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Sizing of Explosion Pressure Relief using the Efflux Function

Robert Blanchard[a]*, Kai Holtappels[b], Martin Kluge[b], Hans-Peter Schildberg[a], Robert Zeps[b]

[a]BASF SE, 67056 Ludwigshafen, Germany
[b]Bundesanstalt für Materialforschung und –prüfung, Unter den Eichen 87, 12205 Berlin
robert-john.blanchard@basf.com

Determination of deflagration venting requirements in chemical/process plants is usually carried out using well established standards employing an empirically based formula. However, this formula is shown to have severe shortcomings, especially in the range of low K_G-values, where either negative or inconceivably large venting areas can be predicted.
Due to these shortcomings a method has been developed using the efflux function for gases as a basis to predict the mass flow through a vent opening in a vessel during an internal explosion. The simulated rise in pressure due to the internal explosion is quantitatively determined from the K_G-value, with the mass flow through the vent opening in the vessel resulting from the pressure difference between the vessel and its surroundings. This enables the maximum overpressure as a function of the pressure relief surface area to be predicted. The method takes into account the temperature of the efflux gases and turbulence enhancement brought about by the venting process.
In the following paper explosion pressure relief experiments are described and the results from these experiments are compared to predictions from the efflux method. It is shown that by adjusting the assumed turbulence which evolves during the venting process, the reduced explosion pressure can be reasonably well reproduced.

1. Introduction

An important factor when considering the safe operation of process plants is the effective mitigation of the effects of unwanted internal gas-phase explosions (i.e. damage to internal components, vessel bursts, flying debris, jet flames etc.). According to EN 1127-1 this can be realised by employing one of two principles: explosion prevention or explosion protection. The former relates to the prevention of the formation of an explosive atmosphere and/or avoiding ignition sources. However, many industrial chemical processes require the handling of mixtures of combustibles and oxidator gases at high temperatures, making it impractical to take this approach. In these cases explosion protection can be considered. Explosion protection can be defined as “halting the explosion and/or limiting the effects to a tolerable level by protection methods, e.g. isolation, venting, suppression and containment”. When considering explosion venting, in order to allow for safe/practical operation of process plants, vent sizes must be sufficient to reduce the maximum explosion overpressures to levels which the plant can withstand whilst interfering as little as possible with the operation/building of the plant.
Current explosion venting standards (EN 14994 and NFPA 68) use the following equation, also known as the Bartknecht formula (Bartknecht 1993), to determine the required venting area based on the reduced explosion pressure (p_{red} / barg), the static activation pressure of explosion venting (p_{stat} / barg), the volume of the vessel to be vented (V / m^3) and the K_G-value of the mixture:

$$A = \left\{\left[\left(0.1265 \cdot \log\left(K_G\right) - 0.0567\right) \cdot p_{red}^{-0.5817}\right] + \left[0.1754 \cdot p_{red}^{-0.5817} \cdot \left(p_{stat} - 0.1bar\right)\right]\right\} \cdot V^{2/3} \quad (1)$$

Several criticisms have been levelled at the Bartknecht formula including that K_G-values used during the development of the formula are different to those measured today with current standards (EN 13673),

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negative venting areas can result from gases with low K_G-values and that relatively large changes in the K_G-value result in relatively small changes in the required venting area (Blanchard 2013). Furthermore, it has been shown that for the EN 14994 and NFPA 68 methodologies the disparity between predicted and measured reduced pressures is much larger than that obtained with other simple methodologies (Bauwens 2012; Sustek and Janovsky 2012) and that the Bartknecht formula can grossly overestimate vented overpressures (Kasmani 2013).

In order to address these problems, particularly those relating to gases with low K_G-values, a method was developed based on the efflux function to predict explosion venting requirements. This method is described in the following paper, alongside past and current experiments which are used to validate the method. The validation experiments comprised measurement of K_G-values in a closed reactor, followed by determination of the reduced explosion pressure in the same vessel. Using the K_G-value and the maximum explosion pressure measured in the closed vessel, the Efflux Method was used to predict the vented explosion pressure, taking into account the characteristics of the vented vessel.

2. Efflux Method

The maximum temperature or temperature difference brought about by an explosion can be inferred from the explosion pressure ratio in a vessel of constant volume and by assuming that the number of moles of gas do not significantly change (as would be the case for combustion of most flammable gases in air). In the example shown in Eq(2) the gas has an explosion pressure ratio of 10 at 25 °C, the explosion generates an increase in temperature of 2682 K / °C, therefore, before they start to cool, the reaction products will have a temperature of 25 + 2682 = 2707 °C.

$$\frac{p_1}{T_1} = \frac{p_2}{T_2} \Rightarrow \frac{1}{298} = \frac{10}{\Delta T + 298} \Rightarrow \Delta T = 2682\ K \quad (2)$$

It should be noted that due to many vessels not being spherical, this calculation also introduces a certain conservatism to the determined venting area (Drahme 2010), i.e. the explosion pressure ratio will decrease with increased elongation up until flame acceleration effects are observed.

The pressure-time curve resulting from an explosion in a closed vessel can be approximated by a sigmoidal curve generated using Eq(3), which is rotated by 180°. The constants a, b and c can be varied in order to yield the required explosion pressure and maximum rate of pressure rise. Then assuming that the pressure, p, is directly proportional to the temperature, T, a temperature-time curve can be created using the maximum explosion pressure to determine the maximum temperature as calculated by Eq(2). This assumes that there is no net increase or decrease in the number of moles present before and after the explosion, which for lean hydrocarbon-air mixtures is practically the case, and that the volume remains constant.

$$y = ae^{be^{cx}} \quad (3)$$

These pressure-time curves have been shown to provide a good analogue to curves determined through experimentation (Blanchard 2013). After the explosion, the pressure/temperature of the product gases will not stay constant but will begin to fall, however this phase of the explosion is uncritical for the current assessment as the maximum explosion overpressure and rate of pressure rise have already been experienced by the system. Enhancement of the rate of pressure rise brought about by the turbulence during the venting process can also be simulated with this method by multiplying the maximum rate of pressure rise in a closed vessel by a given factor (A_T).

The pressure-time curve or heating rate can be applied to a certain mass of gas to simulate the pressure rise in a closed vessel. In order to take the venting of the vessel into account, this heating rate is again applied to the mass of gas in the vessel, but additionally the rate of loss of mass due to the efflux of gas from the vessel is determined after the activation pressure of the venting device has been achieved, thus calculation of the reduced pressure in the vessel as a function of time is possible. The rate at which mass flows out of the vessel is determined using the efflux equation:

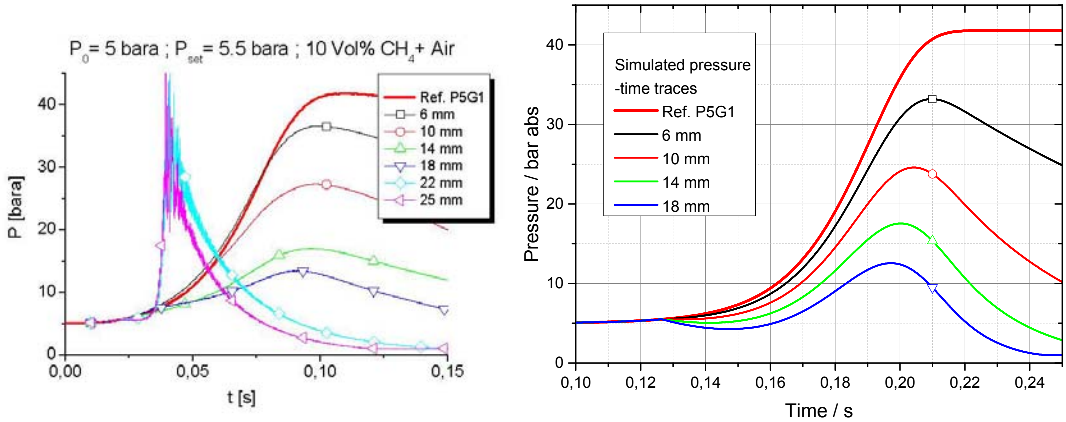
$$\frac{-dm}{dt} = F \cdot \alpha \cdot \Psi \cdot p_1 \cdot \sqrt{\frac{2 \cdot \bar{M}_w}{R \cdot T_E}} \quad (4)$$

where F is the venting area (m^2), Ψ is the efflux function, p_1 is the pressure inside the vessel (same units as the later determined dp), α accounts for the effective fraction of the venting area, F, through which gases are

able to escape (i.e. α = 1 signifies that the entire surface area, F, is available for venting) and T_E is the temperature of the efflux gases.
For efflux calculations the molecular mass $\bar{M}_w$ of the efflux gas was assumed to be equal to that of air. The temperature of the efflux gases was determined from the aforementioned heating rate, therefore, it is assumed that the gas in a particular vessel is heated homogeneously during the course of an explosion. In reality this is not the case as the combusted gas will be at a much higher temperature to the uncombusted gas, however, using this kind of approximated heating profile shows good agreement to experimental results. Therefore, in summary, at a given time, a given mass of gas is present in the vessel at a given temperature, taking these factors into account allows the pressure in the vessel at this time to be easily calculated.
Venting calculations were carried out using a time-step of one millisecond, with the pressure calculated by the previous time-step being used in Eq(4) to determine the efflux rate and hence the pressure for the next time step. The validity of using a time-step of one millisecond was proven by the fact that further decreasing the time-step by a factor of 10 had no significant influence on the resulting reduced pressure-time curve.
The results from the Efflux Method are compared to small-scale experiments found in the literature and as hitherto no industrial scale explosion venting tests have been reported which enabled a satisfactory validation of the efflux method, tests were carried out in a 5 m^3 vessel in order to provide validation data for the Efflux Method.

2.1 Comparison with small scale experiments

The influence of the venting diameter on the pressure-time profiles of methane/air explosions (p_{ini} = 5 bar abs, p_{stat} = 5.5 bar abs) measured in a vented 6 l autoclave are reported in (Poli 2013). These experiments are particularly useful for comparison with predictions from the Efflux Method as the pressure-time profile in the closed autoclave was also recorded. Therefore, from the unvented measurements (P5G1 in Figure 1 (a)) a pressure-time/temperature-time curve resulting from Eq(3) could be generated for the combustion of the aforementioned gas in order to provide a basis for the latter venting predictions using the Efflux Method.



(a) (b)

Figure 1: Influence of the venting diameter on the pressure profiles of a vented 6 l autoclave without obstacles (a) (Poli 2013) and pressure time traces simulated using the Efflux Method (b), A_T = 1.

From Figure 1 it can be seen that the predictions from the Efflux Method show a good fit to the experimental data recorded for venting diameters from 6 to 18 mm, with the error in the predicted p_{red} being between +18.3% and -2.2%. In these simulations, no increase in the rate of pressure rise due to the venting process was used, i.e. A_T = 1. The experiments with the 22 and 25 mm bursting discs were not simulated, as at these conditions extremely high turbulence brought about by the venting process increases the rate of pressure rise during venting significantly, which leads to a much increased p_{red}, as compared to the experimental data from the test with an 18 mm bursting disc. These effects can be taken into account with the Efflux Method by increasing the turbulence factor A_T, however, at the moment there is no solid experimental basis which enables the reliable prediction of when these effects take place and when they can be discounted. However, as the presence of these effects could potentially lead to under-sizing venting surfaces, it is highly recommended that they be better characterised in order to enable prediction of the A_T value as a function of the initial conditions (i.e. vent surface to volume ratio).
As the scale of these tests is rather small in comparison to many industrial sized vented vessels, further validation tests were carried out in a larger vessel, as described in Section 3.

3. Experimental

Validation tests were carried out in a 5 m³ vessel, shown in Figure 2, with an internal length of 2196 mm and an internal diameter of 1856 mm (L/D = 1.18). The vessel has a pressure rating of 30 bar abs at 20 °C. The front end of the vessel is closed by a 50 mm metal plate with a diameter of 800 mm, for venting tests the blind flange mounted to the metal plate can be replaced by a burst disc to give a venting area of ~0.01 m². For larger venting areas of up to 0.5 m² the metal plate can be removed.

Figure 2: Test vessel with inner volume of 5 m³ (L/D = 1.18); official pressure rating of 30 bar abs at 20 °C.

The ignition source used was a fusing (exploding) wire igniter mounted to the top of the vessel. In order to achieve ignition in the centre of the vessel, an igniter was used which consisted of two insulated, 1000 mm long electrodes with a 5 mm separation distance, holding a nickeline wire of 0.12 mm diameter on its ends. The ignition energy was provided by a 1.5 kVA/230 V insulating transformer. When the igniter is activated, the wire melts and an electrical arc is generated between the electrodes for a defined time period (maximum half a period of the supply voltage, 0.01 s). An electronic control unit allowed switching a defined time period of the mains electricity to the igniter system, a time of 5 ms was used, which corresponds to ignition energies in the range of 10 J and 20 J as recommended in various European standards for the determination of explosion characteristics. The ignition energy was then calculated from the measured current- and voltage-time-histories.

Pressure measurement was achieved by use of piezoresistive pressure transducers (company: Keller, type: PA-10), measuring range 0 bar to 10 bar. One transducer is mounted to the flange at the rear of the vessel. In the case of the determination of explosion characteristics in the closed vessel another transducer was mounted to the flange at the metal plate. The resolution of the pressure transducers is 1×10^{-4} bar, linearity is better than 0.5 % full scale (FS). The typical sampling frequency for the pressure records was 10 kHz. The pressure transducers were calibrated using of a high precision pressure measuring device (company: WIKA, type: CPG 2500). A minimum of four 1.5 mm coated thermocouples (type K according to EN 60584-1), two on top and two at the bottom, were mounted to the vessel in order to gain qualitative information on the flame propagation direction. The measuring point of the thermocouples is located at approximately 20 mm from the vessel walls. All sensors were connected to the corresponding amplifiers. The digitised signals were switched to an A/D-converter (company: Jet Systemtechnik GmbH, type: MCL-USB, 16 channels, 16 Bit A/D, sampling frequency: 500 kHz) and a computer for displaying, storing and analysing the data. The required gas mixtures were prepared using of a stationary 5-channel gas mixing device for the production of potentially explosive multicomponent gas mixtures. The stationary system was capable of producing a maximum flow rate of 12 Nm^3/h and has a maximum operating pressure of 1 MPa.

All tests were carried out according to the following procedure. In the first step the 5 m³ vessel was evacuated, flushed with about 0.2 bar abs of the intended gas mixture and evacuated again. Then the gas mixture was filled into the vessel up to the intended initial pressure, in this case 1 bar abs. In order to ignite the mixture in a quiescent state, ignition was initiated five minutes after finishing the filling process. In conjunction with the ignition, the data acquisition was also triggered.

3.1 Comparison of venting experiments and efflux method predictions

An experiment was first carried out in the aforementioned vessel, with no pressure relief and a gas mixture consisting of 11 vol.% methane in air at an initial pressure of 1 bar abs and an ambient initial temperature.

From the pressure-time profile in Figure 3, “Pressure (Experimental)” a maximum rate of pressure rise of 10.1 $bar \cdot s^{-1}$ (K_G = 17.3 $bar \cdot m \cdot s^{-1}$) and a maximum pressure of 6.8 bar abs were determined. Employing Eq(3), these values were used to simulate the heating profile which resulted in the pressure-time profile, shown as “Pressure (Efflux 3.0)” in Figure 3. In the Efflux Method it is assumed that the heating of the gases in the closed vessel is homogeneous, however, as also shown in Figure 3, during the experiment, the temperature at the top of the vessel is greater and rises with a higher rate than the temperature at the bottom of the vessel. Therefore, in the experiment it can reasonably be assumed that the combustion is somewhat driven by buoyancy effects.

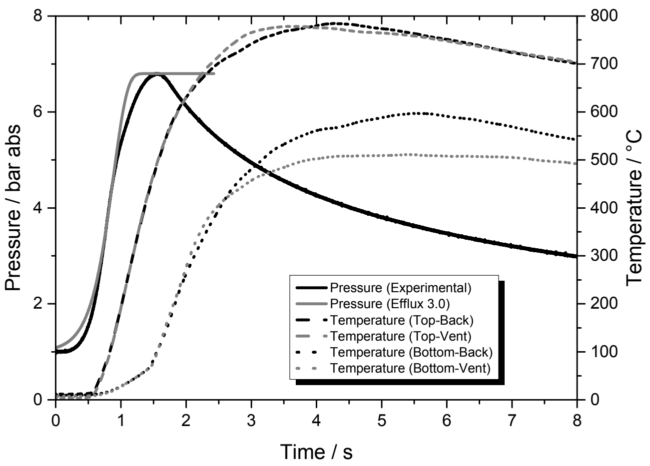


Figure 3: Measured pressure- and temperature-time profiles for a gas mixture consisting of 11 vol.% methane in air, centrally ignited in a closed 5 m^3 vessel at an initial pressure of 1 bar abs and an ambient initial temperature, and a pressure-time profile as predicted by the Efflux method.

The simulated pressure time profile shown in Figure 3 does not match the experimental pressure-time profile as well as that shown for the 6 l autoclave in Figure 1 (a). This is probably due to the flame in the 6 l autoclave experiments propagating spherically as opposed to the buoyant combustion observed in the 5 m^3 vessel.

After the experiment in the closed vessel, an experiment was carried out in the same vessel, with the same gas mixture, but with a DN120 vent opening (F = 0.0113 m^2). During static testing the bursting disc used was activated at 1.9 bar abs. The vented pressure-time profile from this experiment is shown in Figure 4 along with the vented pressure-time profile as predicted with the Efflux Method and the temperature as measured at four points in the vessel. Based on the experimental pressure-time profile it is not completely clear whether p_{stat} takes place at 1.9 bar abs or later around 3 bar abs. However, further experiments are planned whereby the breaking of an electrical circuit over the bursting disc will allow exact determination of the pressure at which the bursting disc is activated. From the temperature measurements taken during the vented experiment, it can also be seen that buoyancy driven combustion is taking place.

The reduced explosion pressure showed good agreement to the experimental value when a turbulence factor of 2 was used in the Efflux Method (A_T = 2), i.e. the simulated unvented pressure-time profile from Figure 3 was manipulated so that the maximum rate of pressure rise was doubled to 20.2 $bar \cdot s^{-1}$, this curve was then used as the basis for the determination of the vented explosion pressure. In this case both the measured and simulated p_{red} was 5.0 bar abs. In the region where turbulence increases the rate of pressure rise in the experimental results (between 3.5 and 5 bar abs), the Efflux Method predictions show good agreement to the experimental pressure-time profiles. That the pressure-time profiles do not overlap before p_{stat} is not a major concern as the turbulence factor is applied to the entire simulated pressure-time curve, in reality this increase in the rate of pressure rise will only occur after p_{stat} has been exceeded. However, for the Efflux Method it is not necessary to describe the pressure-time profile accurately before the bursting disc operates, as whether p_{stat} is achieved quickly or slowly will have no effects on the calculated p_{red}. However, it should be stated that it is not the goal of the current method to completely reproduce the vented pressure-time profile but to provide a simple empirically based tool for prediction of the reduced explosion pressure so that vent sizing can be carried out with fewer of the problems described in Section 1 relating to the Bartknecht formula.

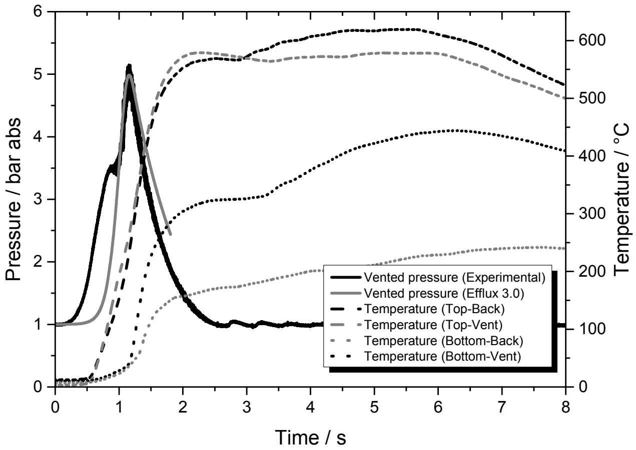


Figure 4: Pressure- and temperature-time profiles for a gas mixture consisting of 11 vol.% methane in air, centrally ignited in a 5 m^3 vented vessel (F = 0.0113 m^2, p_{stat} = 1.9 bar abs) at an initial pressure of 1 bar abs and an ambient initial temperature, and a vented pressure-time profile as predicted by the Efflux method.

4. Conclusions and suggestions for further work

The objective of the current work is to provide a simple, empirically validated, method whereby only the K_G-value, the maximum explosion pressure of a gas mixture in an unvented vessel and the physical characteristics of the system (volume, initial pressure/temperature, p_{stat}, venting area, etc.) are required in order to determine the reduced explosion pressure. As large-scale testing is not always a viable option, this will allow vent sizing to be carried out based on easy to conduct laboratory measurements which will also avoid problems associated with current standard methods for determining venting requirements.

The predictions from this method have shown an initial good agreement to small-scale experiments when a turbulence factor of 1 is used and good agreement to large-scale experiments when a turbulence factor of 2 is used. However, it is not the goal of this paper to present a finished article, but to illustrate the methods use and comparison of its results to some experimental data. In order to gain acceptance as a robust and reliable approach to predict required venting areas further experiments are required in order to provide a solid empirical basis, whereby the output of the Efflux Method is be compared to experiments looking into how the reduced explosion pressure is affected by the vent area to volume ratio, p_{stat}, K_G-value, p_{max}, initial pressure and temperature, vessel geometry, efflux temperature, turbulence enhancement, efflux direction, etc.

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