Probabilistic modelling of internal gas explosions

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Summary

Three different categories of models for prediction of overpressure due to internal explosions are discussed. These are:

(i) Empirical and codified models

A short summary of some of these is given (Eurocode model, Cubbage and Simmonds, Rasbash et al and NFPA). The models are valid for a limited range of variables such as volume, burning velocity, mass of fuel (air mixture), and vent areas.

(ii) Phenomenological models

For the prediction of explosions inside vented compartments there is one group of models referred to as phenomenological models (e.g. as implemented in the computer programs CHAOS and SCOPE). These are based on 1D considerations, trying to model some of the physics involved in the process. Input will be a rough geometry model. Output from phenomenological models will also be limited, as the geometry may only be divided into a limited number of boxes, thus the computed pressures will be the average over a large volume.

(iii) CFD-models

In the Computational Fluid Dynamics (CFD) approach one attempts to resolve the physics numerically by dividing space into small boxes (control volumes) and implementing models for various phenomena like fluid flow and turbulence. In each cell, all variables are assumed constant in one time step, and based on the flow balance and fluxes, as well as physics taking place inside the cell in the next time step, the variables may change. For explosions further models will have to be incorporated compared to a standard CFD-model, as flame propagation and combustion will have to be modelled.

Probabilistic concepts for estimation of gas explosion loads are subsequently described.The algorithm is composed of four natural sub-algorithms:

1. Estimation of probability model for fuel concentration due to gas dispersion at one leak area
2. Estimation of the probability distribution function for ignition events
3. Estimation of the probability distribution function for ignition events

4. Estimation of gas explosion overpressure for a given homogeneous cloud made of flammable fuel-air mixture

Having addressed these four steps, application of probability of exceedance curves is also elaborated upon.

Keywords

Probabilistic models, structures, internal gas explosion

Background / Introduction

According to the Memorandum of Understanding, the Activity 4 of COST TU0601 concerns the engineering modelling of relevant exposures. The task includes the modelling and assessment of the probabilistic characteristics of extreme exposure events in the first place. In addition one needs information on other (normal) loads and structural properties as they determine to a large extent the effect of the event.

Problem statement / Key issues

Explosions account for a substantial number of accidental actions in buildings. For adequate design a model for in particular internal gas or dust explosions is wanted. However, literature from a structural perspective is scarce as well as the number of interested experts. This note is an attempt to bring together some material.

Methodology

In an explosion a very large amount of energy is released in a very short time. The energy can be released via pressure, temperature, radiation and flying debris. The origin of an explosion may be of a physical or a chemical nature. Examples of physical origins are: lightning, steam pressure vessels, nuclear power. Chemical explosions are mostly caused by the detonation or deflagration of combustible gas-air-mixtures. Most gas explosions within buildings result from leakage of explosive combustible gas.

The following are necessary for an explosion to occur:

- Fuel, in the proper concentration;
- An oxidant, in sufficient quantity to support the combustion;
- An ignition source strong enough to initiate combustion.

The fuel involved in an explosion may be a combustible gas (or vapour), a mist of combustible liquid, a combustible dust, or some combination of these. The most common combination of two fuels is that of a combustible gas and a combustible dust, called a “hybrid mixture”.

Gaseous fuels have a lower flammability limit (LFL) and an upper flammability limit (UFL). Between these limits for the fuel air ratios, ignition is possible and combustion will take place. The maximum explosion pressure is normally reached at the so-called stoichiometric mixture. Combustible dusts also have a lower flammability limit, often referred to as the minimum explosive concentration. For many dusts, this concentration is about 20 g/m³. The oxidant in an explosion is normally the oxygen in air. Moisture absorbed on the surface of dust particles will usually raise the ignition temperature of the dust because of the energy absorbed in vaporizing the moisture. However, the moisture in the air (humidity) surrounding a dust particle has no significant effect on an explosion once ignition has occurred.

Gas or dust explosions can be divided into two groups: deflagration and detonation:

At a ***deflagration*** the continuation of the chemical reaction is caused by transport of heat. The flame front travels through the mixture at a subsonic speed (0.1 - 100 m/s). Exact values for this propagation speed, however, are very difficult to establish and depend on many circumstances. As long as the medium is homogeneous and undisturbed, a point wise ignition will lead to a spherical flame front. Due to the release of energy the material expands during reaction (in the end the reacted gas cloud will roughly have doubled the original diameter). The expansion leads to pressure waves in the surrounding gas air mixture and in the air outside the cloud. These pressure waves travel with the local speed of sound. The shape of the pressure wave is indicated in Figure 1a. Peak pressure values may vary from 10 to 1000 kPa or kN/m^2.

At a ***detonation*** the continuation of the chemical reaction is caused by the high pressures in a shock wave, travelling at a supersonic speed (100-10000 m/s). A typical value for the pressure is 2000 kN/m^2 but the peak duration is very short (12 ms). The shape of the shock wave is indicated in Figure 1b. It is possible that a flame front, starting with low speed, accelerates. In that case a transition of a deflagration to a detonation can happen. This mechanism, however, occurs nearly only in long pipelines or tunnels. An exception may be acetylene. Another phenomena is that the deflagration pressure wave is transformed into a shock wave. This phenomena is caused by the dependence of the speed of sound on the pressure itself; the higher the pressure (and temperature) the higher the speed, and vice versa.

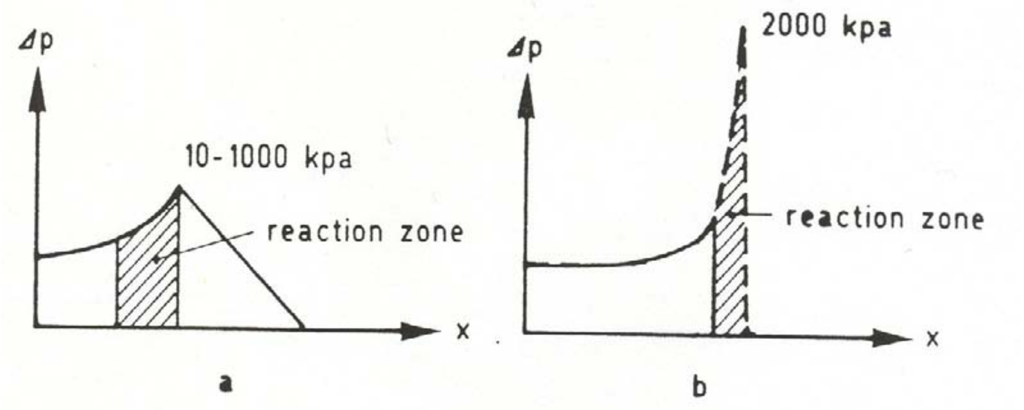

Figure 1: Pressure waves inside the explosion medium: (a) deflagration, (b) detonation

In completely closed rooms with infinitely strong walls gas explosions may lead to pressures up to 1500 kN/m^2, dust explosions up to 1000 kN/m^2, depending on type of gas or dust. In practice, pressures generated are much lower due to imperfect mixing and the *venting* that occurs due to failure of doors, windows and other openings. Windows respond in a brittle manner because the thinness of the glass makes very little deformation possible before there is complete disintegration. For this reason, coupled with their relatively lightweights and low static strengths, they make good explosion vents. But venting is also caused by failure of non-structural relatively weak wall panels or even top story roofs. A typical pressure time relationship as a function of time is shown in Figure 2. First a pressure is being built up following the "closed vessel curve". Then the pressure is released because of breaking of panels and subsequent venting of the explosion. After some time of low pressure, however, so-called acoustically driven flame instability can occur [4]. This phenomenon can occur only in relatively large spaces (room size) and has not been observed in small scale vessel experiments. The very high frequent load, however, is of limited structural significance.

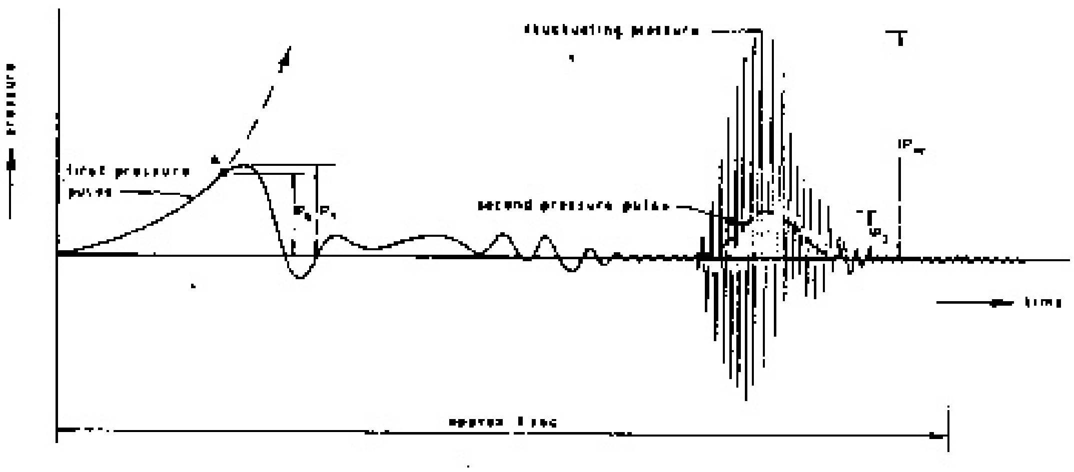

Figure 2: Pressure as a function of time as observed in tests [Dragosavic 1973]

Main findings / Discussion

(1) Pressures due to internal explosions

Empirical and codified models

Numerous empirically methods predicting explosion overpressures based on explosion venting, are published in the literature. Annex A gives a short summary of some of them (Eurocode model, Cubbage and Simmonds, Rasbash et al and NFPA). The models are valid for a limited range of variables such as volume, burning velocity, mass of fuel (air mixture), and vent areas. The empirical correlations are based on the concept of a vent coefficient K:

$$K = \frac{A_s}{A_v} \qquad (1)$$

where A_s means the area of side of enclosure, and A_v the area of the vent opening.

Loads on structural members are not only determined by the peak pressure in the room , but also depends on the total configuration. For instance in figure 3 the column D will be loaded by an almost all sided pressure and may survive the explosion. Rules for calculating loads on elements are present in various documents.

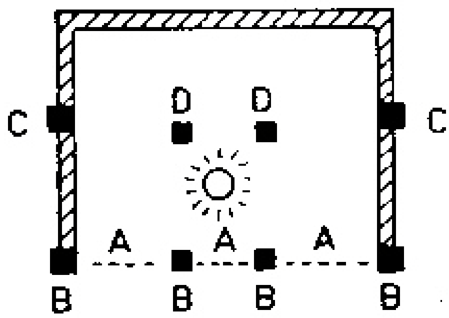

Figure 3: Different situated columns will be loaded differently (panels A are venting panels).

Phenomenological models

For the prediction of explosions inside vented compartments there is one group of models referred to as phenomenological models (e.g. as implemented in the computer programs CHAOS and SCOPE). These are based on 1D considerations, trying to model some of the physics involved in the process. From ignition, the flame will accelerate and is influenced by the obstruction density. The heat release generates overpressure and flow towards the vent opening. A typical module may be divided into a limited number, typically less than 10 different boxes (control volumes). Effects not picked up by the physics will be handled by a range of empirical constants found from calibrating against a range of relevant experiments.

Input will be a rough geometry model. The available vent area is of importance, and for each subdivision of module in the simulation, the blockage will have to be estimated. The chamber of ignition will have to be given. Now and then, these models are applied for other situations than developed for, e.g. for less confined modules that are not typical 1D situations. High uncertainty should be expected for such applications. In principle such models can be considered just as CFD-models with a very coarse (poor) grid resolution.

Output from phenomenological models will also be limited, as the geometry may only be divided into a limited number of boxes, thus the computed pressures will be the average over a large volume. No local pressure peaks will be picked up, this is another reason why these models are of low value when applied to more open process areas and modules. Validation of these models will generally be through comparison of simulation results with experiments.

CFD-models

In the Computational Fluid Dynamics (CFD) approach one attempts to resolve the physics numerically by dividing space into small boxes (control volumes) and implementing models for various phenomena like fluid flow and turbulence. In each cell, all variables are assumed constant in one time step, and based on the flow balance and fluxes, as well as physics taking place inside the cell in the next time step, the variables may change. For explosions further models will have to be incorporated compared to a standard CFD-model, as flame propagation and combustion will have to be modelled. Thus equations for:

- mass balance (continuity)
- impulses
- entalpy
- turbulence
- fuel transport and mixture fraction.

are solved for each time step and control volume.

If only blast pressures in the far field are to be assessed, models like [Clutter, 1999] may be used. This is a reduced model. Based on a simplified geometry representation, and assumption on constant (high) burning velocity, blast curves for a specific situation can be generated. By treating the geometry simplified, details about the flame development will be lost, and one has to assume an explosion strength.

Several of the weaknesses with the different empirical curves are avoided with this approach, but on the other hand simulation time will be significant, and close to the same as for a full CFD-simulation. Also advanced CFD-models can be used for such a simplified approach, if it is considered too expensive to generate the detailed geometry model.

There is a range of CFD-models that claim to simulate gas explosions. To be able to develop such tools properly good knowledge about experiments and physics will be needed.

Special purpose CFD-models, like FLACS, EXSIM and Auto Reagas have a greater potential to perform well, as all of these simulators are developed by people doing experimental and theoretical work within gas explosions. Still, significant differences will be seen between the models, both with regard to applicability and validity. Despite the much better resolution in space compared to phenomenological models, there is still a lot of physics taking place at smaller scales than the grid cell (typically 0.5m-1.0m in an offshore or industrial module). Examples of such sub-grid models are:

- Turbulence
- Flame propagation / wrinkling
- Water deluge.

This is one reason why effort related to model development and validation is important, and that there will be differences between different CFD-models, even if they may seem similar.

Since geometry and scenario details are of high importance for explosions, the special purpose CFD-models need to represent geometry properly. Porosities/blockages are calculated due to geometry mapping onto the simulation grid. Geometries can be either defined by hand or imported from CAD systems. EXIM and Auto Reagas use a similar concept.

The output from a simulation with CFD-models has few limitations. Output may be either pressures, flames or any other parameter modelled, either as a 2D/3D fieldplot of one variable at one or more (movie) time steps or transient pressure traces at certain locations or wall panels.

One group of explosion models also aims at adaptive grid refinement around fine geometry, shocks, flame fronts, etc., e.g. [Watterson, 1998]. This approach is considered close to useless for a typical offshore geometry, as the whole volume will consist of either detailed geometry, pressure/density gradients, flame interfaces etc. Still the fine grid to be applied will not be fine enough to resolve the physics properly (i.e. by Direct Numerical Simulation). Hence, sub-grid models will have to be developed. With this approach, the development of sub-grid models will be very resource demanding. For special applications like tunnel explosions, it may still be a good idea.

In practice, the accuracy of the CFD models is limited by:

Available computation power limiting the numerical resolution that can practically be used

- Accuracy of numerical models
- The underlying empirical sub models for
- Reaction zone
- Turbulence generation
- Turbulence length scale
- Turbulent combustion

Some of the relevant conclusions regarding selection of prediction tools can be summarised as:

- The phenomenological code SCOPE and 'simple' CFD codes FLACS, AutoReaGas, and EXSIM are in widespread use.
- Phenomenological and CFD methods generally give fairly good accuracy (within an factor of two) so these models yield solutions that are approximately correct.
- The limitations associated with empirical and phenomenological methods (simplified physics and relatively crude representation of geometry) can only be overcome through additional calibration.
- It is recommended to develop 'advanced' CFD codes that will allow fully realistic combustion models and resolution of all obstacles. However it is likely to be many years

before such tools are available. This is primarily due to the large computational expense of this type of model.

Further evaluation of the methods can be found e.g. in [Czujko, 2001].

Statistics

Explosion loads fall into the category of accidental loads. The most important statistical description is concerned with the probability of such a loading being present or not. As a function of time the ***occurrence of an explosion*** can be considered as a Poisson process:

$$P(\text{at least one explosion during } \Delta t) = 1 - \exp(-\lambda \Delta t) \approx \lambda \Delta t \qquad (2)$$

where λ is the probability of an explosion event per unit of time. The value of λ depends on the type of explosion. For internal explosions in nonindustrial buildings an extensive survey performed in the UK gives some interesting data [Moore]. The values are in the order of 2×10^{-6} per year for dwellings and 6 to 14×10^{-6} for shops and industrial buildings. Present rates may be smaller due to improved safety measures. In the US higher values (18×10^{-6}) have been found for residential buildings [11]. In the Netherlands yearly about 20 explosions are observed leading to $\lambda \cong 5 \times 10^{-6}$ as an average per dwelling/building. The occurrence rate found, however, depends on whether small explosions (giving little damage only) are also taken into account.

The next step is to model the ***magnitude of the explosion***, conditional upon occurrence. For internal explosions the maximum pressure can be taken as the maximum of the "breaking pressure" and the "vent controlled pressure". For the breaking pressure a proper resistance model should be selected. The "vent control pressure" as observed in practice (as good as possible) can be estimated from Figure 3. The Eurocode line may be considered as an average and the coefficient of variation is about 0,7.

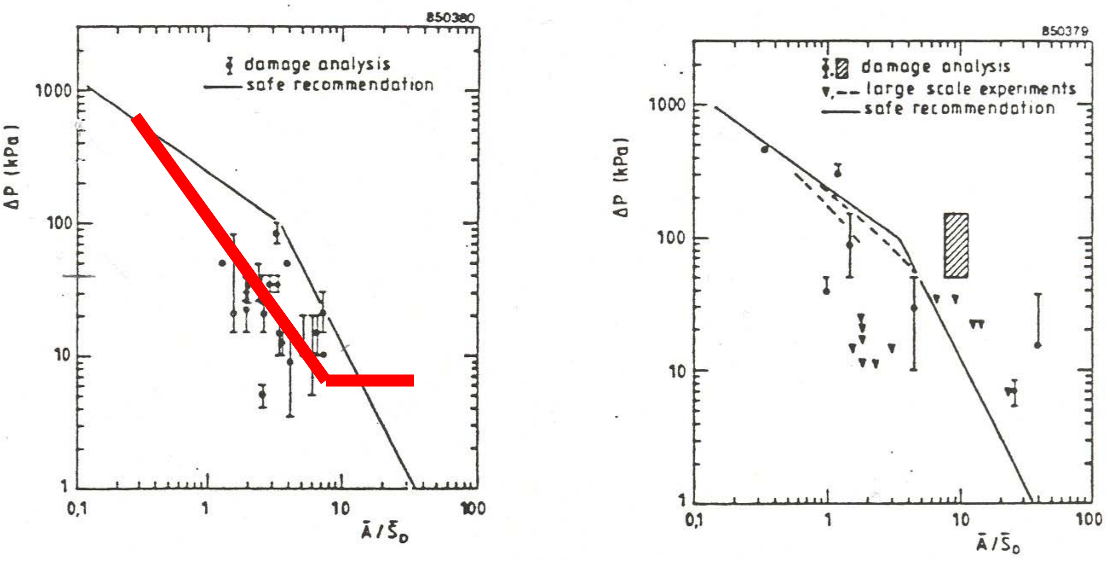

Figure 3 The relationship between the vent parameter $\overline{A}/\overline{S_o}$ and the peak pressure [Zeeuwen and van Wingerden] for dwellings (left hand side) and industrial buildings (right

hand side) where $\bar{A} = 0.6\ A_v/A_s$ and $\overline{S_o} = 7\ S_o/c_o$ (dimensionless burning velocity) and c_o is 340 m/s. The red line shows the Eurocode recommendation.

The magnitude of the overpressure, depends on many factors and data parameters, deterministic and random (see Annex A). Some of them are common with the probabilistic model of the fuel concentration, while others are not. Depending on the desired accuracy of probabilistic model, random parameters can be represented by random variables, random processes (in time) and random fields (in space and time). For example, a random vector describes a random position of leakage, but the flow rate of gas is a random process (function) in time. The wind velocity and wind direction can be modelled by a random field or a random process (for averaged wind over some volume).

When the fuel-air cloud has been formed in some area of the investigated volume, it can be ignited. A weak ignition source is a common cause of gas explosion. The combustible fuel-air cloud can explode due to a spark within an area with the fuel concentration within flammability limits or due to autoignition of gas after contact with a hot spot. These events can take place at different sub-volumes of the investigated volume/structure. The probability of gas explosion at those areas may vary.

Consistent algorithms for estimation of gas explosion loads are given in [Czujko, 2001].The algorithm is composed of four natural sub-algorithms:

1. Estimation of probability model for fuel concentration due to gas dispersion at one leak area
2. Estimation of the probability distribution function for ignition events
3. Estimation of the probability distribution function for ignition events
4. Estimation of gas explosion overpressure for a given homogeneous cloud made of flammable fuel-air mixture

In case of estimation of CDF for gas explosion overpressure three extra parameters are considered as random: position of ignition source, time to ignition and strength of ignition. It has been assumed that all random parameters/factors are modeled with help of random variables.

Probability of exceedance curves

The output from the probabilistic analysis is typically expressed by means of ”Probability of exceedance” curves. These are calculated based on the loads at each of the walls and roof/floor components which are considered. For cases where there are multiple options for risk prevention and/or mitigation, each of the options can be represented by separate curves. In this manner, quantification of the effects of each of the possible actions can be readily assessed.

Depending on the duration and shape of the pressure peak, the importance of the maximum explosion pressure on the structure will vary. For very short pressure peaks, that will often be seen in low confinement situations, the maximum value may not be so important, unless the pressure impulse exceeds a certain limit. For this reason, it may be worthwhile to include the pressure impulse as a 3rd variable. 3D-surfaces plotting probability of exceeding both a pressure level and an impulse level can be useful for a simplistic structural assessment.

When numerical methods are applied, other model uncertainty factors will clearly be relevant as compared to the analytical approach. For quantification of the model uncertainty related to numerical models, see e.g. Paik et. al. (2009).

Limitations

The limitations of the different approaches which are applied for assessment of explosion loading clearly depend on the particular method that is selected. For the simplest methods the degree of accuracy that can be achieved is a limiting factor. For the most accurate methods based on extensive numerical simulations, a strong limitation will be the required computation time. Furthermore, the degree of precision which is associated even with the most refined calculations is frequently unknown unless comparable benchmark tests are available.

Recommendations

The various types of prediction models need to be selected based on consideration of the purpose of the calculation. It is recommended that for critical scenarios with potentially high consequences the most advanced calculations should be applied.

There is clearly a significant potential for further development of the most complex numerical models both with respect to increase of accuracy and reduction of computation time.

Outlook to further research

In order to reduce the model uncertainty related to calculation of explosion loads, there will be a continuous development of numerical CFD models. In order to calibrate the models and verify that the proper physical and chemical effects have been included comparison with results from experimental tests will be crucial. In order to reflect the inherent uncertainties related to input parameters and calculation models a probabilistic representation is essential. In parallel with numerical and experimental developments there will hence be a corresponding updating of the probabilistic models. Improving the predictive power of the calculation models will then at the same time reduce the variation range of the random variables.

Example / Illustration / Case studies

The models mentioned in Annex A will be compared for a simple example of a room (see figure 4) having a ground floor area of about 5 m x 12 m and a height of 3m. The vent area corresponds to a total window area of 30 m^2. This gives the following data:

V	Volume	180 m^3
As	Area of side of enclosure	200 m^2
Av/V	Vent area parameter	0.01 - 0.20 m^{-1}
pv	Vent breaking pressure	3 kN/m^2
So	Burning velocity	0.45 m/s
W	Mass density of vent material	20 kg/m^2

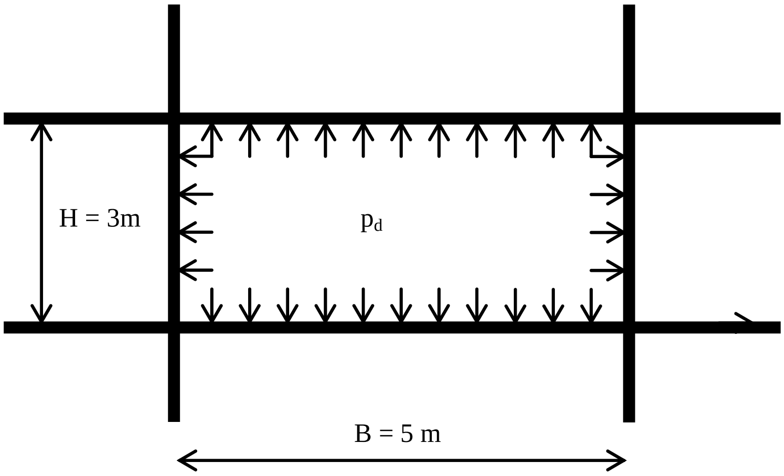

Figure 4: Pressure in a small room of 3m x 5m, length 12 m; the front and back facade (2x3x5=30 m2) may be considered as venting panels

Given these numbers the following results for an internal explosion of natural gas (all converted to in kN/m^2) is obtained:

			Av/V [m^{-1}]	Av [m^2]	K	EN	cubbage	rasbash	nfpa
						kN/m^2	kN/m^2	kN/m^2	kN/m^2
			0,01	1,60	125,00	404,50	89,49	534,11	3125,00
V	160	m3	0,02	3,20	62,50	104,50	44,86	269,42	781,25
As	200	m2	0,03	4,80	41,67	48,94	29,99	181,20	347,22
pv	3	kN/m2	0,04	6,40	31,25	29,50	22,55	137,08	195,31
So	0,45	m/s	0,05	8,00	25,00	20,50	18,08	110,61	125,00
W	20	kg/m2	0,06	9,60	20,83	15,61	15,11	92,97	86,81

			Av/V [m^{-1}]	Av [m^2]	K	EN	cubbage	rasbash	nfpa
			0,07	11,20	17,86	12,66	12,98	80,36	63,78
			0,08	12,80	15,63	10,75	11,39	70,91	48,83
			0,09	14,40	13,89	9,44	10,15	63,56	38,58
			0,10	16,00	12,50	8,50	9,16	57,67	31,25
			0,11	17,60	11,36	7,81	8,35	52,86	25,83
			0,12	19,20	10,42	7,28	7,67	48,85	21,70
			0,13	20,80	9,62	6,87	7,10	45,46	18,49
			0,14	22,40	8,93	6,54	6,61	42,55	15,94
			0,15	24,00	8,33	6,28	6,18	40,03	13,89
			0,16	25,60	7,81	6,06	5,81	37,82	12,21
			0,17	27,20	7,35	5,88	5,48	35,88	10,81
			0,18	28,80	6,94	5,73	5,19	34,15	9,65
			0,19	30,40	6,58	5,61	4,93	32,60	8,66
			0,20	32,00	6,25	5,50	4,70	31,20	7,81
			0,21	33,60	5,95	5,41	4,48	29,94	7,09
			0,22	35,20	5,68	5,33	4,29	28,80	6,46
			0,23	36,80	5,43	5,26	4,11	27,75	5,91
			0,24	38,40	5,21	5,19	3,95	26,79	5,43
			0,25	40,00	5,00	5,14	3,80	25,91	5,00

Notes:

1. Some of these formula have been used outside the claimed domain of application: For Cubbage and Rasbash the assumption is that $K \leq 5$ and for NFPA that W < 12,2 kg/m^2. Nevertheless all results are presented over the total range.
2. Rashbash seems to conside with the upperbound curve in Figure 3 for $\bar{A} / S_o < 4$.
3. NFPA seems to coincide with the upper bound curve in Figure 3 for $\bar{A} / S_o < 4$.
4. The Eurocode is more or less an average for $\bar{A} / S_o > 2$, for smaller values it approaches the upper bound.
5. Cubbage seems to be a bit on the low side.

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Annex A: Description of empirical pressure models

(1) Eurocode EN 1991-1-7

The pressure model for ***rooms in buildings*** in the Eurocode is given by the maximum of

$$p_d = 3 + p_v$$

p_d = 3 + 0.5 p_v+0,04/(A_v/V)^2

where A_v is the area of venting components [m^2], p_v is the uniformly distributed static pressure at which venting components will fail and V the volume of room [m^3]. The range of application is up to V = 1000 m^3 and the ratio A_v/V should be within the interval from 0.05 till 0.15 m^{-1}. The explosive pressure acts effectively simultaneously on all of the bounding surfaces of the room. The peak pressures may be considered as having a load duration of 0.2s.

In ***tunnels***, for the case of detonation, the following pressure time function may be taken into account:

$$p(x,t) = p_0 \exp\{-(t - \frac{|x|}{c_1})/t_0\} \qquad \text{for} \frac{|x|}{c_1} \le t \le \frac{|x|}{c_2} - \frac{|x|}{c_1}$$

$$p(x,t) = p_0 \exp\{-(\frac{|x|}{c_2} - 2\frac{|x|}{c_1})/t_0\} \qquad \text{for} \frac{|x|}{c_2} - \frac{|x|}{c_1} \le t \le \frac{|x|}{c_2}$$

$$p(x,t) = 0$$

for all other conditions

p_0: peak pressure (=2000 kN/m2)

c_1: propagation velocity of the shock wave (~1800 m/s)

c_2: acoustic propagation velocity in hot gasses (~800 m/s)

t_0: time constant (=0.01s)

¦x¦: distance to the heart of the explosion

t: time [s]

In case of deflagration the following pressure time characteristic should be taken into account:

$$p(t) = 4p_0(\frac{t}{t_0})(1 - \frac{t}{t_0}) \qquad \text{for } 0 \le t \le t_0$$

p_0 is the peak pressure (=100 kN/m^2) for a typical liquefied natural gas fuel;;

t_0 is the time constant (= 0,1 s);

t is the time.

(2) Cubbage and Simmonds

This is probably the most widely used of the formulae which are presented. The Cubbage and Simmonds' equations contain terms expressing the effect of characteristics of both the gas-air mixture and the enclosure in which the explosion occurs. They may be used for any type of gas-air-mixtures since the influence of combustion characteristics of different gases on the pressure generated is allowed for by the burning velocity S_0 This is the velocity with which the flame front moves relative to the unburned mixture immediately ahead of it.

$$P_1 = S_0 \cdot \frac{(4.3 \cdot K \cdot W + 28)}{V^{\frac{1}{3}}}$$

$$P_2 = 58 \cdot S_0 \cdot K$$

P_1: pressure of the vent removal phase [mbar]

P_2: pressure of the venting phase [mbar]

S_0: burning velocity [m/s] (natural gas 0.45 m/s)

K: vent coefficient, dimensionless

W: weight per unit area of the vent cladding [kg/m^2]

V: volume of room [m^3]

Range of application:

- Max and minimum dimensions of room have a ratio less then 3:1: $L_{max} : L_{min} \leq 3 : 1$
- The vent area coefficient; K, is less then 5: $K \leq 5$
- The weight per unit area of the vent cladding W must not exceed 24 kg/m^2

(3) Rasbash et al

The equation of Rasbash et al. can be expected to predict the maximum overpressure generated in a given situation, irrespective of whether this relates to P_1 or P_2.

$$P_m = 1.5 P_v + S_0 \{ [\frac{(4.3K \cdot W + 28)}{V^{\frac{1}{3}}}] + 77.7K \}$$

P_m: maximum overpressure [mbar]

P_v: static pressure at which venting components will response [mbar]

S_0: burning velocity

K: vent coefficient

W: weight per unit area of the vent cladding

V: volume of room

Range of application:

- Dimensions of room have a ratio less than 3:1: $L_{max} : L_{min} \leq 3 : 1$
- The vent area coefficient; K, is between 1 and 5: $1 \leq K \leq 5$

- The weight per unit area of the vent cladding does not exceed 24 kg/m^2: $W \leq 24$ kg/m^2
- The response pressure of the vent cladding, overpressure required to open it, does not exceed 70 mbar: $P_v \leq 70$ mbar

(4) NFPA 68, Guide for Venting of Deflagrations, 2002 Edition for low strength buildings

The Guide for Venting of Deflagrations of the National Fire Protection Association proposes for low strength buildings the following equation to determine the maximum pressure developed in a vented enclosure during a vented deflagration of a gas- or vapour-air-mixture:

$$P_{red} = (C^2 \times A_s^2) / A_v^2$$

P_{red}: maximum pressure developed in a vented enclosure (deflagration)

A_v: vent area in m^2

A_S: internal surface area of enclosure in m^2

C: venting equation constant in (bar)$^{1/2}$

The maximum pressure P_{red} can not be larger than the enclosure strength P_{es}. P_{red} should not be greater than 0.1 bar.

From the following table the values for the venting equation constant can be seen:

gas- or vapour-air-mixture	**venting constant C (bar)$^{1/2}$**
anhydrous ammonia	0.013
methane	0.037
gases with fundamental burning velocity < 1.3 that of propane	0.045
hydrogen	not available

There are no dimensional constraints on the shape of the room besides that the shape is not extremely one dimensional. As a check the following equation should be used:

$$l_3 < 8 \times (A / U)$$

where l_3 is the longest dimension of the enclosure, A the cross-sectional area in m^2 normal to the longest dimension and U the perimeter of cross section in m. The vent closure should weight not more than 12.2 kg/m^2.

(5) NFPA 68, Guide for Venting of Deflagrations, 2002 Edition for high strength buildings

The required vent area for a rectangular enclosure is determined according to the following equation:

$A = [(0.127 * \log_{10} K_G - 0.0567) * p_{Bem.}^{-0.582} + 0.175 * p_{Bem.}^{-0.572} (p_{stat.} - 0.1)] * V^{0.667}$

A vent area [m^2]

p_{max} maximum explosion overpressure of the dust

K_G deflagration index of gas [bar m s^{-1}]

p_{Bem} design strength of the structure [bar]

p_{stat}: static activation overpressure with size of existing vent areas [bar]

V: volume of enclosure [m^3]

This equation is valid for the following conditions:

- $V \leq 1'000\ m^3$
- $L/D \leq 2$, where L is the greatest dimension of the enclosure, $D = 2 * (A / \pi)^{0.5}$, A is the cross-sectional area normal to the longitudinal axis of the space
- $p_{stat} \leq 0.5$ bar, $p_{stat} < p_{Bem.}$
- $0.05 \leq p_{Bem.} \leq 2$ bar
- $K_G \leq 550$ bar m s^{-1}

For elongated rooms with $L/D \geq 2$ the following increase for the vent area has to be considered:

- $\Delta A_H = A * K_G (L/D - 2)^2 / 750$
- ΔA_H increase for vent area [m^2]

Annex B: Table CFD parameters

Deterministic factors	Random factors
type of problem: e.g. gas explosion in vessels, gas explosion in buildings / off-shore modules, gas explosion in uncon-fined process areas	position of leakage points. (They can be even deterministic with different proba-bilities of gas dispersion events.)
shape and sizes of structure / processing area	flow rate of gas/liquid
shape, location and sizes of equipment	wind direction and velocity
type of fuel and oxidiser	air exchange rate due to natural ventila- tion [and forced ventilation
size, location and type of explosion vent area	ignition source: strength and position
mitigation system	time to ignition: time delay after gas has been released
minimum ignition energy as a function of fuel concentration	temperature field
autoignition temperature	
flammability limits (in terms of fuel-air concentration) as a function of tempera ture	
stoichiometric composition, which gives usually the highest explosion pressure	