

Violence of Dust Explosions in Integrated Systems

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INTRODUCTION

Dust handling systems generally consist of several machines and vessels interconnected by ducts or pipelines. An explosion starting in such a system can propagate throughout the entire system as long as no additional measures are taken. Any gas or dust explosion will generate combustion products which will expand. This will onset a flow field ahead of the flame. In dust handling systems consisting of several vessels and interconnecting pipelines this flow field will cause turbulence at the walls, intersections, narrowings and if present on obstructions. This turbulence enhances the combustion rate. Increase of the combustion rate results in an increase of the flow field velocities in the unburned mixture, generating more intense turbulence. This more intense turbulence will enhance the combustion rate even more, etc. The position feedback mechanism which is established can cause very high combustion rates resulting in very high rates of pressure rise and pressures in such integrated systems. This effect is illustrated in Figure 1.

In addition to the high combustion rates pre-compression (pressure-piling) in closed interconnected vessels may lead to maximum overpressures far beyond those found in a single vessel. This effect arises especially when a larger vessel vents via a pipeline into a smaller vessel (without vent openings). The pressure in the smaller vessel increases due to precompression by the explosion in the large vessel. At ignition by flames reaching the smaller vessel the pressure in this vessel has already increased considerably. Upon exploding the maximum overpressure that can be reached has the potential to be much higher than one would expect on the basis of constant volume combustion. This effect was demonstrated by Bartknecht [3] and Heinrich [4].

To prevent the spreading of a dust explosion from one vessel into another, and therefore the effects described above, several methods of explosion isolation can be applied. Examples are rapid injection of an extinguishing agent, fast-acting mechanical valves, rotary locks and diverters. Introduction of such systems allows application of protecting techniques such as explosion venting for each vessel in accordance with the NFPA-

guideline 68 (1988). If these systems are not included the guideline cannot be applied.

For several reasons (economical, practical) it may not always be possible to apply explosion isolation techniques. For instance guidance on dust explosion venting of interconnected vessels is sparse, partly because little experimental work has been done. Some work is known on gas explosions in interconnected vessels but in general these were performed in closed vessels [2,3,4,9]. In addition to the effects of flow-induced turbulence and pressure-piling which are very dependent on the geometrical details of the installation and which were noticed in all these studies, it was found by Phylaktou and Andrews [9] that due to shock waves running back into the system the pressure development in the vessel in which ignition was effected was influenced as well.

In order to be able to give some guidance on dust explosion venting of interconnected vessels a comprehensive experimental programme was started in the UK [7]. The work considers venting of two interconnected vessels. Vent opening sizes, length of the interconnecting pipeline and the volume of the vessels are the main variables. The experiments are performed with toner dust. So far only preliminary results have been published.

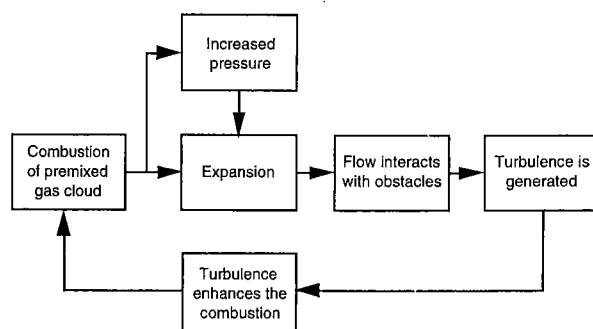


FIGURE 1. Positive feedback loop causing flame acceleration due to turbulence.

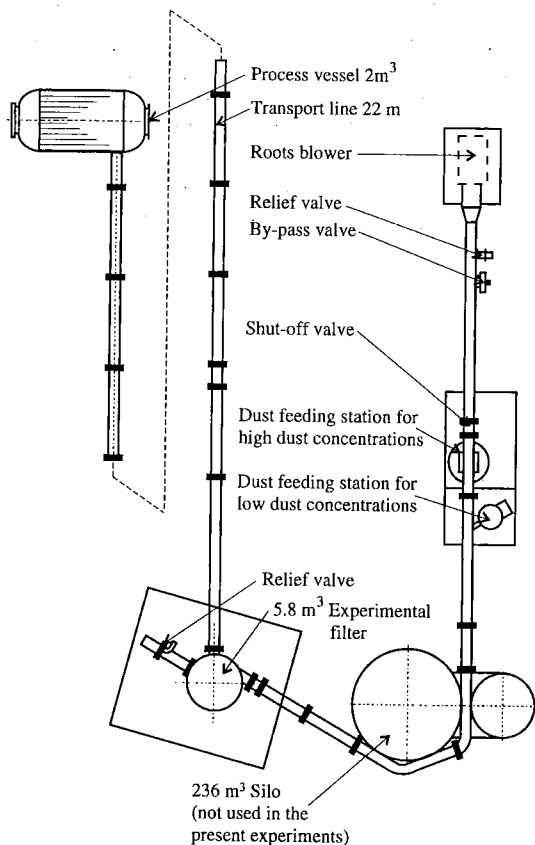


FIGURE 2. Layout of site showing dust feeding system, filter, 22 m duct and 2m³ vessel.

In this paper experiments performed at CMR in Norway are described. A fixed combination of two vessels and an interconnecting pipeline was considered. The main variables were the reactivity of the dust, the dust concentration and the vent opening size in the vessel where ignition was effected. Further some work was done on venting of the interconnecting pipeline.

EXPERIMENTAL SET-UP

The experiments were performed at an experimental site for dust explosion research on the island of Sotra, west of Bergen.

To study the explosion propagation in connected vessels a 5.8 m³ bag filter unit and a 2 m³ process vessel were used. They were interconnected via a 15 cm diameter, 22 m long duct. The complete test arrangement is shown in Figure 2.

The bag filter has a cylindrically shaped enclosure with a conical hopper at the bottom. The total volume is 5.8 m³. In the tests reported here the bag filters were taken out from the filter enclosure. The main body of the filter enclosure can withstand explosion pressures of up to 5 bar.

The filter unit is provided with six square vent openings of 0.23 m² each, arranged symmetrically around the main cylindrical body of the filter enclosure, as shown in Figure 3. The vent openings are provided with flanges on to which any desired type of vent cover can be bolted. In the present tests bursting discs having a static opening pressure of 0.1 bar, were used.

The 2 m³ process vessel is cylindrical. It can be provided with a vent opening of 0.25 m² or less. In the present project a vent opening of 0.25 m² was used in every test. To cover the vent opening bursting discs were used (static opening pressure 0.1 bar).

Dust-air mixtures in the system were generated by a dust injection system consisting of a conventional pneumatic conveying line of i.d. 155 mm and a Roots blower. With no dust

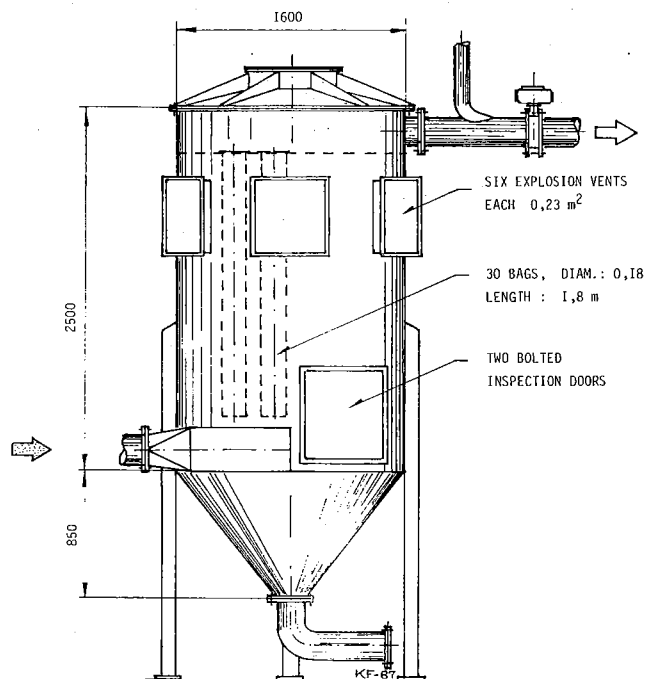


FIGURE 3. Projection of 5.8 m³ bag filter.

in the pipeline, the upstream static pressure was close to atmospheric and the mean linear air velocity in the conveying time was 38 m/s. During dust injection, the static pressure would increase depending on experimental modus chosen, up to 5 mbar.

The dusts were fed into the pipeline from a 1.5 m³ hopper a few meters downstream of the blower by means of a rotary lock. The feeding rate was varied according to the chosen operational modus, obtaining dust concentrations from below the explosive limit (about 30 g/m³) up to about 2000 g/m³.

The ignition source used in the reported experiments was 25 g of dried nitrocellulose contained in a small bag and ignited by a pair of electrically fired Ce-Mg 100 J fuse heads. The total energy liberated by this ignition source was about 100 kJ. In all experiments ignition was effected in the centre of the filter unit.

For monitoring and timing purposes, a data acquisition and control system, including a 13 bit high speed voltmeter (100 kHz), a 24 channel high speed FET multiplexer and a 16 channel general purpose switch, was used. All timing and measuring operations were automatically controlled by a computer linked to this system.

The development of explosion pressure with time was monitored by means of three piezoelectric pressure transducers: one transducer placed in the filter unit, one in the duct and one in the process vessel.

EXPERIMENTAL PROGRAM

The experimental programme comprises studying the influence of:

- the type of the dust
- the dust concentration
- the vent opening size in the vessel where ignition is effected
- the presence of vent openings in the interconnecting duct

on explosion propagation in the integrated system.

For varying the type of dust, five dusts were used in these experiments. These were maize starch, peat dust, polypropyl-

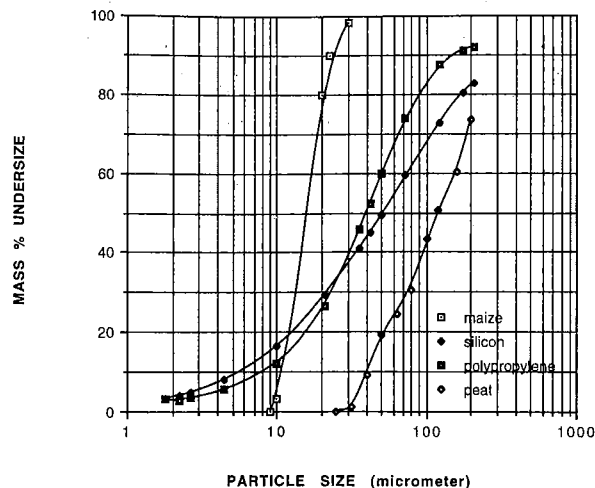


FIGURE 4. Particle size distributions (Laser diffraction combined with dry sieving) of the dusts used in the present research programme.

ene dust, silicon powder and a wheat dust. The moisture content of the wheat dust was 12%. The moisture content of the maize starch was 11.1% and for the peat dust 11.8% was measured. The moisture content of polypropylene and silicon was less than 1%. The particle size distributions of the maize starch, the peat dust, the polypropylene and the silicon are given in Figure 4. The particle size distribution of the wheat dust is unknown.

The maximum explosion pressure and the maximum rate of pressure rise were determined in the 20 l spherical apparatus in accordance with the ISO standard 6184/1 (International Organization for Standardization, 1985). The results are presented in Table 1.

Variation of the dust concentration for the dusts used during the experiments in the integrated system was performed over a relatively wide range.

In addition to variation of the dust type and the dust concentration some variations were carried out regarding the geometry. To reduce the strength of the explosion in the bag filter somewhat a small vent opening was introduced. The size of the vent opening was varied from 0.04 m² to 0.08 m². To reduce the power of the explosion during its propagation through the interconnecting pipeline a total number of 3 vent openings could be introduced each having a diameter of 40 cm.

EXPERIMENTAL RESULTS

The data presented in this section were acquired by direct pneumatic injection of dust clouds of different concentrations. To find optimum conditions feeding rate and time were varied. The overall dust concentration in the system was, after a certain

Table 1 Standard explosion properties of dust used in the present investigation

Dust type	P _{max} (bar)	K _{St} (bar.m.s ⁻¹)
Maize starch	7.4 bar	145
Peat	7.6 bar	118
Silicon	7.1 bar	140
Polypropylene	6.5 bar	130
Wheat	5.2 bar	55

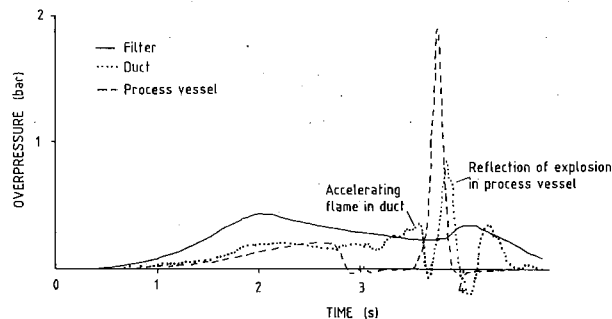


FIGURE 5. Pressure-time histories measured at three positions in the integrated system, viz. in the filter (P1), in the duct (P2) and in the process vessel (P3) during a maize starch explosion. Dust concentration 1000 g/m³. Vent opening size in filter 0.04 m². Vent opening size in process vessel 0.25 m².

feeding time, assumed to be equal to the feeding rate. This might not be true for every dust. The variation of the different parameters, however, will still give the maximum explosion values. Prior to ignition the feeder and air flow were stopped. The closing of a valve near the filter prevented the explosion from travelling back towards the feeding system. Possible deposition of dust after the feeding was stopped, will be counteracted by the flow and turbulence generated by the explosion itself.

General Observations of the Flame Propagation Process

The flame propagation process in the integrated system is as follows: Ignition in the filter leads to a strong ignition of the fuel in the interconnecting pipeline. Partly due to the strong driving force of the explosion in the filter the flame starts to accelerate in the pipeline, generating a flow field and hence turbulence in the unburned dust-air mixture. This turbulence will also assure the presence of a dust-air mixture ahead of the flame: deposition is prevented. An accelerating flame propagates through the pipeline, eventually igniting the dust-air mixture in the process vessel giving rise to a very strong explosion there. The strength of this explosion is mainly caused by the turbulence generated by the explosion.

Figure 5 shows three pressure-time histories measured during a maize starch explosion in the filter (P1), the interconnecting duct (P2) and the process vessel (P3), respectively. The particular conditions in this experiment gave rise to a very strong explosion in the process vessel. A maximum explosion overpressure of 0.97 bar was measured. According to the NFPA-guideline 68 (NFPA, 1988) a vent opening of 0.1 m² is needed to assure that the pressure will not exceed this pressure assuming an explosion in an isolated vessel. In the process vessel a vent opening of 0.25 m² was installed which is 2.5 times as large as demanded by the NFPA guideline. The recently published draft version of the new VDI-guideline in Germany (VDI, 1992) demands a vent opening of 0.06 m² for isolated vessels. This is four times smaller than necessary in the situation of the integrated system. This shows the completely different situation when an explosion in a vessel is ignited by a flame running from another part of an integrated process system in which no isolation techniques have been applied.

The pressure-time history in the filter is as would be expected for a vented explosion. The "multiple-peak" pressure time-history measured in the duct is typical for an accelerating flame in a tube. The pressure-time history measured in the process vessel exhibits a very steep strong peak due the explosion there.

Table 2 Frequency of ignition breakthrough in duct and process vessel after an explosion in the filter for several initial conditions

Process conditions (dust type, dust concentration, vent size in filter)	ignition breakthrough frequency in duct (%)	ignition breakthrough frequency in process vessel (%)
maize; 500 g/m ³ , 0.04 m ²	43	29
maize; 500 g/m ³ , 0.08 m ²	25	25
maize; 1000 g/m ³ , 0.04 m ²	80	80
maize; 1000 g/m ³ , 0.08 m ²	30	15
peat; 275 g/m ³ , 0.04 m ²	0	0
peat; 450 g/m ³ , 0.08 m ²	100	50
peat; 450 g/m ³ , 0.04 m ²	100	0
wheat; 650 g/m ³ , 0.04 m ²	0	0
wheat; 650 g/m ³ , 0.08 m ²	0	0
wheat; 1350 g/m ³ , 0.04 m ²	0	0
wheat; 1950 g/m ³ , 0.04 m ²	0	0

The initial pressure rise is due the explosion in the filter. Pressure waves generated by this explosion reached the vessel long before the actual explosion in the vessel causing a gradual increase of the pressure there up to the moment the vent cover mounted onto the process vessel fails resulting in a drop of the pressure to atmospheric.

The pressure peak generated by the strong explosion in the process vessel runs back into the integrated system. In the duct the maximum pressure of the pressure wave decays but causes in fact the highest pressure measured in the duct. Due to further decay in the duct and expansion in the filter the pressure caused in the filter by the pressure vessel explosion is lower than the maximum pressure which was caused by the explosion in the filter itself.

Not every explosion in the filter gives rise to an explosion throughout the entire integrated system depending on the dust reactivity. An overview of the frequency of explosion occurrences in the duct and process vessel after an explosion in the filter is shown in Table 2 for maize, peat and wheat.

These results clearly demonstrate that there is a dependency of ignition breakthrough (defined as an explosion is observed in the process vessel) and reactivity. For the low reactive wheat ($K_{St} = 55 \text{ bar.m.s}^{-1}$) no ignition breakthrough was found in any test.

The optimum concentration of maize starch is 1000 g/m³. The frequency of ignition breakthrough for this concentration is clearly higher than for the less reactive concentration of 500 g/m³. A similar observation was done for the peat dust experiments.

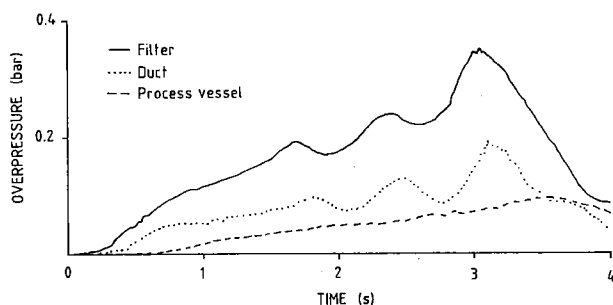


FIGURE 6. Pressure-time histories measured at three positions in the integrated system, viz. in the filter (P1), in the duct (P2) and in the process vessel (P3) during a wheat explosion. Dust concentration 650 g/m³. Vent opening size in filter 0.08 m². Vent opening size in process vessel 0.25 m².

The pressure time histories of an explosion of wheat dust are shown in Figure 6. The figure shows that the shape of the pressure-time history is more or less the same on the three locations except for some superposed pressure waves which can only be noticed in the duct and the filter. The maximum overpressure decays as a function of distance from the filter. In addition to that the bursting disc on the process vessel remains intact. All these factors clearly indicate that the explosion did not propagate into the duct, i.e. it was quenched.

From Figure 7 the influence of the reduced explosion pressure in the filter on the pressure development in the duct for maize starch dust-air mixtures can be seen. As the figure shows there seems to be a direct relationship between the driving pressure in the filter and the maximum overpressure in the duct in spite of large scatter. For drawing up this figure only situations where the explosion propagated into the duct were taken into account. The pressure wave running back from the process vessel into the duct after the explosion in the process vessel, was not considered (Figure 5). The figure indicates that an important reason for the flame acceleration in the duct is the expansion of combustion products generated in the filter into the duct. This process is still continuing when the flame has already propagated deep into the duct.

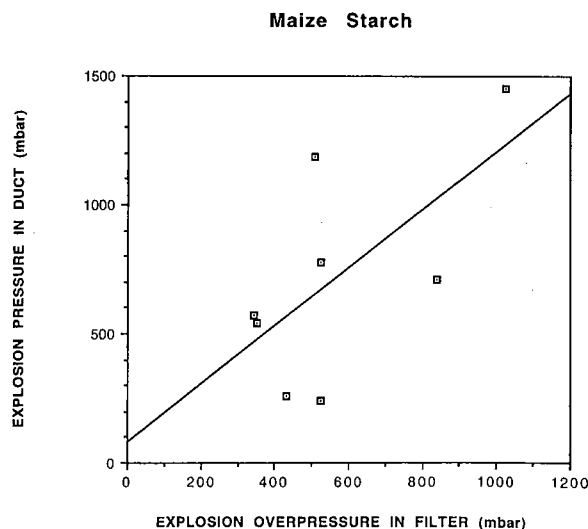


FIGURE 7. Relationship between maximum overpressure in filter and maximum overpressure in duct (Maize starch; 1000 g/m³).

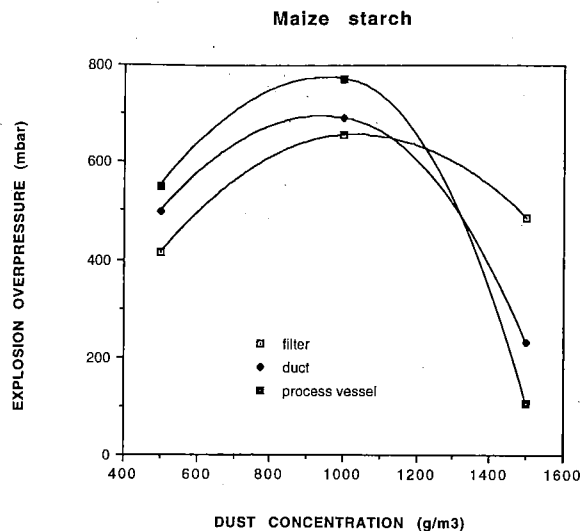


FIGURE 8. Influence of dust concentration on explosion pressure development in integrated system. Maize starch; vent opening in filter 0.04 m² (at the concentration of 1500 g/m³ data for a 0.08 m² opening were used).

Dust Concentration and Dust Type

The explosion effects in the integrated system were investigated for several dust types over a wide range of concentrations. For example, Figure 8 shows the maximum reduced explosion pressures in the filter, the duct and the small process vessel for maize starch as a function of the dust concentration. In presenting the maximum explosion overpressure the pressure waves running back from the process vessel into the duct after the explosion (see Figure 5) were not considered. At concentrations where an ignition breakthrough occurred the results of only these experiments were used for drawing up this graph. The presented results are average values of several tests. At low and medium dust concentrations the explosion accelerates through the duct leading to high peak pressures in the duct and the connected vessel. High dust concentrations reduce the

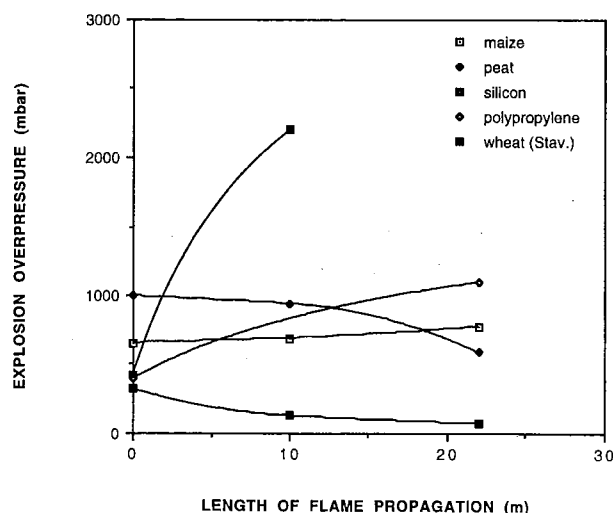


FIGURE 9. Pressure development in the integrated system for various dust types. Vent opening in filter 0.04 m². Silicon tests were performed with a decoupled process vessel.

acceleration and it becomes very difficult to obtain flame propagation through the duct.

Similar relationships were found for silicon, wheat and peat. For polypropylene only concentrations of 450 g/m³ were tested. For peat an ignition breakthrough occurred for concentrations of 450 g/m³ only. Wheat did not give rise to an ignition breakthrough at any concentration whereas silicon gave ignition in the range of 500-1200 g/m³ (tested up to 1600 g/m³).

Figure 9 illustrates the pressure development in the integrated system for all dust types that were tested. The pressures were measured in the filter unit (0 m), the duct (10 m) and the process vessel (22 m). The results of the optimum concentrations have been plotted. With the exception of wheat only pressure results have been used where an ignition breakthrough occurred. The results are averages of several tests at similar conditions.

Figure 9 shows that the dusts used in the present investigation can be subdivided in three areas:

- It is not possible for flames in wheat-air mixtures to propagate into the duct and further down into the system;
- Polypropylene, maize starch and peat appear to respond more or less the same. It should, however, be mentioned that a large variation is found in pressures in the filter even though the K_{St} -values are in the same order;
- Silicon appears to respond far more reactive than the other dusts in the integrated system even though the K_{St} is in the same order as those of polypropylene, maize starch and peat.

The strength of the silicon explosions led to performing these tests with the process vessel being isolated from the rest of the integrated system. The results of these particular tests show that a K_{St} -value is not always sufficient to describe dust explosion reactivity under all circumstances.

Variations of Geometry Details

During the present program some parameters were varied with respect to the geometry of the integrated system. These parameters were:

- the size of the vent opening in the filter
- the number of small openings in the interconnecting duct.

The size of the vent opening clearly had an effect on the maximum overpressures in the filter and due to the lower driving pressure also an effect on the flame propagation further down the integrated system. This has been illustrated in Figure 10 for maize starch. A variation of the size of the vent opening by a factor of 2 had an effect on the overpressures in the integrated system by a factor of 2 as well. Further it was found that when the driving pressure decreases by using larger vent openings in the filter also the frequency of ignition breakthrough decreases.

Some tests were performed to investigate the effect of introducing venting in the interconnecting duct. Up to a maximum of 3 15 cm diameter openings could be introduced in the duct evenly distributed over its length. The results of these tests, performed with maize starch can be seen in Figure 11. The figure demonstrates that a reduction of the driving force due to venting eventually also results in a decrease in the pressures in the duct and in the process vessel. The pressures in the filter are as could be expected unaffected. Further it should be mentioned that the presence of the vent openings had no effect on the frequency of ignition breakthrough into the process vessel.

PREDICTIVE TOOLS

The results presented in this paper show that explosion propagation in complex integrated systems is very sensitive to many

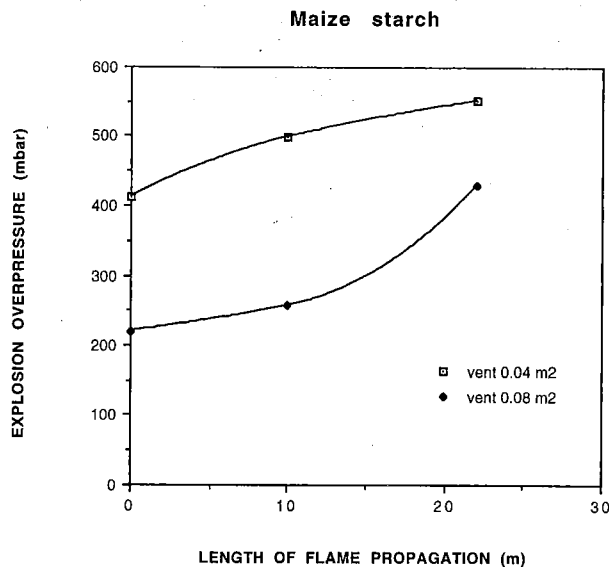


FIGURE 10. Maximum overpressure in the filter, duct and process vessel using vent openings of 0.04 and 0.08 m² in the filter. Maize starch; 500 g/m³; average values of several tests.

factors such as dust reactivity and geometrical details. This sensitivity is characteristic for explosions in complex geometries: small changes to an explosion scenario can lead to considerable changes in the explosion effects. Due to this sensitivity it will be very difficult to predict maximum overpressures due to dust explosions in integrated systems quantitatively in spite of the experimental efforts going in the UK at present (Lunn, 1992).

Probably the only method to account for all possible variations in an explosion scenario (dust type, location of ignition source, vessel shape and volume, pipe lengths and shape, etc.) is a computational fluid dynamic (CFD) tool. At CMR such

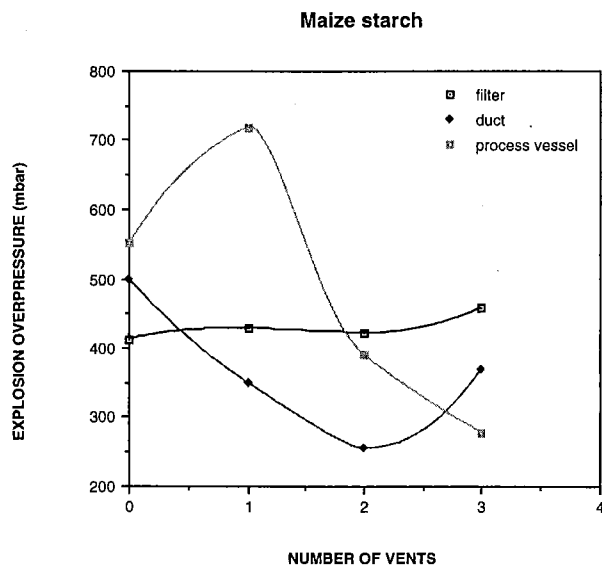


FIGURE 11. Influence of evenly distributed 15 cm diameter vent openings in the duct (perpendicular to the explosion propagation) on the explosion process in the integrated system. Maize starch, 500 g/m³, average values of several tests.

a tool has been developed for prediction of gas explosion events in complex geometries. The most recent version of this simulator (FLACS-93; Van Wingerden et al., [11]) has been provided with a combustion model describing turbulent burning velocities as a function of turbulence parameters and the laminar burning velocity. For gases this model is based on experimental data gathered by Abdel-Gayed et al. [1]. The model would also describe quenching by too intense turbulence. For dusts such experimental data are not available yet but such research has been started. Laminar burning velocity measurements have been reported by Proust [10] and measurements of turbulent burning velocities as a function of turbulence parameters have been reported by Kauffman et al. [6]. This research should lead to a combustion model suitable for describing dust explosions. Implementation of this combustion model in FLACS would allow one to predict dust explosion propagation in any complex geometry.

To show the possibilities of such a tool a simulation has been performed for the present experimental set-up. As no attempt has been made to predict the explosion effects quantitatively the set-up has been slightly idealized. The volumes of the vessels, length and diameter of the pipeline and the vent openings in the vessels have been represented correctly. The position of the ignition source and the way the vessels and pipeline were connected have been slightly changed. The burning velocity of the combustible was chosen to be 0.37 m/s (methane) which according to Proust [10] is approximately twice the burning velocity of maize starch.

The results of the simulation are shown in Figures 12 and 13. Figure 12 shows a few "snapshots" of the flame propagation in the system. From this figure it can be seen that very high flame speeds occur. The figure also shows that the explosion in the vessel where ignition was effected is still proceeding at the moment the flame reaches the second vessel. The expanding combustion products in this vessel will contribute to the flame speeds developed in the duct and therefore also the strong explosion in the second vessel.

Figure 13 shows pressure-time histories measured at the same locations as in the experiments. A comparison with Figure 5 shows a striking similarity: even the overpressures that are reached in all parts of the system are almost alike. All features described in the section on general observations of the flame propagation process when discussing Figure 5 can be found again in Figure 13 demonstrating the possibilities of tools like FLACS also for describing propagation of dust explosions in complex geometries.

CONCLUSION

An experimental investigation to study dust explosion propagation in an integrated system consisting of two vessels and an interconnecting pipeline has been performed. The experiments demonstrate the potential strength of such explosions. Whenever possible isolation techniques such as fast acting valves, rotary valves, etc. should be applied to prevent a positive feedback mechanism of explosion generated turbulence and combustion. This positive feedback mechanism can cause explosion pressures to increase to extreme values which are difficult to withstand for the equipment in which these explosions occur.

The present investigation showed that the more reactive a dust is the higher the chance of flame propagation throughout an entire integrated system is and the stronger the effect may be. The explosion pressures in vessels in integrated systems can be much higher than predicted by accepted venting guidelines.

Dusts with similar K_{St} -values do not always show similar explosion behaviour in such integrated systems.

Introduction of larger vent areas in the vessel where the explosion is initiated reduces the driving force and as such can result in a decrease of the overall effect in the integrated system.