CHEMICAL ENGINEERING TRANSACTIONS

VOL. 31, 2013

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Eddy De Rademaeker, Bruno Fabiano, Simberto Senni Buratti

ISBN 978-88-95608-22-8; **ISSN** 1974-9791

DOI: 10.3303/CET1331111

Limitations of Gas Explosion Venting Due to Accelerated Flame Propagation and Elevated Initial Pressure

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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.

For the design of gas explosion 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. Moreover, a gas explosion venting at turbulent conditions caused by over sizing or by obstacles rather leads to an under-sized system. The present investigation was focused especially on the influence of certain obstacles as well as the influence of elevated initial pressures on explosion venting behaviour of quiescent hydrogen, methane or ethylene in air.

1. Introduction

The explosion protection in the chemical safety engineering deals with the origin of explosive atmosphere and their effects on plants, products, environment and human life. For this purpose, the protection includes both technical solutions as well as statutory provisions in form of laws, regulations or standards. If the danger of explosion could not be completely avoided by preventing the formation of an explosive atmosphere, or by preventing any effective ignition source, at least a constructive explosion protection like gas explosion venting systems must be able to mitigate the explosion effects to an acceptable level.

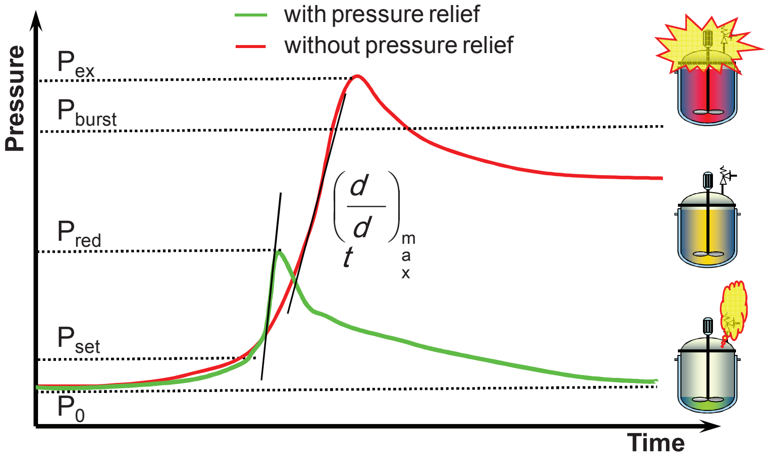

Figure 1: Schematic pressure profiles of gas explosions with and without pressure relief.

Please cite this article as: Poli M., Graetz R. and Schroeder V., 2013, Limitations of gas explosion venting due to accelerated flame propagation and elevated initial pressure, Chemical Engineering Transactions, 31, 661-666 DOI: 10.3303/CET1331111

As part of this safety concept, containers have to be protected against excessive pressure (Figure 1) by venting devices such as bursting discs. The safety device relieves at P_{set} the overpressure in a vessel in such a way that the rupture strength of the container has to be adjusted only to the remaining reduced explosion pressure P_{red}, which should be ideally smaller than the burst pressure P_{burst}.

Widely accepted design rules are described, amongst others, in NFPA 68 “Standard on Explosion Protection by Deflagration Venting” and EN 14994 “Gas Explosion Venting Protective Systems“. Here, two safety characteristics are essential for the design: the explosion pressure P_{ex} – normally the peak value in a closed vessel - and the maximum explosion pressure rise $(dp/dt)_{max}$ and/or according to the cubic law the K_G-value (1). Latter is important for most vent sizing methodologies and is proportional to the vent area. The recommended semi-empirical design criterion of Bartknecht is inapplicable if the boundary conditions exceed K_G-value higher than 550 bar m/s. Therefore, the major constraint is the fact that the maximum explosion pressure rise depends significantly on whether turbulent combustion exists (Razus and Krause, 2001). Nevertheless, turbulence exists in all nonreactive or reactive flows and can be enhanced by forcing the flow through or around an obstacle (Park et al., 2008).

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

Difficulties arise in the assessment of turbulence. 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., 2010). Furthermore, over sizing of relief apparatus at an elevated initial pressure has also in some cases been shown to enhance turbulence and lead to higher overpressures (Daubitz et al., 2001) and finally to undersized devices.

Therefore, it is essential to provide a broader data base to verify the existing rules or to determine the safety-relevant parameters for accelerated flame propagation.

2. Experimental set up

For a better safety assessment or design of protective systems the turbulent combustion and explosion behaviour of quiescent hydrogen or methane in air were investigated at initial pressures up to 7 bar using vessels up to 100 L. A systematic study was performed to investigate the influence of turbulence on the overpressure development during accelerated flame propagation. Moreover, experimental results 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.

Three different kinds of vessels were used for the purposes of the present experimental investigations. Here, the influence of the vent size on the venting behaviour at elevated initial pressure was analyzed in a vertical and cylindrical 6-L-autoclave (L/D = 1.1) without any obstacle, whereas the influence of obstacles during gas explosion venting on the maximum pressure rise was generally studied in an horizontal 86-L-autoclave (L/D = 3.3) or in a similar 62-L-autoclave, which is pressure-resistant up to 100 bar and was used for tests with mixtures of hydrogen or ethylene in air.

The set-up mainly consisted of pneumatically driven valves, a modified spark igniter using a melting wire (ignition energy 8 – 16 J) and bursting discs made of different materials, which depends on the desired opening pressure P_{set}. The internal turbulence was generated by optional orifices with a bore diameter of 100 mm and by varying the vent size. However, the venting behaviour under initially quiescent conditions is of special interest.

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.

Gas mixtures were produced using the partial pressure method and mixed by a paddle in a rocking pressurized tube. The gas mixture was then introduced into the evacuated vessel, to the desired test pressure. Generally, gas mixtures close to stoichiometric concentration (10 vol % CH_4 or 28.5 vol % H_2 in air) were used.

3. Results and discussion

A preliminary study in a 6-L-autoclave was necessary in order to cover a relevant range of K_G-values and therefore to get a better understanding of the explosion behaviour in closed vessels by varying e.g. the initial concentration or initial pressure. Detailed descriptions of these tests were published in (Daubitz et al., 2001). The pressure profiles of the present study show the same results with the 86-L-autoclave. These curves are used along the current paper as a 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. Moreover, these results facilitate to predict the behaviour of other gas mixtures in similar explosions.

The comparison of vented and non vented systems for laminar (without obstacle) and enhanced turbulent deflagration (with obstacle) is shown in figure 2, where, for the laminar burning condition a decrease in P_{max} to P_{red} from 6.2 to 1.2 bar was observed. 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. Here, 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 and due to distortion around the orifices. However, with the enhanced turbulence condition a decrease of only 20 % of the P_{max} was seen. This example illustrates the problem of accelerated deflagration in explosion protection. The pressure $P_{red,turbulent}$ of a turbulent but vented system reaches a higher pressure than the pressure $P_{ex,laminar}$ of the laminar deflagration in a closed vessel. This phenomenon is caused by smaller heat losses due to higher flame propagation. Therefore, from safety point of view assuming a laminar case is not acceptable if the peril of turbulence could not be excluded.

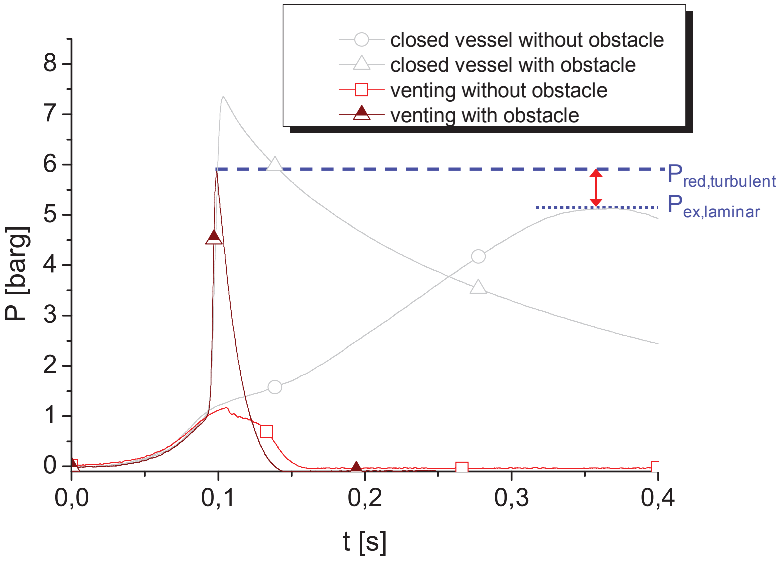

Figure 2: Comparison of pressure profiles for the vented and the closed 86-L-autoclave at 1 bar and 10 vol. % CH_4.

Ordinary pressure profiles of vented gas explosions with laminar flame propagation registered a decrease in P_{red} with increasing vent area, as expected. Figure 3 shows the influence of venting size on the pressure profiles at elevated initial pressure. It is worth mentioning that at P_0 > 5 bar the venting device enforces the turbulence generation only by depressurization whereby no obstacles are inside the vessel. The effect of turbulence during depressurization 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 depressurized system (Ref. P5G1) and therefore the venting of the turbulent gas explosion leads also to an inacceptable state from the safety perspective. This phenomenon of turbulent flame propagation was also detected by the author at the 86-L-autoclave at similar initial conditions but with L/D-ratio of 3.3 and horizontal venting direction as well as different position of the spark igniter.

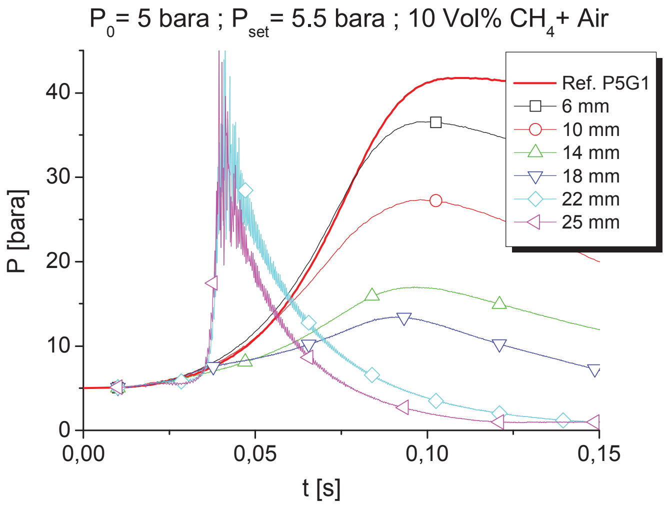

Figure 3: Influence of the venting diameter on the pressure profiles of a vented 6-L-autoclave without obstacles (Daubitz et al., 2001).

An additional series of tests was performed in the 86-L-autoclave and lead to figure 4, where the influence of vent size is illustrated for turbulent cases at $P_0 = 5$ bar. Although critical turbulent venting occurs compared to the laminar case in closed vessel (see Ref. P5G1) the $P_{red,turbulent}$ decreases with increasing vent size until full-opened vessel and therefore uncritical venting. This means that at elevated initial pressure P_0 a range of vent sizes is probable, which induce a turbulent combustion only by venting, as also observed in the test with the 6-L-autoclave.

A comparison of the K_G-values for explosions with initial pressures of 1, 2 and 5 bar with and without obstacles, shows 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 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 (equation 1) is applicable only if the initial conditions are comparable, especially if the turbulent state is identical.

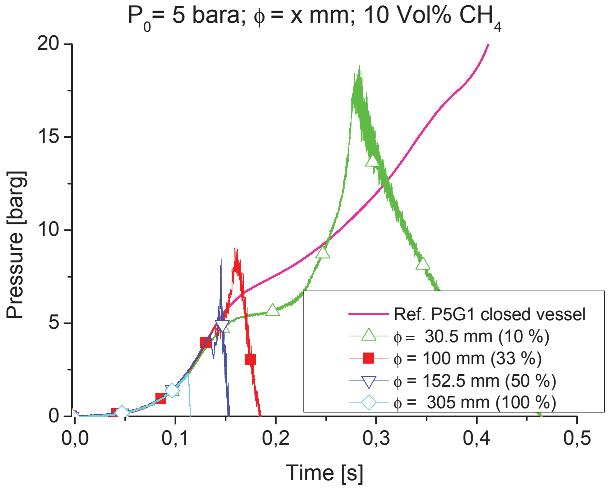

Figure 4: Influence of the vent size on the enhanced deflagration behaviour in the 86-L-autoclave.

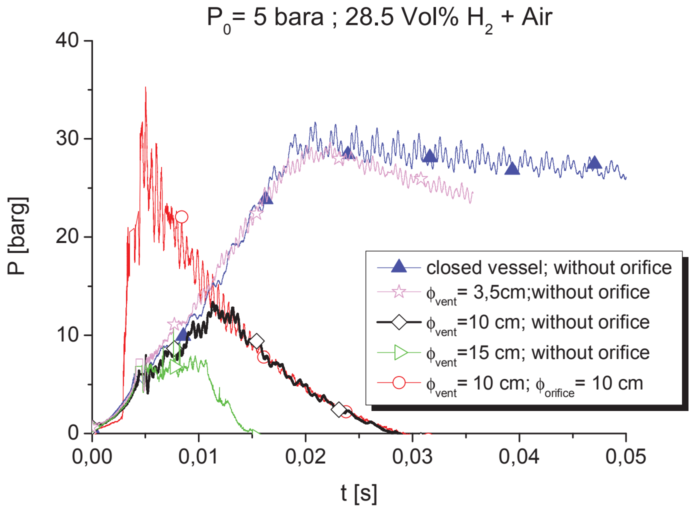

Figure 5: Comparison of laminar and turbulent hydrogen-air-explosions in the 62-L-autoclave.

These research findings include preliminary results of hydrogen-air-mixtures at elevated initial pressure, where a turbulent gas explosion venting has the potential to support the deflagration to detonation transition (DDT). Compared to the results of methane-air-mixture the hydrogen explosions are approximately 10 times faster. Here, at an initial pressure of P_0 = 5 bar the depressurized autoclave with an internal obstacle (bore diameter of 10 mm) result in a maximum peak value of P_{ex} = 35 barg, a flame speed of 2000 m/s and a K_G-value up to 11200 bar m/s (Figure 5). Comparable tests without an additional orifice result in P_{ex} = 14 barg, a flame speed of 165 m/s and a K_G-value below 500 bar m/s.
Under the investigated range of initial pressure (P_0 = 1…7 bar) with hydrogen-air or ethylene-air mixtures, it was not possible to observe a significant acceleration of the flame propagation only by turbulence generation at venting device (without orifice). It should be noted that the hydrogen-air-combustion is a priori a very fast reaction, so that the influence of additional turbulence on the acceleration of the deflagration is reduced.
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. With the 62-L-autoclave the highest overpressure development and maximum pressure rise were observed when the ignition source was not in centre but far away from the opening and near the opposite flange.

4. Simulation

In order to predict the limitations of accelerated gas explosion venting at elevated initial pressure by using the ANSYS CFX code a preliminary study results in the following set of models. The Reynolds Averaged Navier-Stokes equations were solved using the Shear Stress Transport model of Menter to compute the averaged turbulent stresses. The flame propagation of premixed combustion was calculated by the Burning Velocity Model and the flamelet libraries. To control the flame stretch and flame extinction in a non adiabatic autoclave with a constant wall temperature the Zimont correlation was used, whereas thermal radiation was calculated by the Discrete Transfer Model. The ignition processes of the gas explosion were described by the spark ignition model. Simulations with the closed 6-L-autoclave leads to the result that pressure curves of experiments and simulations are in good agreement. They were able to predict the pressure rise before 0.5 s satisfactorily and P_{max} within 15 % of the measured value at P_0 = 5 bar. Due to the numerical stability the set of models was not suitable for the strong dynamic venting behaviours.

5. Conclusions

Experiments show that turbulence is important and its effect on the reduced explosion pressure should not be ignored. The turbulence inducing elements may result in strong rise of combustion rate during the explosion causing considerably higher pressure. 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. However, current standards like NFPA 68 or

EN 14994 are inapplicable to the investigated boundary conditions. The predictability of these strong dynamic venting behaviours by using a more sophisticated method like CFD simulation is also limited due to model accuracy and numerical stability.

Last but not least, they 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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