity flames to propagate into less confined but obstructed regions, where the high velocity of the flame may be sustained. Some recently published data by Harris and Wickes [43] show examples of such an effect which was observed when flame propagation in repeated obstacle arrays was studied. They showed that if a flame entered the unconfined obstacle array at a high velocity, the flame was able to stabilise at a high velocity and high explosion pressure. However, if the flame had a low velocity in the beginning of the array, it was not able to accelerate to high velocities and the corresponding explosion pressure was low.

12.9. FLACS simulations

The FLACS code was originally developed for simulation of gas explosions in offshore modules. In a process plant a gas explosion scenario will involve a larger variety of parameters than for an offshore module. In a process plant the fuel may be

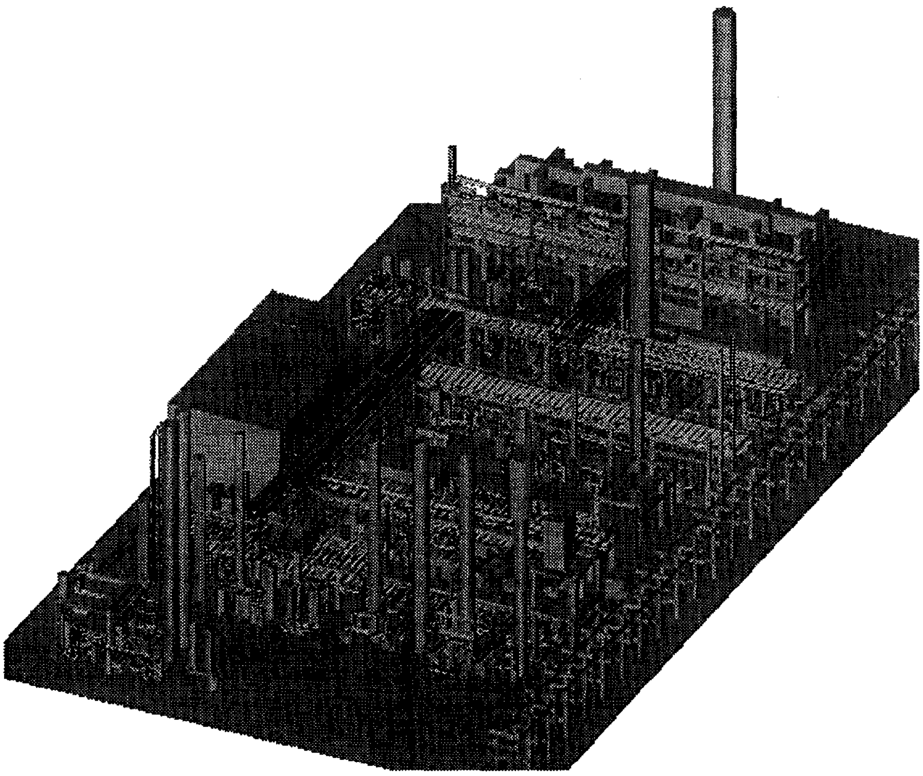


Fig. 149. The Naphta Cracker II plant in Beek in The Netherlands which was involved in a vapour cloud explosion in 1975, as represented by the FLACS code.

very reactive like hydrogen and ethylene, may be a mixture of fuels or any kind of single fuel. The geometrical layout will also vary greatly from case to case. The physics of gas explosions in a process plant is of course the same as in an offshore module. The models in FLACS should be capable of handling gas explosions also in process plants. Bjerketvedt and Nornes [105], Savvides and Tam [84] and Salvesen and Van Wingerden [106] have used the FLACS code for simulation of gas explosions in process plants.

The simulations performed by Salvesen and Van Wingerden considered a large process plant in Beek in The Netherlands which was involved in a strong vapour cloud explosion in 1975 [119]. The process plant involved was a naphta cracker (Naphta Cracker II) plant (dimensions: 160 m × 70 m × 40 m). After a major release of what according to the official report must have been C_3–C_4 hydrocarbons (propylene, butane) ignition occurred resulting in the death of 14 people, 107 injured people and extensive damage to the plant. The investigation after the incident revealed explosion pressures based on calculations on the damage (up to 1 bar locally), the size and location of the flammable cloud and the point of ignition.

The simulations revealed that the gas that was involved in the accident was not propylene as assumed by some of the sources used in the official report but more likely ethylene, or a mixture of ethylene and propylene or butadiene. Pressures generated for propylene were in the order of 14–15 mbar, whereas for ethylene pressure in the order of 10–14 bar were generated. Unknown factors such as mixture composition and concentration profile in the cloud make it more or less impossible to simulate the explosion in detail. Nevertheless the simulations showed the possibilities of FLACS also for process plants. Fig. 149 shows the plant as it was represented by FLACS.

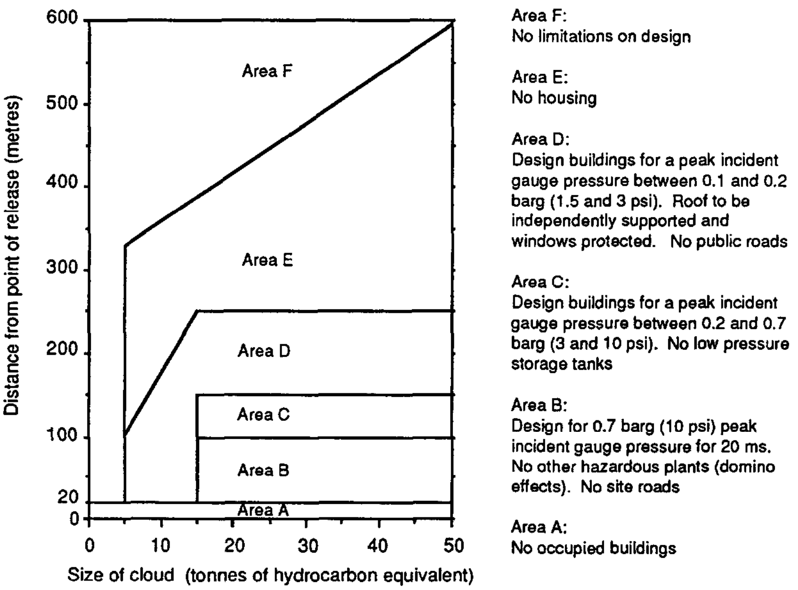


Fig. 150. Summary of the main restrictions imposed on design against gas explosions. Note: Area E limitations apply in areas E-A and so on [107].

12.10. Plant layout

To keep the loss potential low, it is important to separate different units and buildings. Different process areas should be kept separated in order to avoid domino effects. Keeping congestion to a minimum is also important. All activities not absolutely necessary for the operation of the plant should be placed away from potentially hazardous areas. Buildings which may be subjected to blast from explosions, should be blast resistant. Fig. 150 shows an example of restrictions on design and layout of a process plant, as suggested by Kletz [107].

12.11. Guidelines

1. Keep congestion to a minimum. As crowdedness increases so does the loss potential.
2. Make the units small and separate them with open areas to facilitate flame deceleration.
3. Buildings where internal gas explosions can occur should have large explosion vent areas or —best of all— no walls.
4. Separate different process areas, in order to avoid domino effects.
5. Try to avoid gas leaks into confined areas such as buildings, tunnels etc.

13. FLACS simulations

To predict the consequences of a gas explosion in an industrial environment is not a simple task. Nomograms or simple scaling laws can be useful for interpolation and scaling of experimental data. However, they may give misleading results if they are used outside their range of validity [71]. Parameters such as geometry (i.e. confinement, size, type of obstacles, geometrical layout), gas type and concentration, affect the rate of flame propagation and thereby the explosion pressure. Moen et al. [77] have shown that simple vent area recommendations may be totally inadequate for enclosures containing obstacles (Fig. 151). More advanced tools than nomograms and simple scaling laws have to be applied for simulating gas explosions in industrial environment.

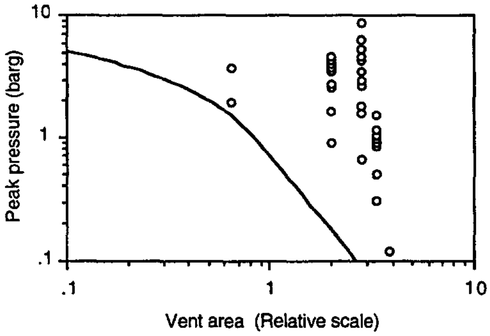


Fig. 151. Experimental results from CMR Raufoss experiments compared with scaling law.

This was also the main conclusion of the report British Gas wrote on behalf of the UK Department of Energy (1990) [71]. Explosion venting guidelines, simplified theoretical models and complex numerical codes were reviewed.

Explosion venting guidelines were seen as largely inapplicable because of the small scale of the experimental data on which they are based and because of their inadequate treatment of turbulence generated by leaks and obstacles.

Simplified theoretical models (empirical and approximate theoretical models) could with further development become adequate techniques perhaps.

Numerical models can provide a framework for developing a more general offshore explosion model.

For the last ten years CMR has had a large activity on gas explosion research. Important knowledge has been generated and formalised through the development of numerical tools like FLACS (FLame ACceleration Simulator).

The FLACS code is a three-dimensional gas explosion and gas dispersion simulation tool. The model takes account of the interaction between the gas flow and complex geometries such as structures, equipment and pipework. The FLACS code produces quantitative information, e.g. in the form of pressure–time curves. By performing sensitivity studies alternative scenarios and layouts can be tested and their explosion hazard potential can be identified. FLACS has been applied in the design of more than 30 offshore platforms and for accident analyses after the West Vanguard and the Piper Alpha accidents. It is being increasingly used also for onshore applications.

According to the British Gas report (1990) [71] the FLACS code "stands alone in being the most developed and validated on general offshore explosion modelling".

The objective of this section is to describe

- The FLACS code.
- What FLACS can do.
- How a typical FLACS project normally progresses.

This section is not intended as a user manual for FLACS and CASD. References to the FLACS and CASD user manuals are Storvik et al. [108] and Langeland et al.[109–111].

13.1. Route through a FLACS simulation

The first version of FLACS, used in the beginning of the 1980s, was a research tool with simple input and output facilities [50,51]. However, the geometries that were studied became gradually more complex. It was realised that communication between the user and FLACS had to be improved. An advanced user interface to FLACS was developed (based on CAD and computer graphics technology) and given the name CASD (computer aided scenario design).

Fig. 152 shows the connections between CASD and FLACS. CASD generates the scenario definition to FLACS and presents the results from the FLACS simulation.

The first step of a FLACS simulation is to generate the geometry (i.e. geometrical layout of the plant, compartment or offshore module) that is to be investigated. Gas cloud composition, size and location, location of ignition point, and specific output parameters have to be determined before the simulation of the gas explosion can start.

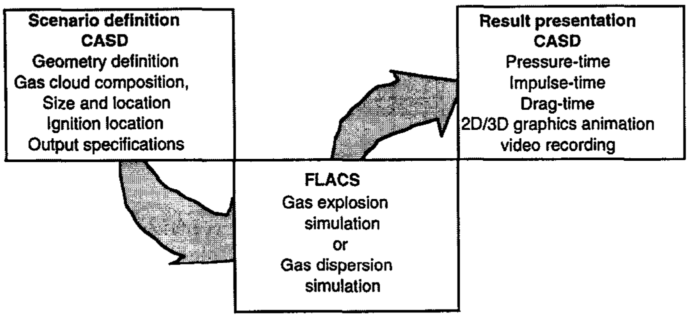


Fig. 152. The route through a FLACS simulation.

The running of FLACS is an extensive numerical task which requires a fairly large computer. In FLACS simulations the three-dimensional Navier–Stokes equations are solved. The FLACS output is presented by the CASD program. Typical output can be time-series plots like pressure–, impulse–, and drag–time plots as well as coloured shaded-image contour representations of velocities, flame location, pressure etc. Three-dimensional animations of the explosion development can also be generated.

13.2. Geometrical layout

A realistic representation of the layout of an industrial facility for a FLACS simulation, requires a fairly high degree of detail. In offshore modules objects with a size from 0.3 m and upwards will typically be included. In areas with high density of smaller objects, these smaller objects may also have to be taken into consideration.

Geometrical layout such as equipment, piping, walls etc. in the simulated geometries are represented as cylinders and boxes which are aligned with the main axes of the module. Pipes are represented as long cylinders. Beams which are not vertical or horizontal are represented by vertical or horizontal beams with blockage similar to the original beams. Fig. 153 shows a line drawing of an input geometry for a FLACS simulation.

Walls are represented by boxes with zero width in one direction. Porosity for walls and decks is a value between 0.0 and 1.0, defining the fraction of the area available for

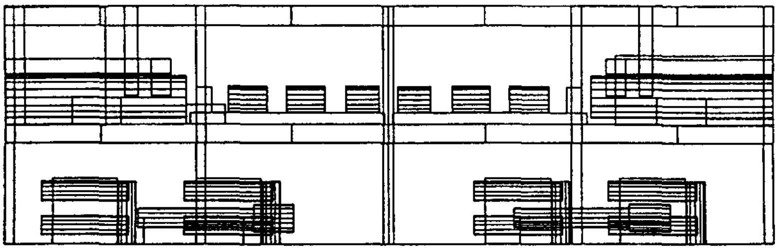


Fig. 153. Line drawing of an input geometry for FLACS simulation.

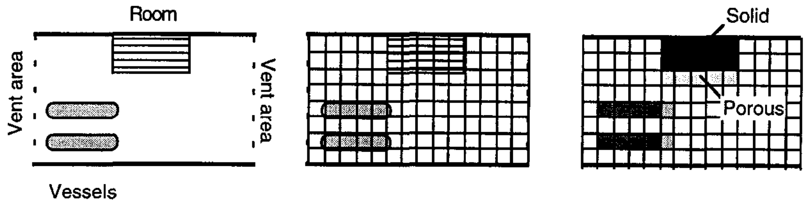


Fig. 154. The FLACS code uses porosity, resistance and turbulence generation parameters on a numerical grid to approximate the geometry. The numerical grid divides the simulation volume into control volumes. The calculations of the explosion parameters are done for each of these control volumes.

flow. A solid wall has a porosity of 0.0. Louvered walls have a porosity equal to the fraction of the area available for flow. The walls and decks can be modelled in four different ways:

1. **Solid**: This is an unyielding wall which is fully closed.
2. **Porous**: This is used for louvered walls and grated decks which are unyielding but partly open to flow.
3. **Blow out panels / Explosion relief panels**: This panel is initially represented by a closed wall which opens up when the simulated explosion pressure reaches a specified value. The opening of the panels is described analytically, based on the pressure and drag forces acting on the panel and the panel characteristics. The opening pressure, maximum travel distance, weight of the panel and final porosity (after opening) can be specified by the user.
4. **Open**: These are open areas which do not offer any resistance to either flow or pressure, except for the modelled beams and main structure.

Owing to limitations in processing speed and memory capacity of today's computers, the control volume in FLACS simulations is in full scale one cubic meter. In many industrial geometries, flame acceleration may be generated in areas where the geometrical details are too small to be resolved on the numerical grid. The geometrical details in these areas are represented by porosities and empirical formulas, depending upon obstacle type and shape which describe momentum loss and turbulence generation.

As shown in Fig. 154, one large obstacle may cover a number of control volumes in the calculation domain. FLACS can also calculate the contribution of a number of small obstacles or parts of an object to the porosity parameters for a single control volume. Verification tests for FLACS with control volume size corresponding to one cubic metre in full scale show good agreement with experiments in scaled-down (1:5 and 1:33) typical offshore modules.

13.3. Explosion scenario

In explosion simulations using FLACS the following explosion scenario parameters may be investigated:

- Size and fuel concentration of the combustible cloud
- Type of fuel
- Location of ignition point

One can assume that a homogeneous stoichiometric cloud covering the whole volume is a worst case situation. The probability for this situation to occur must, however, be considered for each given scenario. Some data exist which may be helpful:

· Experimental results from gas explosions with homogeneous and nonhomogeneous clouds show comparable overpressures.

· Gas dispersion experiments and simulations indicate that large, high-momentum leaks in semiconfined areas will, shortly after the initiation of the leak, result in effectively uniform, flammable concentration within most of the interior volume.

· The ignition probability is largest close to stoichiometry, since the minimum ignition energy is at its lowest for this concentration.

· Nonhomogeneous gas clouds with concentrations in the flammable range may have lower ignition probability than a similar homogeneous stoichiometric cloud. However, the effects of a gas explosion might be equally severe for the two cases.

The FLACS code has the capability of simulating gas explosions with methane, propane, ethane, propylene, ethylene and hydrogen in air. The capabilities of FLACS to handle methane and propane have been extensively verified. As far as the other fuels are concerned, limited verification has been carried out and results from simulations with these fuels should therefore be used with care. Natural gas is treated as a mixture of methane, ethane, propane and butane. Effects of CO_2 and other inerts can also be handled.

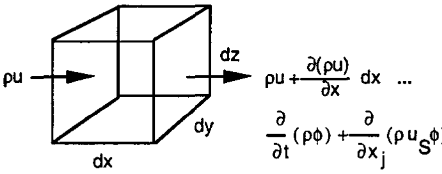
In most cases the ignition point location is uncertain. It may also be difficult to judge where the worst case location is, some knowledge of gas explosions is usually required. The typical scenario uses the expected worst case location or ignition in the centre of the area. It is also common to test out the sensitivity of moving the ignition.

Previously explosion scenarios have mostly been selected on the basis of worst case scenarios for ignition location and gas cloud. However, we foresee that in the future explosion parameters will be more related to risk analysis, where the postulated accident scenario is evaluated based on frequency of the event and where the simulation of gas explosions accounts for release rates, gas dispersion and most probable ignition location.

13.4. The FLACS code

FLACS is a fluid dynamic code that calculates explosion pressure and other flow parameters as a function of time and space for different geometries and explosion scenarios. It takes account of the interaction between flame, vent areas and obstacles such as equipment and pipe work. Recent development of FLACS includes the ability to simulate dispersion in complex geometries, both with diffuse and high-momentum leaks, with or without wind.

The FLACS code solves the full gas dynamic partial differential equations for a set of control volumes, as shown in Fig. 155. The effects of turbulence and chemical reactions are included in the differential equations. The equations are discretized using a finite volume technique and a weighted upwind/central differencing scheme for the convection terms. Velocities are calculated on staggered grids. The effect of turbulence is included through the eddy–viscosity concept by solving equations for turbulent kinetic energy (k) and its rate of decay (ϵ). Combustion is modelled a flamelet model which



$$\frac{\partial}{\partial t}(\rho\phi) + \frac{\partial}{\partial x_j}(\rho u_s \phi) = \frac{\partial}{\partial x_j}\left(\Gamma \frac{\partial}{\partial x_j}\phi\right) + S_\Phi$$

Fig. 155. Partial differential equations solved in FLACS.

consists of a sub model for burning velocity as function of gas mixture, temperature, pressure and turbulence in the reactant. Ignition is modelled by assuming that 50% of the fuel in the control volume in which ignition occurs, is consumed. Thus the temperature is raised and the explosion starts.

13.5. Output from FLACS

A tremendous amount of data is produced when FLACS is solving the pressure, velocity, temperature, density, turbulent parameters and combustion rate in each control volume in time steps of typically 10 ms. All these data cannot be stored during the simulation. Some of the output parameters have therefore to be defined before the FLACS simulation is carried out. These output parameters are typically:

· Number and location of monitor points for pressure, impulse, drag and other parameters

· Location and size of areas for average wall pressure monitoring

· Specification of variables to be presented as field plots (cross-sectional plots)

The pressure–time curves are presented either as local pressure time curves or as average wall pressure curves. Short pressure spikes that may be observed on local pressure time curves will in the average pressure time curves be smoothed out. The average pressure–time may therefore be more relevant for assessment of the average load acting on walls and decks.

13.5.1. Local pressure–time curves

For a number of predetermined locations the local explosion pressure is monitored and presented as individual pressure–time curves. After the main positive pressure pulse, the simulations will then predict a small negative pressure pulse. The magnitude of this negative pulse will depend on the vent arrangement and the geometry.

These plots will then give the maximum explosion pressure in barg at this location along with the duration of the pressure pulse. This is vital information if a dynamic response analysis of the structure is to be performed later on. The curves are well suited for comparing the results of different sensitivity simulations in order to choose the best layout of the area Fig. 156.

13.5.2. Area-averaged wall pressure curves

Area-averaged wall pressure curves can be generated at portions (panels) of the outer walls. For a porous wall or partly open wall, pressure in the open parts will not

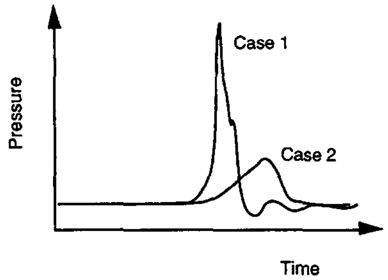


Fig. 156. Typical pressure–time curves from two FLACS simulations of gas explosions in a compartment. In case 2 a wall was opened for explosion venting and the pressure was hence reduced.

contribute to average pressure loading. The average pressure for a panel is calculated as the net force (F) acting on the panel divided by the net area (A) of the panel.

The appropriate portion of a wall for which the average pressure should be estimated will depend on the wall structure. Note that no time-averaging is performed, the pressure is still given as a pressure–time curve!

13.5.3. Drag (i.e. dynamic pressure)

Smaller objects such as pipework, cables etc. will mainly be subjected to drag forces due to the explosion wind. The net drag force on an object can be estimated by multiplying the drag (i.e. dynamic pressure) by the front area and the drag coefficient, C_D, for the object. The local drag or dynamic pressure is presented in Pascal (Pa) (1 bar is 10^5 Pa) and calculated for a number of predetermined locations by use of the following relation:

$$\text{Drag} = 0.5\,\rho u^2$$

For these calculations the local density, ρ, and velocity, u, are used.

13.5.4. Velocity

In a FLACS simulation the flow velocity vectors in x, y and z direction, i.e. u, v and w are predicted.

13.5.5. Maximum positive pressure impulse

The pressure impulse is the time integral of the local pressure–time curves. The pressure impulse is given in Pa s (Pascal-seconds). The maximum positive pressure impulse is at the time when the pressure is ending the first positive pressure phase. The maximum positive pressure impulse is one way of characterizing the pressure time curve, which takes the pressure and the duration of the pressure pulse into account. Maximum positive impulse and maximum pressure is often used to estimate structural response.

13.5.6. Contour plots

To visualise the development of the explosion, contour plots are presented. These contour plots can show variables as pressure, combustion products, fuel concentration and velocity vectors in various cross-sections of the module at specific time steps during the simulation.

The contour plots typically consist of five plots and a text header showing the time after ignition. The first plot shows the geometry in the specified cross section. The second and third plots show the fuel and combustion product concentrations. The overpressure is given in the fourth, and velocity curves are given in the fifth plot.

The information in contour plots is mainly used for visualisation of the flow phenomena and local pressure build up during the explosion. They are very useful as verification of scenario parameters, such as cloud size and location of blow-out panels. The contour plot can also be used for production of video animation of the results.

13.6. Benefits from FLACS simulations

The FLACS code has been evaluated as the most validated code for prediction of gas explosions in offshore modules [71]. The FLACS code is based on the latest knowledge within gas explosion research and is most likely providing the highest quality of results currently available.

FLACS provides quantitative information, such as pressure–time curves for a given explosion scenario. The FLACS results can be applied for evaluation of structural response [1] as part of a risk analysis.

By performing sensitivity studies with FLACS, different layouts such as explosion vent arrangements or location and orientation of equipment can be tested out. The best or the most acceptable solution can be established. In this way the FLACS code can be a very practical and useful design tool. For simple geometrical layouts, however, μFlacs is a more efficient tool for sensitivity studies than is FLACS.

The quantitative results in form of pressure–time plots, contour plots and video animation of the results, makes the results easily accessible. It is easy to understand the main results from a FLACS simulation. The code is therefore an effective tool for transferring knowledge about gas explosions to decision makers.

The benefits from FLACS simulations can be summarised as follows:

- Safer design and operation through transfer of knowledge and practical results can be achieved.

13.7. Accuracy and validity

The solution technique described above is generally first-order accurate in time and space. The relevance of using the order concept in determining the accuracy of simulations of flows in very complex geometries which are not completely resolved by the numerics is, however, somewhat questionable. It is hence very important to verify the performance of FLACS both against simple non-reacting flows which are well documented by others and against more complex flows involving flames propagating in obstructed environments.

[1] A joint project CMI/DNV has evaluated the possibilities of transferring FLACS data to the DNV Sesam code for structural response predictions.

There are mainly three factors influencing the quality of FLACS simulations:
- The quality and appropriateness of physical and chemical models used
- The accuracy and stability of the numerical schemes used
- The representativity of the geometry and scenario implemented by the user

These factors can be, and have been, addressed in FLACS validation studies. A comparison with shock-tube studies showed that FLACS predicted both shock strength and position well [112,113]. Further CMR has a large set of data from a wide range of gas explosion experiments studying the effects on flame speed and overpressure of parameters relevant to industrial plants offshore as well as onshore. FLACS has been extensively validated against this data set. More than 2000 experiments have been performed in the following geometries:
- 10 m tube;
- 1 m and 10 m wedge-shaped vessels;
- 3 m cuboid vessel;
- Scale 1:33 and 1:5 offshore modules.

In addition to these FLACS was validated against experimental data generated at other institutions, such as British Gas [71,96], TNO-PML [83] and Shell Research (SOLVEX).

The effects of varying the following parameters have been studied:
- Scale (1 m and 10 m long explosion vessels)
- Fuel gas type (hydrogen, methane, ethane, ethylene, acetylene, propane, propylene, butane, cyclohexane)
- Fuel gas concentration (between LEL and UEL)
- Fuel gas homogeneity (homogeneous clouds as well as 'real' clouds)
- Fuel gas mixtures (realistic process streams)
- Ignition source strength (sparks, planar ignition sources and flame jets)
- Ignition source location
- Explosion vent size
- Explosion vent position
- Obstacle density (# of obstacles)
- Obstacle size
- Obstacle shape (rounded, sharp-edged, grids)

FLACS has been used to simulate a large number of the experiments listed above. The trends observed when varying the parameters were consistently predicted by FLACS (Fig. 157). In most cases a certain amount of over or underprediction can occur. However, the results are generally within 30–40% of the experimental data. In some instances many repetitions of one experimental scenario have been performed, and particularly in the large-scale experiments the scatter is comparable to the figures quoted above (30–40%) for the FLACS simulations.

The FLACS code combustion model is based on a quasi-laminar formulation and a turbulent combustion concept. The FLACS combustion model does not account for Taylor-type instabilities, nor does it predict transition to detonation and propagation of detonation waves. Even though the FLACS code cannot predict transition to detonation, the result from FLACS can give an indication of whether a transition to detonation is likely to occur or not (high flame velocities and pressures; see Section 7).

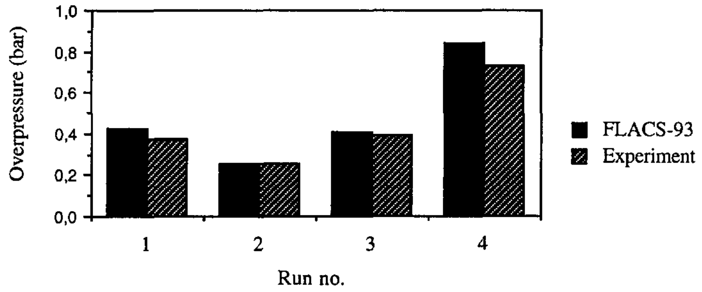


Fig. 157. Comparison of FLACS93 results and experimental results for a 1:5 compressor module. Run 1: central ignition lower deck (methane), Run 2: central ignition upper deck (methane), Run 3: central ignition upper deck (propane), Run 4: central ignition lower deck (propane) [116].

The major uncertainty for the use of simulation results lies in the representativity of the parameter ranges used for verification, e.g. is the range of scales studied representative of industrial plants? No full-scale experimental data exist, hence scaling is a matter of some concern when FLACS results are used. However, scaling from 1 m long to 10 m long explosion vessels, is handled well and it is reasonable to assume this behaviour to be valid for larger scales. Experiments which are being carried out at full-scale will show whether this assumption is valid or not [114] (Fig. 158).

In spite of the uncertainties involved, a recent review of predictive methods for gas explosions concluded that at present FLACS is the best available tool for pressure prediction (British Gas for the Department of Energy, 1990 [71]).

13.8. FLACS projects

This section illustrates the contents and timing of a typical project using FLACS.

CMR's consultancy service on gas explosions, GexCon, has done a large number of projects using FLACS. The following table Fig. 159 shows a schedule for a typical GexCon FLACS project. The project consists of two simulations, one base case simulation and one sensitivity simulation.

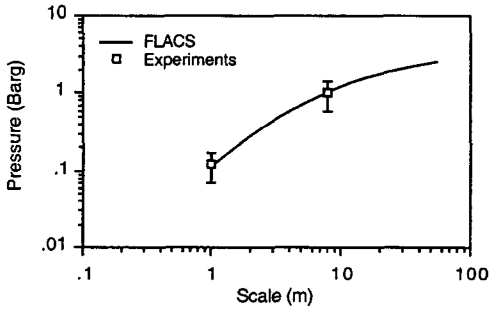


Fig. 158. Scaling with FLACS.

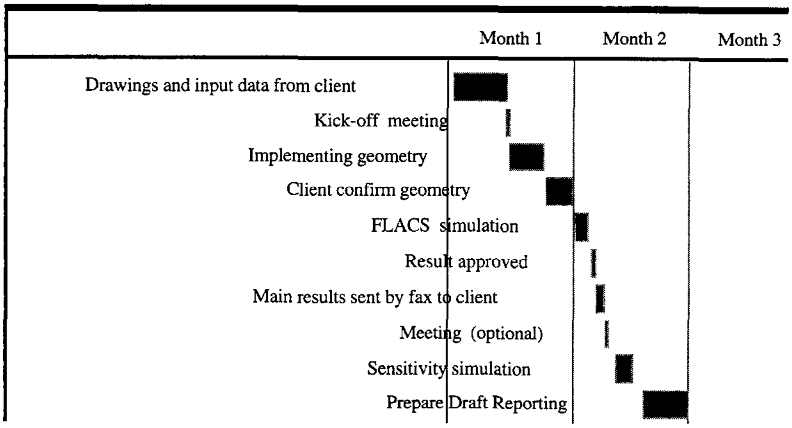


Fig. 159. FLACS project.

The first task in a project is to get drawings and other input data from the client. The following drawings and input data are required, if possible:

· Plan view
· Elevations
· Primary steel work
· Secondary steel work
· HVAC
· Cable trays
· Piping
· Equipment list
· Venting conditions for the explosion (i.e., cladding design, weight, opening pressure, etc.)

A kick-off meeting is arranged, where explosion scenario, layout and required output data are discussed. Implementing the layout geometry for a typical offshore module takes up to one week for an experienced FLACS user. When the geometry has been implemented, a print-out is sent to the client for verification. After verification and possible changes are made, the FLACS simulation is carried out. The results are then approved and sent to the client. Running a sensitivity study, i.e. making minor modifications in geometrical layout, change the gas cloud or ignition location, takes typically from one to three days.

A report will include reference to data used and specify relevant assumptions. Detailed results will appear in an appendix in the form of:

· FLACS pressure–time curves at specified locations.
· FLACS drag (i.e. dynamic pressure/explosion wind) –time curves at specified locations.
· FLACS contour plots showing pressure, combustion products, fuel concentration and velocity vectors in various cross-sections of the module at particular time steps during the simulation.

A video showing the development of the explosion is optional.

Guidelines for FLACS projects:

· Contact your inhouse FLACS user or GexCon as early as possible and discuss when and where running a FLACS simulation is advisable.

· Regular meetings are preferable. One kick-off meeting is an absolute minimum.

· Change one parameter at a time when sensitivity studies are performed.

The FLACS code is available through GexCon [124], CMR's gas explosion consultancy, and are being used inhouse by BP, Elf, Esso (Exxon), Mobil, Norsk Hydro and Statoil.

13.9. Running FLACS on the computer

In this section a sequence of tasks, from preparing input data via simulation to presenting results, is outlined. Following this sequence reduces the possibility for inconsistencies in the input data and partitions the work into manageable tasks. It is important that written or plotted documentation is produced following each task and before starting the next one. The sequence could be:

1. State your problem
2. Define possible parameter variations
3. Define and verify the geometry
4. Define and verify the grid
5. Define and verify the scenario
6. Check for inconsistencies in tasks 2, 3 and 4
7. Calculate and verify the porosities
8. Run the simulation
9. Check the simulation log file for errors
10. Present the results
11. Store all data on tape for later use

If FLACS produces unexpected results it may be that some of the input data are incorrect or inconsistent. Below a check-list for pitfalls is presented:

Avoid large Courant numbers
Locate ignition in an unblocked volume
Locate monitors in unblocked volumes
Define realistic leakage parameters
Make sure vent areas are correct
Make sure gas composition is correct
Avoid strong transient wind build-up
Check disk space and access rights

14. μFlacs simulations

The μFlacs application is basically a PC program where functions for defining, retrieving, computing and presenting gas explosion simulations have been integrated. The purpose of μFlacs is to assist the user in making correct decisions in order to the damage consequences of accidental gas explosions. Its ease of use should encourage sensitivity studies for various layouts of a module or process plant.

The primary fields of usage for μFlacs are expected to be in the early design phase of new geometries where the overall design issues are addressed, and in hazards identification in existing geometries. In both of these fields μFlacs can serve as a screening tool.

μFlacs is a tool which should be used to determine how the layout of an offshore module should look like: optimum positioning of equipment and optimum position of vent openings. The tool has a limited memory capacity. As a result not all obstacles (piping and equipment) can be represented. Therefore the tool cannot be used for quantitative predictions of pressure development in such complex geometries.

For detailed gas explosion simulations, μFlacs cannot replace more advanced tools such as FLACS (flame acceleration simulator). The μFlacs simulator is based on the FLACS code, but μFlacs works with reduced spatial resolution to speed up computing time, it allows a simplified definition of parameters to the simulation, and the simulator is fully integrated with a graphical user interface.

Although μFlacs users should have some basic knowledge in the area of application, the relatively easy use of μFlacs will potentially make it an appropriate educational tool as well.

Details about the use of μFlacs can be found in the user guide [115].

14.1. Hardware and software requirements

To run μFlacs you need:
386 PC or higher
4 Mbyte Ram
Numerical co-processor
WINDOWS 3.0 or higher

14.2. Geometry

Most common drawing facilities are available to the user in the μFlacs graphical user interface. Previously designed geometries can be edited and new geometries designed from scratch. The μFlacs application allows you to create and edit a 3-D description of a process plant. To create or edit the 3-D description μFlacs uses three 2-D view planes (xy, xz, yz). The xy view plane corresponds to a plan view, the xz and yz to elevation views. The view planes are properly scaled to the current application. It is possible to obtain a 3-D view of the design, but the geometry cannot be edited in the 3-D viewing mode.

14.3. μFlacs validation

The validation of μFlacs has been performed by comparing μFlacs simulation results with FLACS simulation results for identical geometries and scenarios. Hence, due to the limited allowable μFlacs scenario (gas type, cloud size, concentration, output facilities, ...) and geometry representations (porosities, wall panel types, number of obstacles, ...), the FLACS input data are not as detailed and extensive as in normal FLACS applications.

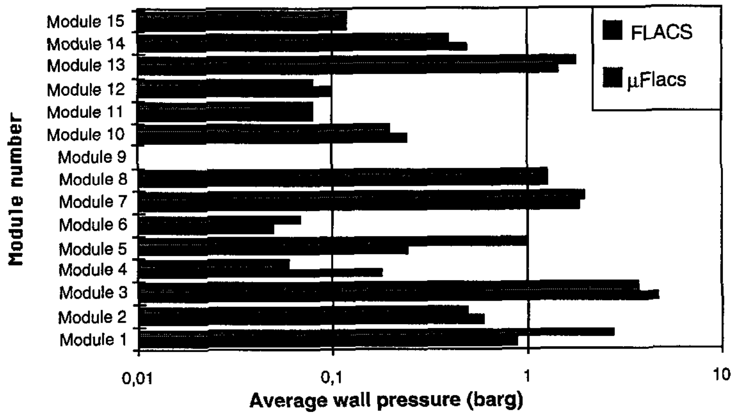


Fig. 160. Comparison between μFlacs and FLACS simulation results for 15 representative offshore geometries.

15 representative offshore geometries have been chosen for comparison between the codes. Some of these geometries have been simulated as part of GexCon work, hence results from the simulations are confidential. This Section summarises the results of the comparison exercise without disclosing any information through which the modules used can be recognised or results attributed to specific modules.

The sizes of these geometries range from 1000 m^3 to 30000 m^3. Module types include process and wellhead modules, a variety of equipment number and sizes are used. Propane or methane are used as fuels. Ignition locations vary. Explosion venting varies between almost closed to three side walls open.

Fig. 160 summarises μFlacs and FLACS simulation results in the form of maximum overpressures for the 15 modules represented in a typical μFlacs fashion (with μFlacs limitations to geometry complexity etc.).

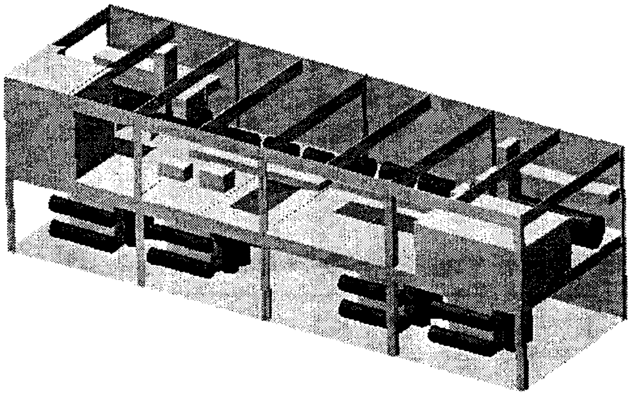


Fig. 161. Output report from a μFlacs simulation.

14.4. Output from μFlacs

Fig. 161 shows a typical output report from a μFlacs simulation.

15. Accident investigation

In the other chapters of this handbook we have been focusing on how to mitigate the consequences of gas explosions. If an accidental explosion has occurred, it is important to find out the causes of the accident and how to avoid similar accidents. The key factors of successful accident investigation will depend on the emergency plan and the expertise of the investigators.

The objectives of this chapter are to:

· List the main activities after an accidental explosion and indicate how a systematic investigation into causes can be performed.

· Discuss what type of damage can be used to indicate the chain of events.

· Present FLACS as a tool for accident investigation.

15.1. Activities after an accident

When an accident occurs, the first phase of actions consists of
(i) rescue and help
(ii) consequence reducing action, e.g. fire fighting
(iii) safe shut-down of the processes involved.

In case of a large accident, task force teams or investigation committees will be involved in the next phase to continue the operation of the facility and to analyse the accident. For minor event, this activity is often done internally by the responsible company. Fig. 162 shows the main objectives of this type of work. As shown in the figure, the co-ordinating function is important since some of these activities will have

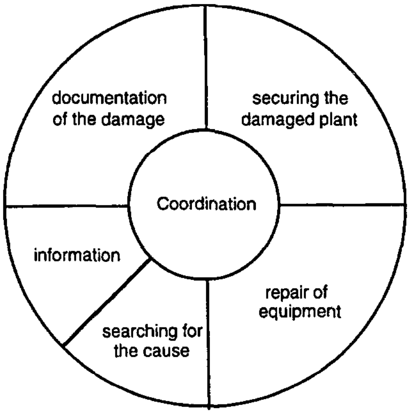


Fig. 162. Objectives of the task force teams [118].

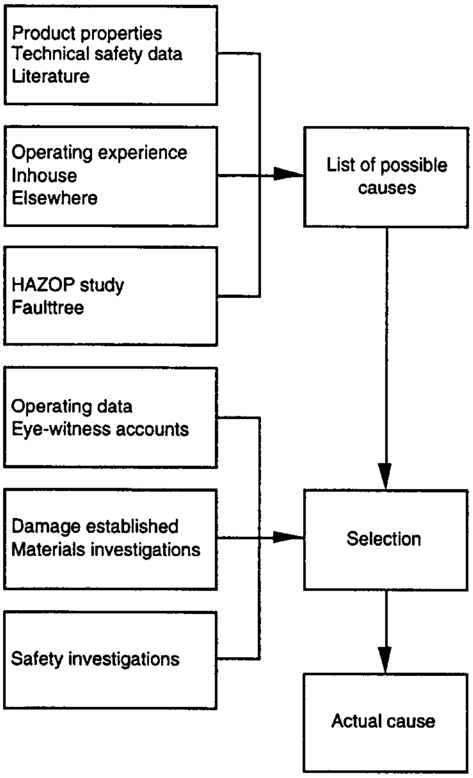


Fig. 163. System diagram of investigation into the cause [118].

different priorities or objectives. For instance repair of equipment and documentation of the damage may be contradictory, if not co-ordinated. By cleaning-up, damage indicators may be lost. After an accident a common reaction is to start cleaning up without documentation of the damage in mind. A person is therefore needed to chair the investigation committee and to co-ordinate all the activities.

Investigating the cause of an accident may require a lot of resources and time. Fig. 163 shows some typical activities in a systematic investigation into the cause of an accident.

The objective of an explosion analysis would be to calculate backwards from observed damage and from eye witness accounts: the operating data, the likely (i) gas cloud, (ii) ignition source and (iii) release source. It is also important to point out what can be done to avoid similar accidents in the future.

Useful references for such work is:

(i) Baker et al. [25]: methods for calculating the effect of explosions from damage indicators.

(ii) Lees [89]: general information on loss prevention in the process industries.

(iii) Kuchta [20]: data for combustible substances.

These sources of information should be available in accident investigations.

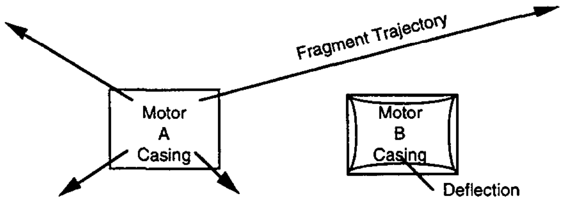


Fig. 164. Fragments and deflection structures give valuable information.

To perform the analysis will require highly qualified personnel. Baker et al. [25] recommended that a team should include an explosion expert, a structural expert and plant operation experts. These experts shall be involved immediately after the accident. Most of the useful damage indicators will otherwise be lost.

Many companies are reluctant to publish accident reports. This attitude may be understood, but Kletz [117] argues that there is a moral obligation to publish information which can prevent other accidents.

15.2. Damage indicators

Documentation of the damage has to start immediately, and should be done by an explosion expert and a structural response expert(s). Take many photographs, both of the area view and the specific damages. Use a professional photographer and make systematic records of locations and directions of all the photos taken.

Organise a fragment map, showing the original position of the fragments and where they landed. Fragments can be a good indicator of where the explosion occurred and of the magnitude of the explosion. Fig. 164 shows the trajectories of four parts of motor casings from an actual case. The casing of Motor A flew up to 15 m from its original position.

The fragments of the Motor A casing tell us that combustible gas has intruded into Motor A and that part of the explosion has been an explosion under Casing A. This explosion has most likely been the initial explosion and damage also tells us that the probable ignition location was under the casing or near Motor A.

Deflection of a ductile structure is another damage indicator. In Fig. 164 the motor casing was deflected. For Motor B, the explosion load must be from the outside. Pipes,

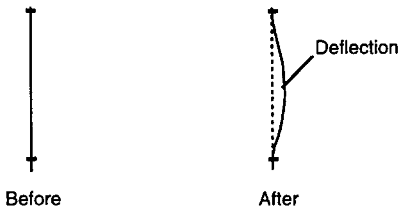


Fig. 165. Deflection of a pipe can be used as a damage indicator.

as shown in Fig. 165, or panels that have deflected can be used to estimate the loads from the explosion [25].

Damaged ordinary window glass can be used to estimate blast wave, i.e. size of cloud and maximum pressure in an explosion area, as discussed in Section 8. Size of the window, thickness of glass, type of glass and percentage of windows broken should be recorded.

15.3. The FLACS code

The FLACS code, as described in Section 13, is a useful tool in accident investigation. The FLACS code is a numerical code that predicts explosion pressure as function of time for different types of scenarios. FLACS takes into account the interaction between flame and geometry. In FLACS simulations, scenario parameters such as:

- size and fuel concentration in the combustible cloud
- type of fuel
- location of ignition point

can be defined.

The FLACS code has been used in investigations following several accidental explosions, e.g. 'West Vanguard' [4], Piper Alpha [7] and Beek [106].

By performing FLACS simulations of different scenarios and comparing the estimated damage with observed damage, a good picture of what actually happened can be obtained.

15.4. Guidelines

- Know the company's emergency plan and procedure for accident investigation.
- Accident investigation has to be co-ordinated with other activities.
- Ask for help from experienced investigators (explosion and structural experts) as soon as possible.

Fig. 166. I only said, "This seems to be a poor time to begin to develop a disaster plan". (Source: John Wiley and Sons Inc. N.Y./Stevens (1970))

· Use tools like FLACS.
· Make an open report of the findings from the investigation (Fig. 166).

16. List of terms and expressions

This chapter contains an alphabetical list of selected terms and expressions used in the handbook. Brief definitions are given. More detailed information can be found in Section 3:

Definitions.

Blast wave	· the air wave set in motion by an explosion
BLEVE	· (Boiling Liquid Expanding Vapour Explosion) an explosion caused by flashing of liquids when a vessel with a high vapour pressure substance fails
Burning rate	· the amount of fuel consumed by the combustion process per unit time
Burning Velocity ·	velocity of the flame front with respect to the unburnt gas immediately ahead of the flame
Combustion	· the burning of gas, liquid, or solid in which fuel is oxidised; involves heat release and often light emission
Confined Gas Explosion	· explosion within tanks, process equipment, pipes, in culverts, sewage systems, closed rooms, underground installations etc
Deflagration	· a combustion wave propagating at subsonic velocity relative to the unburnt gas immediately ahead of the flame
Detonation	· a combustion wave propagating at supersonic velocity relative to the unburnt gas immediately ahead of the flame
Dynamic pressure	· the pressure increase that a moving fluid would experience if it was brought to rest by isentropic flow against a pressure gradient
Explosion	· an event leading to a rapid increase of pressure
Flame Speed	· velocity of a flame relative to a stationary observer
Flash Fire	· a slow deflagration of a premixed, unconfined, unobstructed gas cloud producing negligible overpressure
Flash Point	· the minimum temperature at which a liquid fuel gives off sufficient vapour to form a flammable mixture with air, near the surface of the liquid or within the vessel used
Gas Explosion	· a process where combustion of a premixed gas cloud is causing rapid increase of pressure
GexCon	· CMR's Gas Explosion Consultancy

HVAC	· Heat, Ventilation and Air-Conditioning
Partly Confined Gas Explosion	· occurs when a fuel is accidentally released, mixed with air and ignited inside a building which is partly open
Pressure	· stress which is exerted uniformly in all directions
Reflected pressure	· pressure measured when a blast wave hits an object like a wall head-on
Side-on pressure	· pressure measured perpendicular to the propagation direction of a blast wave
Stagnation pressure	· the pressure that a moving fluid would have if it was brought to rest by isentropic flow against a pressure gradient
Static pressure	· (a) the pressure that would exist at a point in a medium if no sound waves were present, or (b) the normal component of stress exerted across a surface moving with the fluid, especially across a surface which lies in the direction of the flow
Shock Wave	· a fully developed compression wave of large amplitude, across which density, pressure, and particle velocity change drastically
Turbulence	· turbulent flow is characterized by an irregular random fluctuation imposed on mean flow velocity
Unconfined Gas Explosion	· a deflagration in an unconfined, unobstructed cloud
Vapour Cloud Explosion	· gas explosion
VCM	· vinyl chloride monomer

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