HAZARDS OF ACCELERATED GAS EXPLOSION VENTING AND THEIR SAFETY-RELEVANT PARAMETERS

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The effects of a gas explosion in enclosures like vessels can be limited e.g. by gas explosion venting systems. The major design step of this constructive explosion protection method is to determine the required vent area, which depends significantly on whether turbulent combustion exists. However, current standards like NFPA 68 or EN 14994 are applicable only to limited boundary conditions and as far as possible only to laminar flame propagation. Difficulties arise in the assessment or predictability of gas explosion hazard when turbulence occurs.

In this research especially venting at elevated initial pressure has been shown to accelerated flame propagations and therefore, to a considerably higher reduced pressure. Therefore, it is essential to provide a broader data base of turbulent combustion and explosion behaviour to verify the existing rules or to determine their safety-relevant parameters.

For a better safety assessment or design of protective systems the turbulent combustion and accelerated gas explosion behaviour of quiescent methane in air were investigated at initial pressures up to 8 bar using vessels up to 100 litres. In particular a systematic study was performed to investigate the influence of turbulence on the overpressure development during accelerated gas explosion. Moreover, the present study consider the position of the spark igniters, the burning velocity and the maximum pressure rise for different concentration of fuel as well as the size of orifice and/or vent area.

A choice of experimental tests showed under the investigated conditions that not only turbulence inducing obstacles but also over sized vent areas could lead to an increased pressure development and therefore to an inacceptable safety state. Due to the numerous influencing variables of explosion behaviour the presented experimental results help to judge whether another more sophisticated method should be applied than the one described in standards.

KEYWORDS: turbulent combustion, obstacles, explosion acceleration

1. INTRODUCTION AND BACKGROUND

Many industrial processes include a gas explosion hazard. If safety measures are not adequate to prevent a potentially explosive atmosphere or to avoid effective ignition sources in enclosures, at least the effects of an explosion can be limited e.g. by gas explosion venting systems. The major design step of this constructive explosion protection method is to determine the required vent area, which depends significantly on whether turbulent combustion exists. Turbulence will be generated or increased, e.g. by obstacles, bends [1] or by venting itself at elevated pressure (Poli, 2010). However, current standards like NFPA 68 or EN 14994 are applicable only to limited boundary conditions and for the most part to laminar flame propagation.

Difficulties arise in the assessment of turbulence. In this case a more sophisticated method shall be applied and the utilisation of large codes like computational fluid dynamics is inevitable. But there is a general lack of knowledge on the effects of turbulence on gas explosion venting of vessels at elevated initial pressure. The current available data have to be regarded as insufficient. Therefore, it is essential to provide a broader data base to verify the existing rules or to determine their safety-relevant parameters in order to get a better understanding.

As part of a safety concept, reactors and other high pressure containers have to be protected against excessive pressure by pressure relief devices such as bursting discs (Bartknecht, 1993). During the design of safety devices for gas explosions in enclosures the vent area have to be calculated. Hereby, the maximum pressure developed in the vented vessel is P_{red}, which should be ideally smaller than the burst pressure P_{burst} (Fig.1).

Widely accepted design rules are described, amongst others, in NFPA 68 “Standard on Explosion Protection by Deflagration Venting”, VDI 3673 (VDI_3673, 2004) and EN 14994 “Gas explosion venting protective systems”.

Moreover, some additional standards are of interest, which specifies requirements for venting devices (EN 14797) or which specifies requirements for explosion-pressure-resistant equipment (EN 14460) or which describes how to handle explosion isolation systems (EN 15089). In all cases two safety characteristics are essential for the design of explosion protection: the explosion pressure P_{ex} – normally the peak value in a closed vessel – and

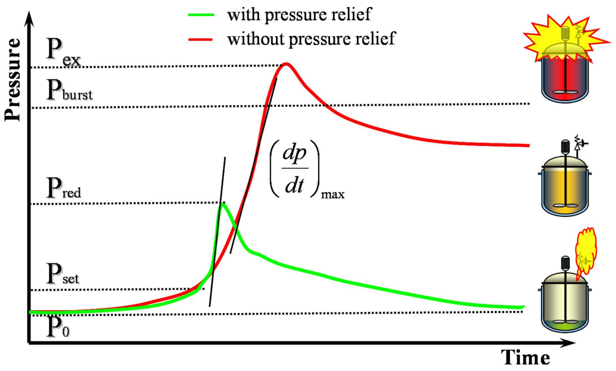

Figure 1. Schematic pressure profiles of gas explosion with and without pressure relief

the maximum explosion pressure rise $(dp/dt)_{max}$ and/or according to the cubic law the K_G-value, Eq.(1). Their determination is described in EN 13673. Latter is important for most vent sizing methodologies and is proportional to the vent area. The recommended semi-empirical design criterion of Bartknecht, Eq.(2), is inapplicable if the boundary conditions exceed $P_{red} > 2$ bar, $L/D > 2$, $V > 1.000\ m^3$, K_G-value > 550 bar m/s. The major constraint is the fact that the maximum explosion pressure rise depends significantly on whether turbulent combustion exists (Razus and Krause, 2001; Steen, 2000; Zalosh, 2008).

$$K_G = \left.\frac{dp}{dt}\right|_{max} \cdot \sqrt[3]{V} \quad \left[\frac{bar \cdot m}{s}\right] \tag{1}$$

$$A = \left\{\left[(0.1265\ \lg(K_G) - 0.0567)P_{red}^{\ -0.5817}\right] + \left[0.1754\, P_{red}^{\ -0{,}5722}(P_{stat} - 0.1\ bar)\right]\right\} V^{\frac{2}{3}} \tag{2}$$

The alternative design criterion of Heinrich, Eq.(3), uses also the K_G-value and derives from the efflux function (Heinrich, 1970). The applicability for higher initial pressures $P_0 > 2$ bar was proved for methane/air mixtures by Hattwig (Hattwig, 1987). He provides the following proportionality for cubic containers up to 20 m^3 and K_G-values less than 100 bar m/s: $A \sim V^{2/3} \sim K_G$. It should be noted that this method is not always conservative (Daubitz et al., 2001).

$$A = \frac{V^{2/3}\ K_G}{\alpha\ p_{red}\ \kappa \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \sqrt{\frac{\kappa}{\kappa+1}\ \frac{2RT}{M}}} \tag{3}$$

The following safety-relevant parameters are well known to influence explosion venting and therefore the maximum pressure developed in the vented vessel (P_{red}):

- Initial boundary conditions (P_0, T_0, gas composition)
- Position, energy and type of ignition source
- Characteristic parameters (K_G-Value, max. explosion pressure P_{ex})
- Geometry of the vessel (e.g. length/diameter ratio, enclosure volume V)
- Number, dimension and position of turbulence inducing obstacles
- The static load vent deployment pressure (P_{stat})
- Efficiency of pressure relief devices.

Turbulence exists in all (un-)reactive flows and can be enhanced, for example, by forcing the flow through or around an obstacle (Park et al., 2008). Furthermore, it is widely accepted that initial or induced turbulence in the system can accelerate the burning velocity by increasing the molecular transportation of heat and mass in reactive flows due to increased convection (Blanchard et al., 2010a). In this paper an enhanced turbulent deflagration is defined by significant acceleration of combustion and all turbulence sources can lead to higher rates of pressure rise and higher maximum overpressures. More complex flow patterns such as those found in industrial applications can therefore lead to a greater enhancement of the turbulence. In particular explosion flames can accelerate to detonation or pressure piling needs to be considered (Heinrich, 1974). Under certain boundary conditions free convection can likewise be important. However, the venting behaviour under initially quiescent conditions is of special interest.

Over sizing of relief apparatus has also in some cases been shown to enhance turbulence and lead to higher overpressures (Daubitz et al., 2001). Consequently the lack of knowledge on turbulence generation or an uncertainty on the influence of obstacles at elevated initial pressure can lead to conservative assumptions and finally to undersized devices.

However, current standards are applicable only to ambient or limited boundary conditions and laminar flame propagation. So they are inapplicable to turbulent gas explosions.

The purpose of the present investigation was to gain a deeper knowledge of the influence of certain obstacles or boundary conditions on explosion venting.

2. EXPERIMENTAL SET UP

Two different kinds of vessels were used for the aims and purposes of the present experimental investigations. Here, the influence of vent size on the venting behaviour at elevated initial pressure was performed in a 6-litre-autoclave without any obstacle, whereas the influence of obstacles during gas explosion venting on the K_G-value was generally performed in an 86-litre-autoclave.

2.1 APPARATUS AND BOUNDARY CONDITIONS

A systematic study was carried out by investigate the influence of vent sizes or turbulence generation on the overpressure development during gas explosions of different methane-air mixtures at 1, 2 and 5 bar (P1, P2, P5). Here, a vertical and cylindrical autoclave of 6 litres with an

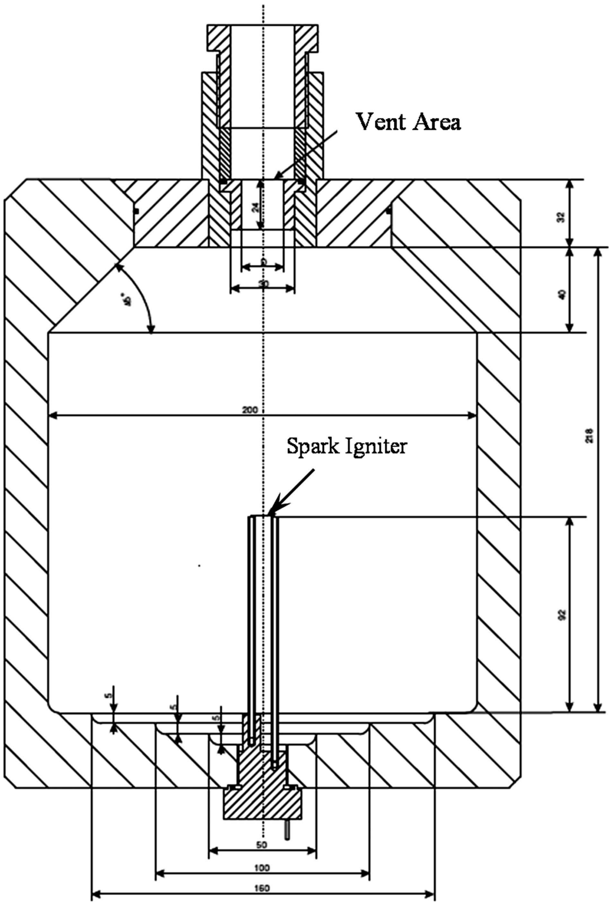

Figure 2. Set up of the 6-litre-autoclave (Daubitz et al., 2001)

L/D ratio of 1.1 and of 200 mm in diameter was used (Fig. 2). A detailed description of the 6-litre-autoclave was published in (Daubitz et al., 2001).

The second vessel with horizontal design is of 86 litres, the total length is 1180 mm and 305 mm in diameter, giving an L/D-ratio of 3.3 was designed by the author and is illustrated in Fig. 3. The set up mainly consisted of pneumatically driven valves, a modified spark igniter using a melting wire and bursting discs made of different materials, which depends on the desired opening pressure P_{set} (e.g. layers of 50 micron acetate, $P_{set} = 1.1$ barg). The internal turbulence was generated by optional orifices with a bore diameter of 100 mm and the vent sizes were variable.

2.2 SENSORS AND DATA COLLECTION

The pressure profile was determined in the axial direction using piezoelectric pressure transducer with the signal being processed by a Sensor Signal Conditioner. Moreover piezoresistive pressure transducer (0…100 bar) were used with the signal processed by the piezoresistive amplifier. All sensors were flush with the inside surface of the tube in order to avoid any additional enhancement of turbulence. The pressure signals were visualized with a sampling rate of 0.18 MHz and a data recorder was used.

2.3 GAS MIXTURES

Gas mixtures were produced using the partial pressure method and mixed by a paddle in a rocking pressurised tube. The gas mixture was then introduced into the evacuated vessel, to the desired pressure. All gas mixtures used were close to stoichiometric concentration (10 vol% CH_4 and 90 vol% Air), unless otherwise stated. For most experimental configurations a number of tests (minimum three) were carried out depending on the reproducibility of the overpressures.

3. RESULTS AND DISCUSSION

Due to the above mentioned effects and influence parameters the predictability, whether a gas explosion venting is turbulent, is insufficient (Bartknecht, 1993). For that reason a preliminary study in a 6-litre-autoclave was necessary in order to get a better understanding of the explosion behaviour in closed vessels by varying e.g. the initial concentration or initial pressure of methane-air-mixtures. Detailed descriptions of these tests were published in (Daubitz et al., 2001).

The pressure profiles presented in Fig. 4 and Fig. 5 show the same results with the 86-litre-autoclave. These curves are used along the current paper as the reference for the laminar flame propagation and will be used as a term of comparison for the identification of turbulent deflagration. It is shown that the addition of inert gas or changes in the initial pressure P_0 can strongly influence the maximum explosion pressure P_{ex} and the K_G-values.

The results presented in Fig. 4 and 5 are used finally for a better identification of turbulent flame propagation.

During venting the pressure in the vessel will continue to rise if the volumetric flow rate into the relief system is less than the rate of increase of the volume of the vessel contents. This can be forced by turbulent gas explosions. More complex flow patterns such as those found in industrial applications can therefore lead to a greater enhancement of the turbulence.

The possible enhancement of the rate of pressure rise was investigated in the closed 86-litre-vessel by the author. Fig. 6 illustrates pressure-time-curves for different initial pressures without orifice or with one orifice and with two orifices. The peak overpressure is not significantly affected by the presence of the orifices as there is a marked effect on the rate of pressure rise. Given the closed nature of the vessels, this could be due to increases in flame area due to distortion around the orifices. Moreover, these experiments indicate an increase in the turbulent burning velocity with increasing pressure, as the area of the flame increases with increasing pressure. Here, the orifices have a significant influence on the pressure profile but the influence of the number of orifices is nearly negligible. It could be also

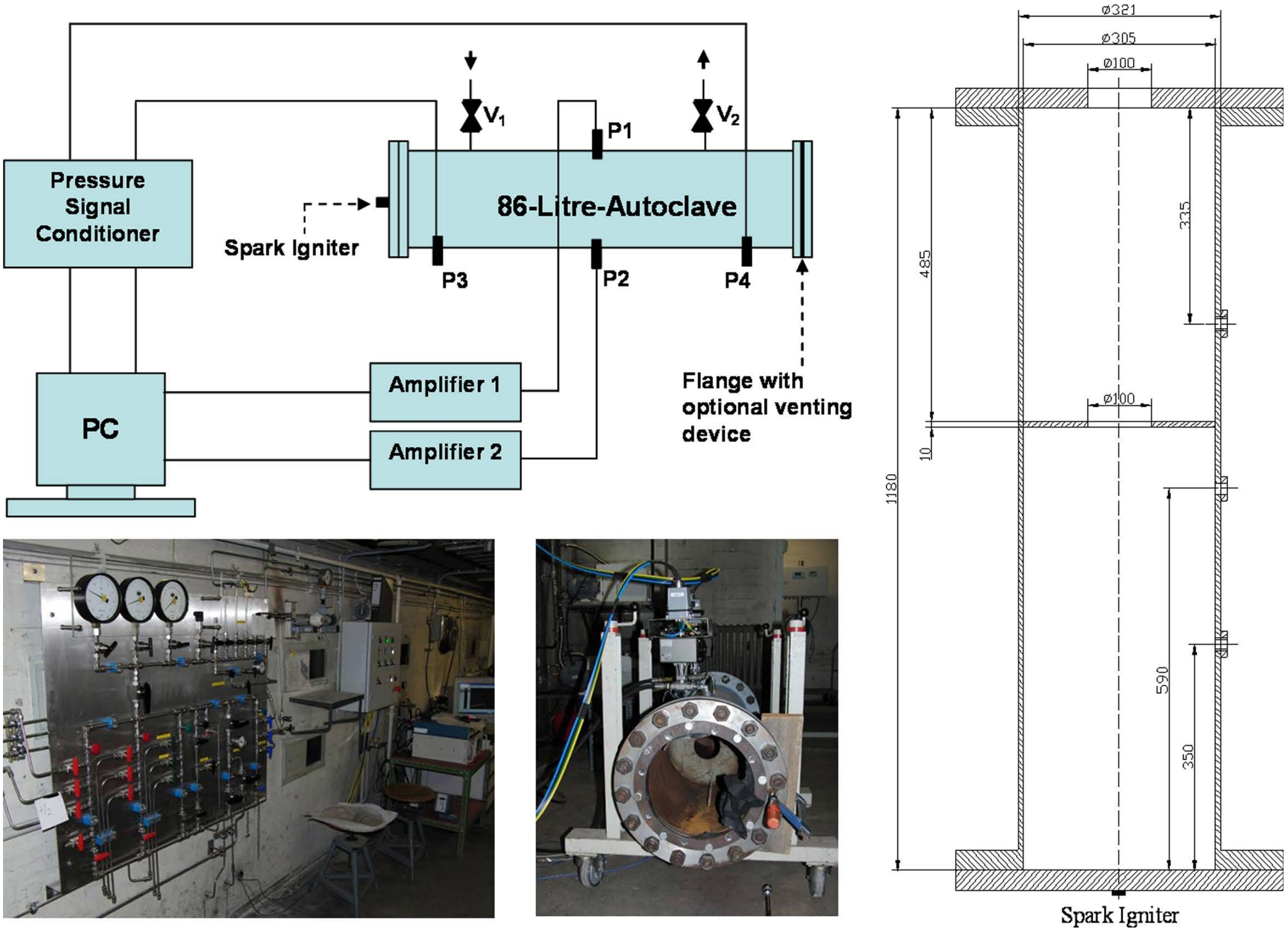

Figure 3. Set up of the 86-litre-autoclave

pointed out that under the investigated conditions the laminar burning velocity decreases with increasing pressure, due to a decrease in thermal diffusivity.

The comparison of vented and non vented systems for laminar (without obstacle) and enhanced turbulent deflagration (with obstacle) is shown in Fig. 7, where, for the

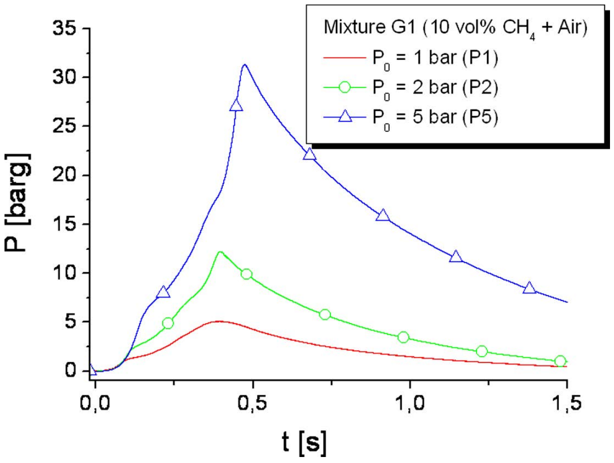

Figure 4. Influence of initial pressure on the pressure profile of laminar explosions.

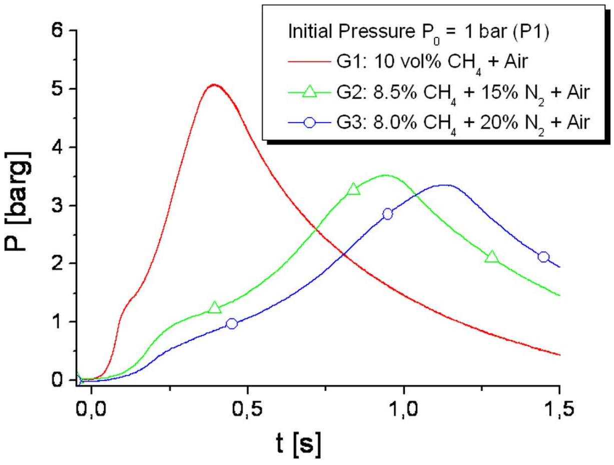

Figure 5. Pressure profiles of laminar methane-air explosions at different concentrations.

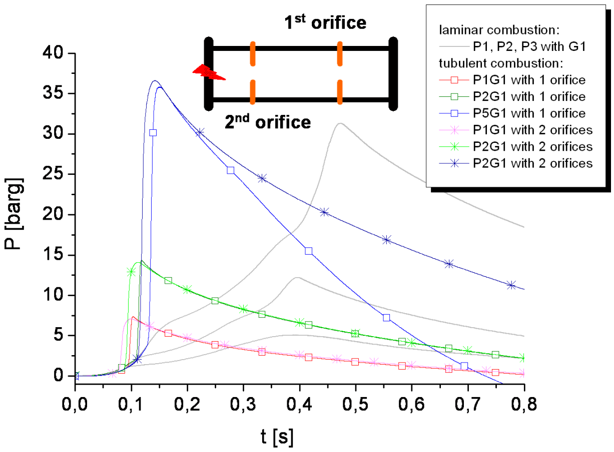

Figure 6. Comparison of laminar and turbulent combustion in the closed 86-litre-autoclave

laminar burning condition a decrease in P_{max} to P_{red} from 6.2 to 1.2 bar was observed. However, with the enhanced turbulence condition a decrease of only 20% of the P_{max} was seen. This example illustrates the problematic of enhanced deflagration in explosion protection. The pressure ($P_{red,tubulent}$) of a turbulent but vented system reaches a higher pressure than the laminar deflagration of a closed vessel ($P_{ex,laminar}$). This phenomenon is caused by smaller heat losses due to higher flame propagation. From safety point of view assuming a laminar case is not acceptable.

Ordinary pressure profiles of vented gas explosions with laminar flame propagation describe – as we will expect – with increasing vent area a decrease in P_{red}. Fig. 8 shows the influence of venting size on the pressure profiles at elevated initial pressure (Daubitz et al., 2001). It is worth mentioning that at $P_0 > 5$ bar the venting device enforces the turbulence generation only by depressurisation whereby no obstacles are inside the vessel. The effect of turbulence during depressurisation is demonstrated by the pressure profiles of tests with venting diameters larger than 22 mm. Despite the increasing relief area the system reached again higher P_{red} than a non depressurised system (Ref. P5G1) and therefore the venting of the turbulent gas explosion leads also to an inacceptable safety state. This phenomenon of turbulent flame propagation was also detected by the author at the 86-litre-autoclave at similar initial conditions but with L/D-ratio of 3.3 and different venting direction as well as different position of the spark igniter (Poli et al., 2010).

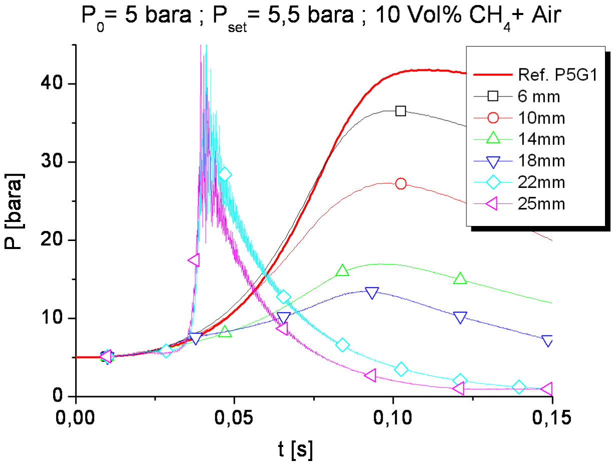

Figure 8. Influence of the venting area on the pressure profiles of a vented 6-litre-autoclave without obstacles (Daubitz et al., 2001)

An additional series of tests was performed in the 86-litre-autoclave and leads to Fig. 9, where the influence of vent size is illustrated for turbulent cases at $P_0 = 5$ bara. Although critical turbulent venting occurs related to the

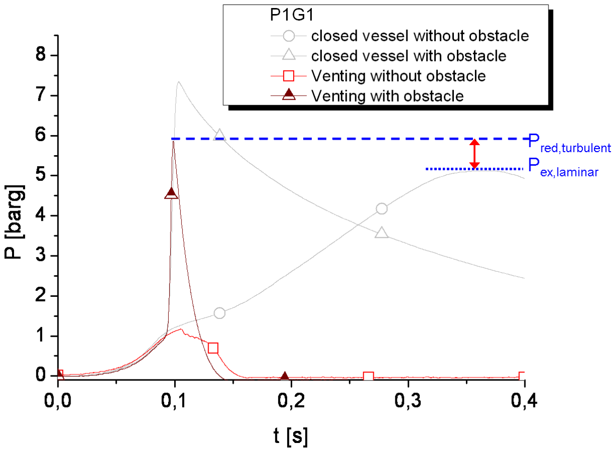

Figure 7. Comparison of pressure profiles of a vented and closed 86-litre-autoclave

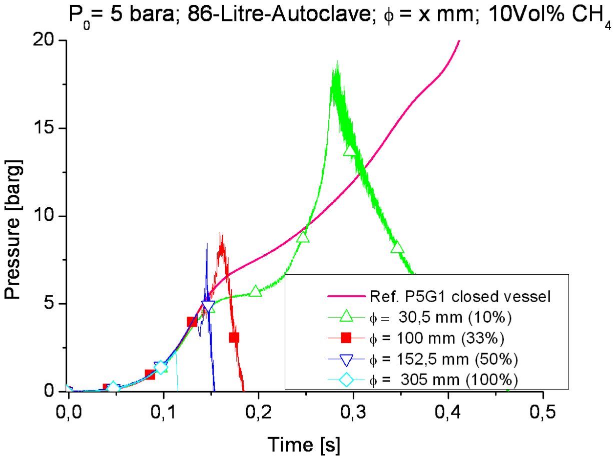

Figure 9. Influence of the vent size on the enhanced deflagration behaviour

Table 1. K_G-values for different methane concentrations and different initial pressures P_0

Different methane concentrations G_i at $P_0 = 1$ bar without obstacle (6L-autoclave)			
Mixture	Composition	P_{ex} in bar	K_G in bar m/s
G1	10 vol% CH_4, 90 vol% Air	7, 9	64
G2	8.5 vol% CH_4, 15 vol% N_2, 76.5 vol% Air	7, 0	26
G3	8 vol% CH_4, 20 vol% N_2, 72 vol% Air	6, 5	15
Different initial pressures P_0 without obstacle (86L-autoclave)			
Mixture at P_0	Composition	P_{ex} in bar	K_G in bar m/s
1 bar (P1)	G1	6, 2	12
2 bar (P2)	G1	15, 6	129
5 bar (P5)	G1	37, 2	177
Different initial pressures P_0 with 1 orifice Ø = 10 cm (86L-autoclave)			
Mixture at P_0	Composition	P_{ex} in bar	K_G in bar m/s
P1	G1	8, 3	478
P2	G1	17, 1	885
P5	G1	41, 1	1844
Different initial pressures P_0 with 2 orifices Ø = 10 cm (86L-autoclave)			
Mixture at P_0	Composition	P_{ex} in bar	K_G in bar m/s
P1	G1	8, 1	353
P2	G1	16, 4	744
P5	G1	41, 8	1629
Venting of 86L-autoclave with $Ø_{orifice} = Ø_{vent} = 10$ cm			
Mixture at P_0	Composition	P_{red} in bar	K_G in bar m/s
P1	G1	6, 8	665

laminar case in closed vessel (compare Ref. P5G1) with increasing vent size the $P_{red,turbulent}$ decreases until full-opened vessel (Ø = 305 mm) and therefore uncritical venting. At elevated initial pressure P_0 a range of vent sizes is probable, which induce a turbulent combustion only by venting.

To derive rules or design criteria the following table could be helpful. The investigated gas mixtures (G1, G2, G3) shown in Table 1 consisted of methane, nitrogen and air. They were selected in such a way that a relevant range of initial pressures and K_G-values, which is an important parameter used in designing plant explosion relief, were covered. Thus results facilitate prediction of the behaviour of other gas mixtures in similar explosions (e.g. tetrafluoroethylene).

A comparison in of K_G-values for explosions with initial pressures of between 1, 2 and 5 bar with and without obstacles, show that in all cases the turbulence caused by the obstacle increases the K_G-value by a minimum of 10 times compared to the laminar case.

In addition, these preliminary results showed that current venting guidance and standards are unsuitable for predicting overpressures in these systems, due to them exceeding the condition of $K_G < 550$ bar m/s. But we should not forget that the cubic law is applicable only if the other conditions are comparable, especially at identical turbulent state. This is due to the mentioned heat loss at the wall and the flow conditions during accelerated flame propagation.

Moreover, the position of ignition has also in some cases been shown to influence the flame propagation due to heat losses, buoyancy or piston like effect and could lead to higher K_G-values (Blanchard et al., 2010b; Cammarota et al., 2010; Kindracki et al., 2007). In this study the highest overpressure development and maximum pressure rise were observed when the ignition source was on the opposite flange of the opening.

4. CONCLUSIONS AND OUTLOOK

For the design of gas explosions venting systems for confinements only little guidance is given when considering the constructional boundary conditions or process conditions. For this reason conservative assumptions are prevalent in practice and in many cases the protective systems become significantly oversized. From safety perspective such safety margins in venting areas can lead to a critical acceleration of the pressure rise. Finally a gas explosion at turbulent conditions caused by over sizing rather leads to an under-sized system and may support the deflagration to detonation transition (DDT). The present investigation was focused especially on the influence of certain obstacles at elevated initial pressures on explosion venting behaviour as well as the determination of their safety-relevant parameters.

The K_G-values and therefore the venting behavior of gas explosion are strongly affected both by initial pressure and obstacles generated turbulence. As a result, common design methods are inapplicable for cases where turbulent combustions can occur, due to the fact that they exceed the condition of $K_G < 550$ bar m/s or due to geometrical limitations.

Measurements of this research justify the necessity for further investigation of the venting of turbulent gas explosions. The future research finding includes results of hydrogen and ethylene in air at elevated initial pressure, where a turbulent gas explosion venting supports the DDT using a similar 62-litre-autoclave or pressure piling needs to be considered. Further work will involve explosions and simulations in more complex geometries like interconnected vessel or with baffles as well as bends. It will enable the derivation of design criteria for emergency relief systems for gas explosions under various boundary conditions in complex geometries.

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