Explosion venting data: A single maximum over-pressure is not sufficient

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Venting Terms and Venting Standards

- Vent Area, $A_v$, non-dimensionalised as
  - **Vent coefficient** $K_v = \frac{V^{2/3}}{A_v}$
    - ($V$ is the vessel volume) - BS EN 14994 (2007)
  - Also $K_A = \frac{A_x}{A_v}$
    - ($A_x$ is the cross-sectional area of the vessel in the plane of the vent) – British Gas Research and successors
  - And $A_v/A_s$
    - ($A_s$ is the internal surface area of the vessel) – NFPA 68 (2013)
  - $A_x$ and $A_s$ can be related to $V^{2/3}$ therefore the different definitions are similar
Mixture reactivity

- Deflagration index, $K_G$

\[ K_G = \frac{(dP/dt)_\text{max}}{V^{1/3}} \]

- Laminar burning Velocity, $S_u$

It can be shown that the two parameters are directly related.
Venting Standards

- standards and guidance focus on providing the correct vent area
  - as function of the mixture reactivity, vessel volume and shape, and some vent properties e.g. for compact vessels

- BS EN 14994 (2007)

\[
\frac{1}{K_v} = \left[ \frac{0.1265 \log_{10} K_G^{-0.0567}}{P_{red}^{0.5817}} + \frac{0.175(P_{stat} - 0.1)}{P_{red}^{0.5717}} \right]
\]
7.2 Venting by Means of Low Inertia Vent Closures.

7.2.1 When $P_{red} \leq 0.5$ bar, the minimum required vent area, $A_{v0}$, shall be determined by Equation 7.2.1a and Equation 7.2.1b:

$$A_{v0} = \frac{A_s C}{\sqrt{P_{red}}}$$  \hspace{1cm}  (7.2.1a)

$$C = \frac{S_u P_u \lambda}{2 G_u C_d} \left[ \left( \frac{P_{max} + 1}{P_0 + 1} \right)^{1/\gamma_b} - 1 \right] (P_0 + 1)^{1/2}$$  \hspace{1cm}  (7.2.1b)
Issues with the Standards

- For a given vent area they give a maximum overpressure – effectively based on correlations of experimental data.
- No insight/understanding of mechanism of pressure generation
- Effect of positioning, number and shape of vents not included
- Effect of ignition location not included

Explicitly or implicitly the above are taken to have no effect
What is needed for model development

- For correct structural design the full pressure profile is needed
  - Experimental data sets of vented explosion overpressures can’t be provided for every potential practical scenario and we need to develop reliable models.

- Ultimately for correct modelling and for validation of such models we need detailed quantitative data that
  - elucidate the mechanisms and processes involved, and
  - give dependencies on the important parameters.
Physical Causes of venting overpressures
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<tbody>
<tr>
<td>Peak due to vent opening at pressure $P_{\text{stat}}$</td>
<td>$P_{\text{burst}}$</td>
<td>$P_1$</td>
<td>$P_1$</td>
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<td>Peak due unburned gas flow through the vent (onset of burnt gas venting)</td>
<td>$P_{fv}$</td>
<td>$P_2$</td>
<td></td>
<td>$P_{\text{emerg}}$</td>
<td>$\Delta P$</td>
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<td>Peak due the external explosion</td>
<td>$P_{\text{ext}}$</td>
<td>$P_3$</td>
<td>$P_2$</td>
<td>$P_{\text{ext}}$</td>
<td>Dominant</td>
<td>$P_1$</td>
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<td>Peak due to maximum flame area inside the vessel</td>
<td>$P_{\text{mfa}}$</td>
<td>$P_4$</td>
<td>$P_3$</td>
<td>$P_{\text{max}}$</td>
<td>Max. burning rate</td>
<td>$P_3$</td>
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<td>Peak due to the reverse flow into the vented vessel</td>
<td>$P_{\text{rev}}$</td>
<td>$P_5$</td>
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<td>Peak due pressure oscillations.</td>
<td>$P_{\text{ac}}$</td>
<td>$P_6$</td>
<td>$P_4$</td>
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<td>$P_2$</td>
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Not all pressure peaks are always present. Which one dominates depends on the test conditions
Test vessel 1 0.01 m³

Experimental set-up for test vessels  (a) Schematic diagram, (b) Photograph.

Test vessel 2 0.2 m³
Gas mixtures and vent designs

- Different gas mixtures: Methane-air (10%), Propane-air (4%, 4.5%), Ethylene-air (6.5%, 7.5%), Hydrogen-air (30%, 40%).

A range of $K_v$ was investigated.

- 16 Joule spark ignition.
- Central and end ignition compared

- Repeatability
  Each test conducted at least three times with each individual result plotted in the graphs.

Influence of the number of vents, the shape of vent and the position of the vent were investigated, as these are stated in the US and EU standards as having no effect. The results show a significant effect for all.
Comparison of the pressure time records for 10% methane-air for $K_v = 7.2$ for free venting and for $P_{stat} = 57$mb.

Vent Static Burst Pressure effects
Effect of vent area

Overpressure against $K_v$ with end ignition for (a) 10% methane-air (b) 4.5% propane-air
End Vs Central ignition
Effect on vent area distribution

**EN 14994-2007:**

6.2 Positioning and shape of explosion vents

Explosion vents shall be positioned so that the effectiveness of the venting process is not impeded. If the enclosure is small and relatively symmetrical, **one large vent is as effective as several small vents of equal combined area**. For large enclosures, the location of multiple vents to achieve uniform coverage of the enclosure surface to the greatest extent practicable is necessary. One shall also assure that nearby plant and personnel will not be at risk from flames, blast and flying debris. Recoil forces shall be taken into account when considering the location and distribution of the vent.

**NFPA 68, 2013:**

A.6.4 The $P_{red}$ developed in a vented enclosure decreases as the available vent area increases. If the enclosure is small and relatively symmetrical, **one large vent can be as effective as several small vents of equal combined area**. For large enclosures, the location of multiple vents to achieve uniform coverage of the enclosure surface to the greatest extent practicable is recommended. Rectangular vents are as effective as square or circular vents of equal area.
Effect on vent area distribution

Fig. 13 Pressure-time records of single and multiple vents for 10% Methane-air and 7.5% ethylene-air (Kv=10.9 and 5.4)
What influences the external explosion

In all tests except for one (methane, small vent area, 4 hole) the external explosion was the highest pressure peak.

The external explosion is a turbulent combustion fire-ball, dependent on the turbulent burning velocity, often expressed in terms of the turbulent Reynolds number

\[ R_l = \frac{u' l}{v} \]

\( u' \) depends on flow through the vent and the pressure loss coefficient (upstream flame speed and BR).

\( l \) is of the order of the width of the solid material between the holes (vents)
External Pressure Vs length scale
Vessel Shape: **Square vs Circular Vents**

![Square vs Circular Vents Diagram](image-url)
Overall results – Methane

Comparison of vent design equations with experiments for Methane-air as $P_{red}$ v. $1/K_v = A_v/V^{2/3}$

- NFPA 68 (2013), L. Flame theory ($C_d = 0.61$)
- Bartknecht (1993) ($P_{stat} = 0.1$ bar), Bartknecht (1993) ($P_{stat} = -0.1$ bar)
- L. Flame theory ($C_d = 0.7$), Bartknecht (1993) ($P_{stat} = 0$)
- Cooper et al., 1986, 0.2 m$^3$
- Kasmani et al., 2010, 0.2 m$^3$
- Cooper et al., 1986, 35 m$^3$
- Solberg, 1979, 0.68 m$^3$
- Hochst and Leuckel, 1998, 49 m$^3$
- Bartknecht, 1993, 1 m$^3$

Vent $C_d = 0.7$

Bartknecht’s results and vent correlation as used in the EU venting standard

Methane-air

$P_{red} (\text{bar})$

$1/K_v$

$A_v/A_s$

$A_s = \text{Surface area of vessel}$
Overall results – Propane

Comparison of vent design equations with experiments for propane-air as $P_{\text{red}}$ v. $1/K_v = \frac{A_v}{V^{2/3}}$
Conclusions

➢ Present results from small vessel tests comparable to results from very large scale tests.

➢ Able to identify and study the various mechanisms of pressure generation

➢ For low $K_v < \sim 7$ the external explosion dominates $P_{\text{max}}$ and for $K_v > \sim 7$ the flow through the vent dominates $P_{\text{max}}$.

➢ Vent number, shape, position and ignition position are all important but not recognised as such in the standards.

➢ Bartknecht’s results (on which the European standards are based) are higher than anybody else’s.

   o Possibly because of the coanda effect on the discharge jet when the vessel is flush with the ground. Similar effects observed in some of our tests.