Prediction of pressure and flame effects in the direct surroundings of installations protected by dust explosion venting

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When applying dust explosion venting as a measure to protect installations one should always bear in mind the secondary effects of application of venting, *viz* blast waves and flames emerging from the vent. These two effects pose hazards to the direct surroundings of explosion vents and these hazards should be considered during the design phase of the equipment. This paper will give an overview of the data and methods that are available to predict flame and blast effects associated with vented dust explosions.

(Keywords: dust explosions; explosion venting; blast and flame effects)

The method used most often to protect equipment and buildings against the consequences of dust explosions is explosion venting. The equipment or building is provided with a vent opening or vent openings with a total size calculated to be such that in the case of an accidental explosion the maximum explosion overpressure will be lower than the failure pressure. In doing so one has to take account of the reactivity of the dust (K_{St} value and maximum explosion overpressure in a closed vessel), the volume of the equipment or building and the pressure at which the vent cover opens. Guidelines to determine the vent opening size have been available for several years[1,2] and are still being improved[3,4]. The simplicity of the method in general has made explosion venting very popular. Nevertheless the method has some disadvantages such as the generation of flame jets and the generation of blast waves. When designing vents these secondary effects, which pose hazards to the direct surroundings of vented structures, must be considered.

In this paper a review is given of experiments that have been performed and methods that are available to determine flame jet and blast wave hazards associated with the venting of dust explosions. In doing so not only will dust explosions be considered but also gas explosions as they can be considered to be similar for these hazards.

Description of dust explosion propagation in vented explosions and the associated generation of blast waves and flame jets

On ignition of a flammable dust–air mixture in a vessel protected by explosion venting a reaction front will propagate through the mixture. Combustion products are generated which will expand. As a result the unburned mixture is compressed and the pressure in the vessel starts to rise. Depending on the position of the ignition point in the vessel and the shape of the vessel a flow field will be established and the unburned mixture will be pushed forward by the combustion products.

With continuing combustion the pressure in the vessel will increase exponentially until the moment of opening of the vent cover. As a result of the pressure difference over the vent opening, the mixture in the vessel starts to flow out of the vessel. The outflowing mixture may either be burned or unburned depending on the position of the ignition source and the moment the vent cover opens.

If ignition is effected at a position far from the vent opening, unburned mixture will be pushed out of the vent opening forming a jet. The jet velocity will strongly depend on the size of the vent opening and explosion overpressures. At the edges of the opening and between the outflowing mixture and the stationary air outside the vessel, turbulence is generated and a recirculation flow is established. This will cause entrainment of air and result in dilution of the mixture pushed out of the vessel. For mixtures that were initially richer than the stoichiometric concentration, this may mean that they become more reactive as their concentration shifts towards stoichiometric.

The turbulent cloud of unburned mixture outside the vented vessel is ignited by the flame once combustion products are vented. For large vent openings this will lead to the generation of an almost spherical flame ball. A representation of this is given in *Figure 1*. This representation is based on the description given in Reference 5. Due to the turbulence

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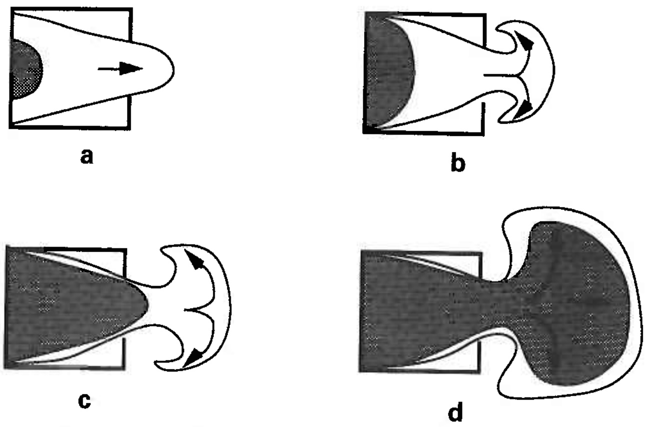

Figure 1 Several phases of the development of an external explosion: (a) start of outflow of unburned mixture; (b) formation of jet head; (c) flame approaches jet head; (d) flame front becomes spherical

the flame speeds are very high resulting in strong blast waves. Small vent openings lead to very high jet velocities. As a result, the mixture displaced from the vent is ejected a large distance from the vent and the external flame propagation is elongated rather than spherical.

The most severe external effects appear to be caused by external explosions, i.e. the explosion of unburned material displaced from the vented vessel. This will be shown later when experimental investigations into blast and flame generation by vented explosions are discussed.

For the scaling of blast generated by explosions, the volume of gas contributing to the blast generation, or, more accurately, the combustion energy that is represented by this volume of gas, is very important[6]. As the external explosion effects appear to be determined by the external explosion, it is important to know how much gas contributes to the external explosion. In the case of ignition at a large distance from the vent opening (the worst case situation), the volume of the mixture expelled from the vented vessel is about 7/8 of the volume of the vessel (neglecting compression effects).

As the external explosion is causing the blast effects, these will be dependent on:

- the size of the vent (turbulence generation; flow field distribution)
- the maximum overpressure in the vessel (turbulence generation; flow field distribution)
- the fuel reactivity
- the volume of the vessel (blast decay; combustion energy)

The decay of blast waves with distance is acoustic when low overpressures are generated (acoustic means that at twice the distance to the blast centre the blast overpressure is decreased by a factor of two). When strong overpressures are generated by the vented explosion the decay of the blast wave will be stronger than acoustic. Blast wave decay may also be stronger than acoustic in a certain direction due to asymmetrical effects. In general this means that in a direction perpendicular to the direction mentioned first, blast decay will be less strong than acoustic.

For the length of the flame jet emerging from the vented vessel, the amount of gas expelled from the vessel is also important. In addition, the shape of the unburned jet and the jet velocity are important factors.

Experimental observations

In this chapter some experimental investigations on blast waves and flame jets generated by vented explosions will be reviewed. Both gas and dust explosions are considered. First we consider blast wave generation.

Blast wave generation

The first published report on measurements of blast waves due to vented explosions was performed with a rectangular 35 m^3 vessel[7]. The experiments were performed with propane gas. Ignition was effected in the centre of the vessel. The results showed that in spite of very strong explosions inside the vessel the blast due to these explosions was very limited. A single sharp spike was measured first which, according to the authors, coincided with the opening of the vent. In spite of the much higher pressures measured in the vessel later during the explosion process, the spike appeared to be the highest blast pressure measured. The higher pressures in the vessel generated some noise outside the vessel only.

In Reference 8 the blast waves due to vented natural gas explosions in a 28 m^3 room were investigated. Polyethylene sheet, glass and hinged explosion doors were used as vent covers. The vent size was varied. Ignition was effected at the wall remote from the vent. Blast wave strengths were measured at two distances on a line normal to the vent. In addition, pressures were also measured at other orientations.

The results showed a linear relationship between the maximum pressure at a given point outside the room and the maximum pressure measured inside (see *Figure 2*). Moreover the results showed a regular relationship between the attenuation of the pressure and the distance from the vent. In fact the pressure halved when the distance to the vent doubled. This result is in agreement with acoustic decay of blast with distance. For short distances, however, acoustic decay appeared to break down. In fact the results showed that the blast centre would be located about 3 m from the vent opening. This would be in agreement with the observations of external explosions mentioned in the introduction. An effect of vent size was not measured. A clear directionality of the blast waves was noticed.

Blast measurements performed during propane explosions outside a 50 m^3 tube ignited by a strong jet[9] or provided with obstacles[10] were compared to blast prediction methods using ideal gas explosions as a blast source (hemispherical gas clouds with a volume

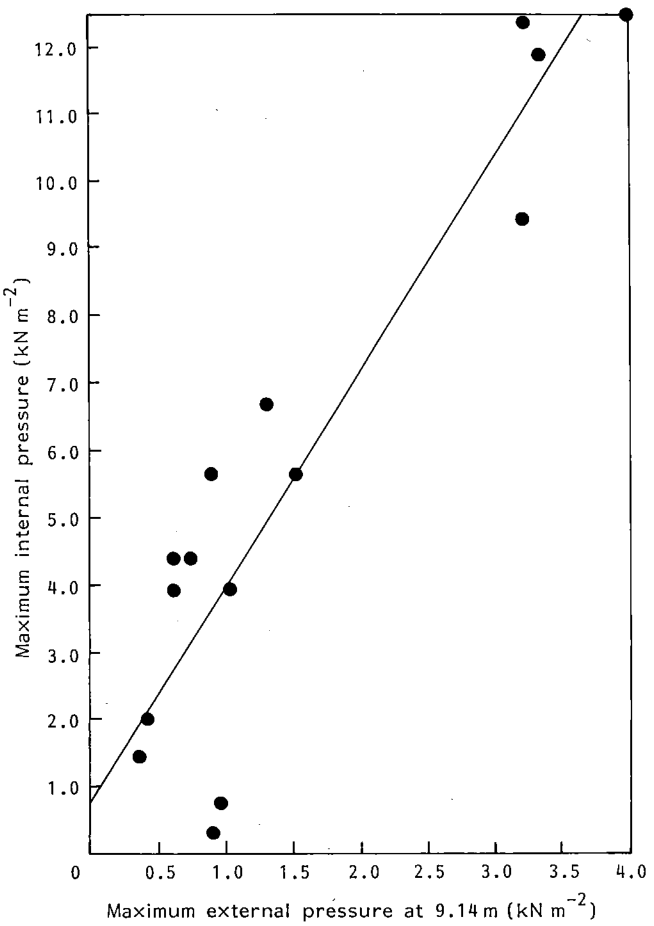

Figure 2 Relationship between internal maximum pressure and external maximum pressure for natural gas explosions in a 28 m^3 room[8]

equal to 50 m^3). The experiments were performed over a wide range of maximum flame speeds and maximum overpressures (up to 14 bar). The results showed reasonable agreement when flame speeds measured in the tube were used as input values for the prediction methods. Unfortunately the maximum pressures in the tube monitored simultaneously with the reported blast overpressures were not documented.

The first blast measurements performed for vented dust explosions were reported in Reference 11. Experiments were performed with three different vessels (0.25 m^3, 1 m^3 and 5 m^3). Variables were the reactivity of the dust (K_{St} value), the opening pressure of the vent cover, the location and orientation of the blast gauge to the vent opening and the size of the vent opening. Results are presented in *Figure 3*. They represent averaged values of experiments in the 1 m^3 and 5 m^3 vessels. A vent opening size of 0.2 m^2 was used in the 1 m^3 vessel giving rise to a maximum overpressure of 0.6 bar. In the 5 m^3 vessel a vent opening of 0.5 m^2 was used resulting in a maximum overpressure of 0.9 bar. The difference between the results of the two configurations is striking and according to the authors this is due to the different size of the vent opening. This finding conflicts with the results found for natural gas where a dependency on the vent opening size was not recognized[8]. Further it was found that the maximum pressures outside the vessel were independent of the volume of the vessel, independent of the vent opening pressure and independent of the dust reactivity. It was also found that there was no correlation between the angle of the position at which the blast was measured and the direction of the venting. This again conflicts with the results presented in Reference 8, where an effect of blast gauge orientation was found. *Figure 3* also demonstrates the decrease of the maximum blast overpressure with distance. For both situations the decrease of blast with distance is acoustic.

Blast measurements of a vented 5.2 m^3 vessel were presented in Reference 12. Experiments performed with methane and propane were presented. Blast measurements were performed at two distances from the vent opening. The pressure–time histories measured outside the vessel resembled those measured inside the vessel. Three peaks were distinguished inside the vessel. The first was due to the opening of the vent cover. The second was probably due to an external explosion, whereas the third was generated due to the onset of an acoustically-driven flame instability in the vessel giving rise to relatively high pressures. The blast waves also exhibited the three peaks (see *Figure 4*). The blast decay of the first two peaks with distance appears to be acoustic. The blast decay of the third peak was stronger, probably due to the presence of the strong flame jet during the generation of the third pressure peak in the vessel. No difference between the results of methane and propane could be distinguished.

The first experiments which showed the importance of external explosions with respect to blast generation were reported in Reference 13. Experiments performed in a 250 m^3 spherical vessel with two dusts of different reactivity showed that dusts with low reactivity and giving rise to low overpressures in the

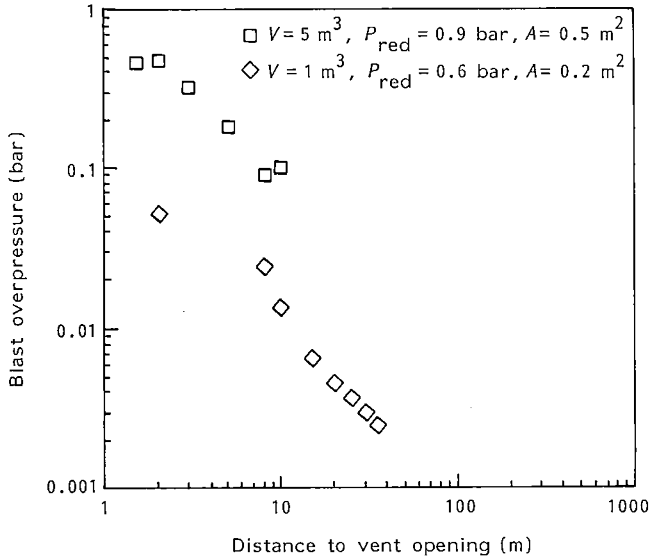

Figure 3 Some results of blast measurements performed during the venting of dust explosions[11]

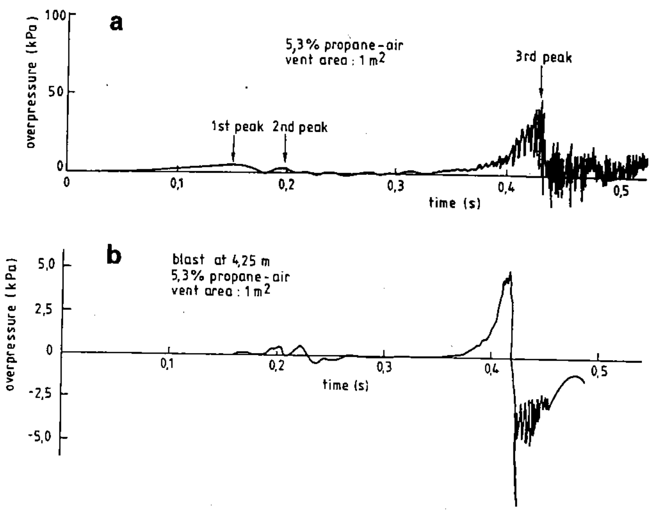

Figure 4 Pressure–time histories of a vented 5.3% propane–air explosion (a) inside and (b) outside a 5.2 m^3 room[12]

250 m^3 spherical vessel generated large clouds of unburned material outside the vessel. When ignited these clouds generated very strong external explosions leading to stronger blast waves than those generated by the more reactive dust under the same circumstances. The results of these experiments are shown in *Figure 5*. It should be noted that in these experiments the relationship between maximum overpressure in the vessel and the blast overpressure at a certain distance is completely different from that found for natural gas[8] (*Figure 2*).

More detailed knowledge of the mechanism of blast generation by vented gas and dust explosions was generated in the investigations described in References 14–16. In Reference 14 experiments performed in a 30 m^3 room were reported. Propane and natural gas were used as flammable gases. The experiments showed that it was the external explosions which caused a distant blast hazard. The external explosions were very strong when ignition was effected near the rear wall of the room. This effect was again maximal for vents of intermediate size because for small vents the effective source is small even though the peak pressure is high. This effect of vent size was in contradiction to Reference 8 and in agreement with Reference 12. *Figure 6* shows three peak overpressure–distance relationships measured for three of the natural gas tests. The maximum pressure is not generated at the vent but at a considerable distance from the vent outside the room. For weak explosions the decay of the blast wave is acoustic (1/*r* decay), whereas for the stronger explosions the decay is stronger than acoustic.

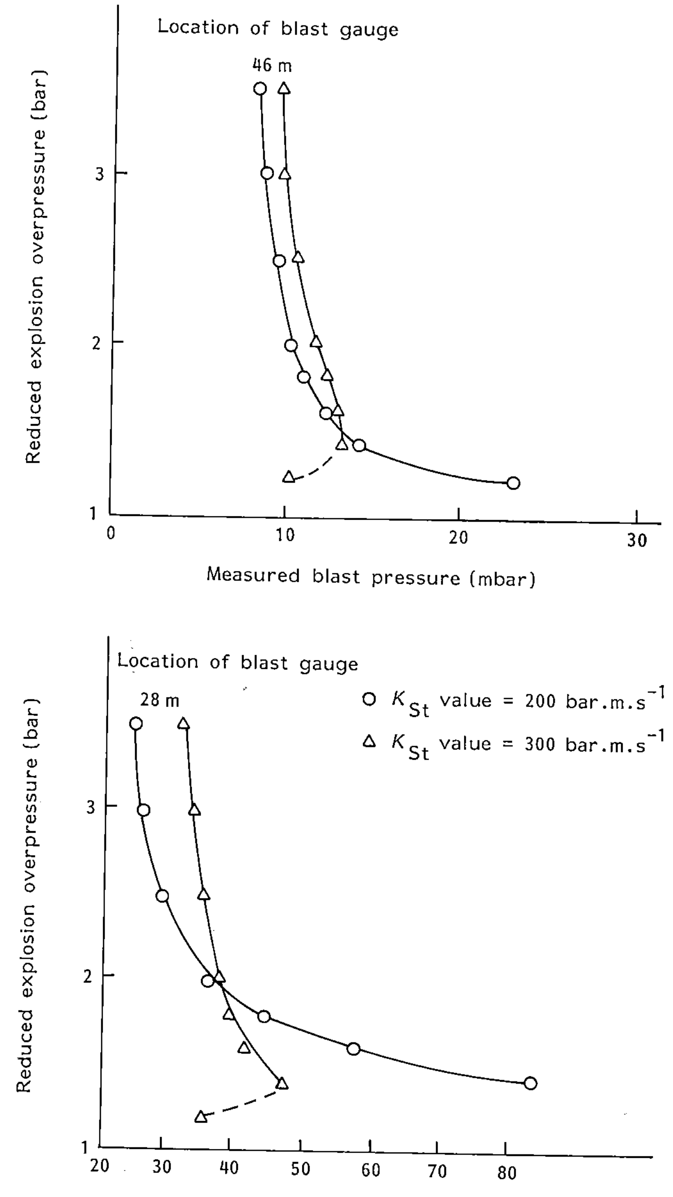

Figure 5 Blast overpressures generated by vented dust explosions in a 250 m^3 vessel for two types of dust[13]

It should be noted that this investigation also showed that the external explosion had an influence on the maximum explosion pressure generated inside the room. The blast wave generated outside the room also ran into the room which in certain situations could increase the internal pressure by a factor of two. Further, the authors noticed that a high external pressure will stop the outflow of gases from a vented vessel. This was also noticed for an investigation into the venting of dust explosions in a 236 m^3 silo[17], and for experiments performed in a 250 m^3 vessel[23]. Finally the occurrence of a strong negative pressure phase was noticed. This negative phase can lead to damage to other structures, e.g. windows, as well.

An experimental investigation performed in a 38.5 m^3 room using methane as a flammable gas also showed that the external explosion gave rise to the strongest distant blast effects[15]. The external explosions were very strong when ignition was effected at the rear face of the room. *Figure 7* shows two pressure–time histories measured outside the room for central ignition and for ignition effected at the rear face of the room. The first spike in the pressure–time histories is due to the external explosion.

The investigation reported in Reference 16 confirmed that the blast-generating mechanisms found for

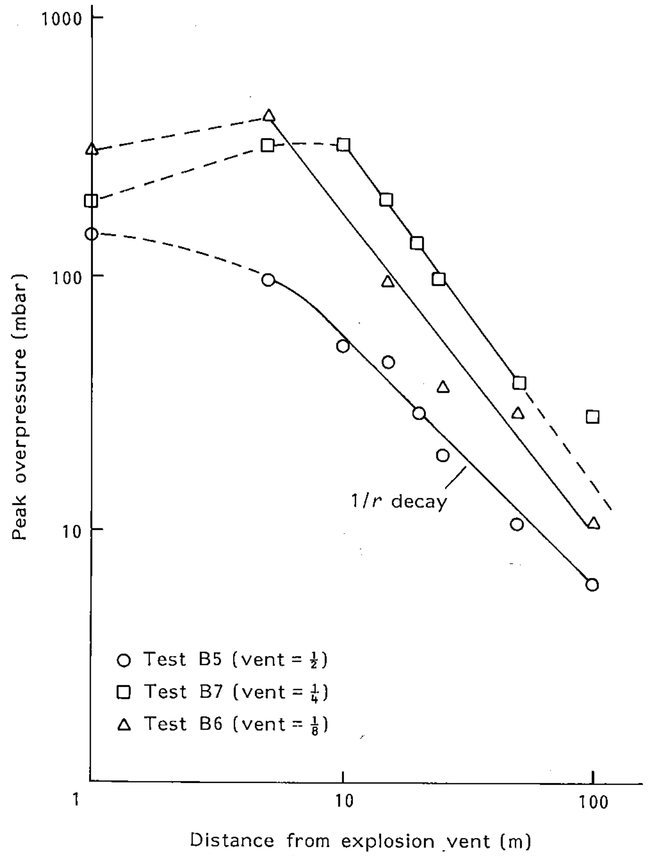

Figure 6 Peak overpressures measured at various locations outside a vented room for three natural gas tests using ignition at the rear face of the room[14]

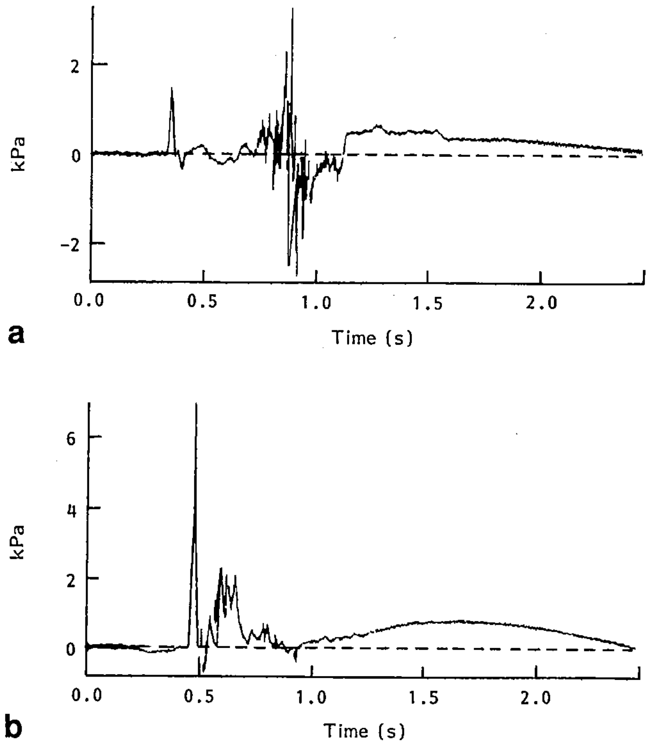

Figure 7 Examples of pressure–time histories measured outside a 38.5 m^3 room (vent opening 4.1 m^2) for ignition effected (a) in the centre and (b) at the rear wall[15]

gas explosions in References 14 and 15 also occur during dust explosions. A comprehensive investigation performed in vessels of 0.3, 1, 10, 60 and 250 m^3 was described. In addition to the vessel volume, the K_{St} value, the size of the vent opening, the ignition source location and the vent opening pressure were varied. The results showed that the maximum peak pressure outside the vessel occurs at a distance of 2–5 m from the vent. Beyond this distance the pressure decays rapidly with distance. This blast wave decay appeared to be stronger than acoustic ($r^{-1.5}$). The maximum peak overpressure outside the vessel increased with decreasing vent area and increasing volume and increased with increasing K_{St} values.

Considering all reviewed experimental observations, the following conclusions can be drawn:

- The strongest distant blast wave effects are caused by explosions of unburned material pushed out of the vessel and subsequently ignited by flames emerging from the vessel.
- The maximum pressure due to the external explosion outside the vessel is dependent on the vent opening size, the maximum pressure in the vessel and the volume of the vessel.
- The blast decay beyond the location of maximum pressure is acoustic or stronger than acoustic.
- The generated blast waves show directionality.
- The external explosion is less important for rooms with small vents and for vessels in which very strong explosions occur.
- The blast waves due to external explosions are accompanied by a significant negative pressure phase.

Flame jet generation

Very few investigations have been performed to determine the size of flame jets generated by vented explosions. Some investigations only mention the maximum size of flame jets as:

- Experiments performed in a 5.2 m^3 vessel with methane and propane: > 5.5 m (Reference 12)
- Experiments performed in a 38.5 m^3 vessel with methane: 18 m (Reference 15)

In References 5 and 14 the authors describe the flame jet generation process in more detail in connection with the occurrence of external explosions. This process has been described above. Only two detailed investigations into the size of flame jets due to vented explosions have been described[16,18].

The experiments in Reference 16 have been reviewed before, with respect to blast generation. These experiments have also been used to measure the size of flame jets. Distance–time diagrams for dust/flame front development are presented. Depending on the vessel size, flame speeds in the jet of the order of 30–70 m s^{-1} were recorded. Little or no dependency of the maximum flame jet length on dust explosion reactivity or vent size was found.