Dust Cloud Characterization and the Influence on the Pressure-Time-History in Silos*

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Using VDI 3673 or NFPA guidelines for venting we have to distinguish between a homogeneous and inhomogeneous dust distribution in principle. Experiments were conducted in a 12 m^3-silo to measure the dust distribution, turbulence and the reduced explosion pressure using three different ways of generating the dust/air mixture: ring nozzles with pressurized dust chambers (1) (homogeneous distribution), (2) pneumatically fed vertically downwards (2) and tangentially (3). Additionally, the dust feeding rate, the conveying velocity and the ignition position was changed. The reduction of the conveying velocity and therefore the decrease of the RMS turbulence velocity will cause a strong reduction of the explosion pressure and the pressure rate, respectively. The results show that the dust concentration in the pneumatically filled silo is inhomogeneous. However, the RMS turbulence velocity and the reduced explosion pressure for the homogeneous distribution and the vertical filling are of the same order. In comparison to that, the tangential feeding results in lower values. Therefore, the calculations for the pneumatical vertical filling according to VDI 3673 guideline (inhomogeneous distribution) will underestimate the resulting pressure, and the equations for the homogeneous distribution should be used.

1 Introduction

The standard explosion data of different dust types including the maximum pressure rise are obtained from closed vessel tests, and somehow represent the energetics of mixture and burning rate, respectively. Those data are used to determine the size of the vent area among other parameters. The vent size is then calculated according the VDI 3673 [14] or NFPA guideline.

Using those guidelines we have to distinguish between a homogeneous and inhomogeneous dust distribution. It is recommended to use the equations for a inhomogeneous dust/air mixture if the dust concentration depends of the location. Normally, a inhomogeneous distribution, which can be obtained in vessels by pneumatically conveying combustible dust axially and centrally, will result in smaller vent areas.

The violence of an explosion depends not only upon the combustion properties of the powder but also upon the dust cloud concentration, uniformity and turbulence [1, 2]. Moreover, the turbulence for example has a great influence on the resulting flame velocity and consequently on the explosion violence [5, 11]. Therefore, it is usual to vary the delay time in explosion experiments to control the turbulence [13, 15], but it is not far proved that one can employ the dispersion induced turbulence to simulate the case in industrial accidents.

In principle, dust explosion experiments can be designed for "worst case" conditions, i.e. dust concentration near stoichiometric and a uniform dust cloud with high turbulence. But in practice, such conditions are rare, if ever exist, and it is impractical to fit safety measures that could protect against this unrealistic situation.

The chief aim of our studies is firstly to measure the dust concentration and the turbulence under real conditions in a silo to determine whether the dust concentration is homogeneous and secondly to find a relation to p_{red} or K_{St} obtained from explosion tests. Furthermore, the dependence of the RMS turbulence velocity on the explosion characteristics should be proved.

2 Experimental approach

Dust concentration measurements

We developed a system for the continuous measurement of dust concentrations in technical processes. Even fast changes and peaks in concentrations can be detected accurately up to 2000 Hz. The dust concentrations can be measured between 20 and 1500 g/m^3 [7].

The measuring principle is based on the reduction of the intensity I_o of a light beam (λ=950 nm) by absorption and light scattering on the length l when crossing a dust cloud. Lambert–Beer's Law describes the connection between the transmission I and the dust concentration c:

$$I = I_o \cdot e^{-c \cdot \epsilon \cdot l} \, .$$

The system is calibrated by systematically changing quantity of dust in a suspension, that is, the concentration can be achieved from Lambert–Beer's Law.

For the use inside of the silo the dust concentration measuring (DCM) probes are equipped with an optimized cleaning system to minimize mismeasurements caused by dust soiling of the optical lenses.

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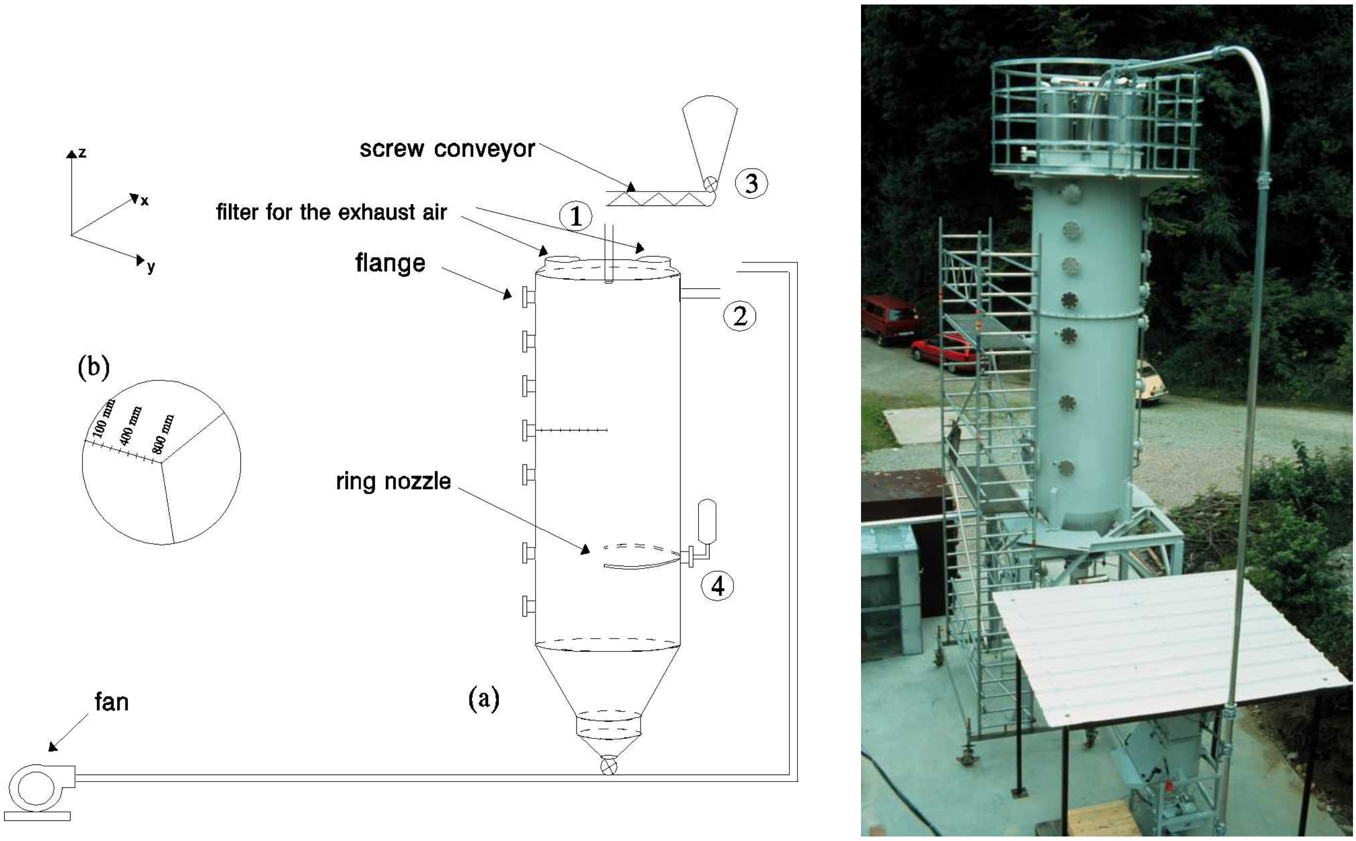


Figure 1: (a) Schematic diagram of the 12 m^3 (9.4m^3)-silo. Four ways of feeding the silo are possible that are pneumatical vertical (1), pneumatical tangential (2), mechanical through a screw conveyor (3) and through four ring nozzle with pressurized dust chambers (4). The measuring probes were mounted at the different flanges. (b) shows the cross-section with the radial positions for the probes. On the right-hand side the practical realization is shown.

Turbulence measurements

Turbulent parameter measurements (u, RMS) are accomplished by means of a transportable and compact single channel–Laser–Doppler–Anemometry System (LDA) [3]. The intersecting volume consists of 15 fringes with a distance of 3.9 μm of each and also a frequency shifting system is used so that flow direction is identified. The turbulence parameters in the experiments were determined by using the ensemble average technique, where 10 realizations are averaged.

The analysis process of the data with LDA–system consists of two major processes: Firstly, the removal of erroneous data points resulting from noise in the measuring signal or from the measurement of more than one particle at the same time [8].
Secondly, the calculation of the mean and the RMS–value using a time averaging procedure [9]. Generally the measured courses of velocity can be divided into a mean velocity and a RMS-value

$$RMS = \sqrt{\frac{\sum_i (u_i - \bar{u})^2}{N}} ,$$

where N is the total number of measurements, u_i is the velocity of "i" particle and $\bar{u}$ is the mean value of the velocity [4].

Silo assembly

To carry out tests with dust clouds in process industries, a cylindrical silo (volume V=12 m^3, L/D=3) has been constructed which can be fed with dust mechanically and pneumatically. This silo is designed for real factory. Figure 1 shows the construction and the different ways of feeding the silo.

For the explosion tests the silo bottom was filled with sand to prevent the pressure wave from leaving the silo. The volume was then reduced to 9.4 m^3.

The dust feeding rate ξ was varied from 1 to 3 to 7 kg/m^3 and the conveying velocity v_c was set to 15 m/s and to the maximum (about 22–25 m/s).

The vessel wall is equipped with various flanges where the measuring system is mounted in a systematic order, so that measurements at different levels of the vessel can be realized. Since the probes were installed in tubes which have a length of 1 m, it is possible to vary the position of the measuring volume in radial direction. This allows also to change the orientation of the intersection volume of the LDA to measure particles with a horizontal and a vertical velocity component, respectively.

The measurements of the velocity and the turbulence were carried out with corn starch and wheaten flour.

Ring nozzle The required quantity of dust is dispersed into the silo by an air flowing from pressurized bottles with an initial overpressure of 20 bar, which forces the dust in the dust chamber through four perforated ring nozzle according to ISO standard method [10].

To avoid a fast soiling on the optical measuring probes in the 9.4 m^3–vessel we used corn starch concentrations between 30 g/m^3 and 120 g/m^3 for LDA measurements.

The pressure recording in explosion tests were realized with quartz pressure transducer (accelerated compensated) at three different levels in the silo. The silo was vented with PE-film (p_{stat} = 0.1 bar).
The chemical igniter (10 kJ) was located a the level 0.75m, 2.6 m and 3.75 m.

From previous explosion tests the ignition delay time was derived according VDI guideline to 850 ms for K_{St}=100 bar m/s and 1300 ms for K_{St}=200 bar m/s.

Pneumatical filling 30 s after the pneumatic is started, the rotary air lock is turned on to feed the undried corn starch (K_{St}=140 bar m/s). 30 s further the dust/air mixture is ignited during the feeding of the silo. The exhaust air leaves the silo through an outlet (Ø75mm) at the top.

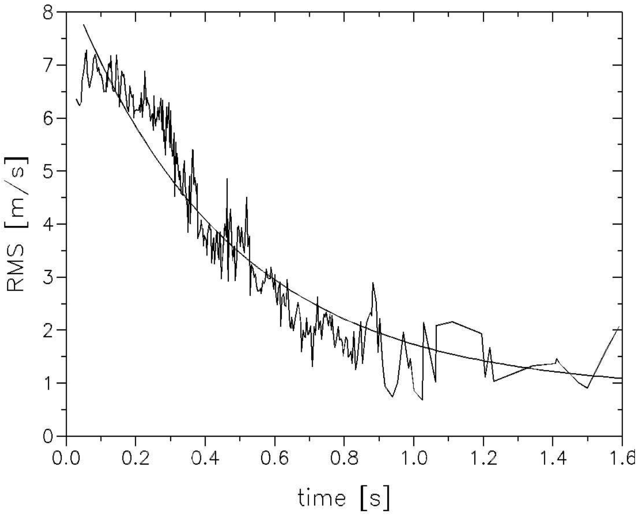


Figure 3: RMS turbulent velocity as a function of the time at the center of the 9.4 m^3-silo with the regression curve according to $RMS = 7.7 \cdot e^{-2.16 \cdot t} + 0.85$. The dust was dispersed using ring nozzles.

3 Results

3.1 Dust concentration

In the 12 m^3–silo the dust concentration varies from one dust type to another as shown in Figure 2. However, independently from the amount of dust, the same tendency can be noticed by vertical feeding:

1. if the distance to the silo wall is smaller than 400 mm the dust concentration decreases with increasing the height of the measuring level.
2. from the interval from 600 mm to 800 mm one reaches, near the top, the immediate area, where the dust beam is still collimated and highly concentrated.

Increasing the dust feeding rate ξ from 1 to 3 kg/m^3 using vertical feeding the dust concentration becomes 2.5 times higher and from 3 to 7 kg/m^3 about 1.5 times.

Feeding the silo tangentially most of the dust is circulating in a small layer near the silo wall, where the dust concentration in the remaining volume is about 100 g/m^3 for corn starch and 50 g/m^3 for wheaten flour using a dust feeding rate of ξ=7 kg/m^3.

3.2 Turbulence parameters

3.2.1 Ring nozzle

Figure 3 gives the RMS turbulent velocity as a function of the time. It is shown that the dispersion process is strongly time dependent. The decay was first fitted with the function $y = (a \cdot t + b)^{-\frac{5}{4}}$ [6, 12], but the function

$$y = a \cdot e^{-b \cdot t} + c$$

optimized the fit of the decay.

As can be seen in Figure 3 at 850 ms the RMS turbulent velocity is decreased to 2.1 m/s and at 1300 ms to 1.3 m/s.

3.2.2 Pneumatical vertical feeding

The turbulence parameters in the 12 m^3–silo for vertically feeding are shown for the dust feeding rate of 3 kg/m^3 and for tangentially feeding for 1 kg/m^3 in Figure 4 as a function of the measuring position for the maximum v_c.

Filling the silo vertical the z–component of the velocity will increase near the dust beam where the velocity of the outgoing air near the wall has opposite sign. The horizontal velocity components for vertical filling are nearly constant within their error limits. The horizontal components of the RMS-values have approximately the same course as the vertical. Their amount, however, seems tendentious to be lower.

The influence of the conveying velocity v_c on the RMS turbulence velocity is shown in Figure 5 for pneumatically filling.

3.2.3 Pneumatical tangential feeding

During tangential feeding the expected increase of the horizontal component of the velocity near the silo wall can been seen. The RMS turbulent velocity is nearly constant.

We found the velocity and the turbulence neither depending on the type of dust nor on the dust feeding rate within the error limits at the considered conditions.

We should take into account that the measurements are not made at the same time, that means that the turbulence is not illustrated at a fixed point of time. On the above mentioned assumption that the flow is steady it is allowed to interpret the illustrated velocities as a flow field.

Figure 5 gives the results for the two conveying velocities filling the silo tangentially.

Filling the silo mechanically through a screw conveyor the maximum RMS turbulence velocity is about 0.5 m/s.

ential feeding

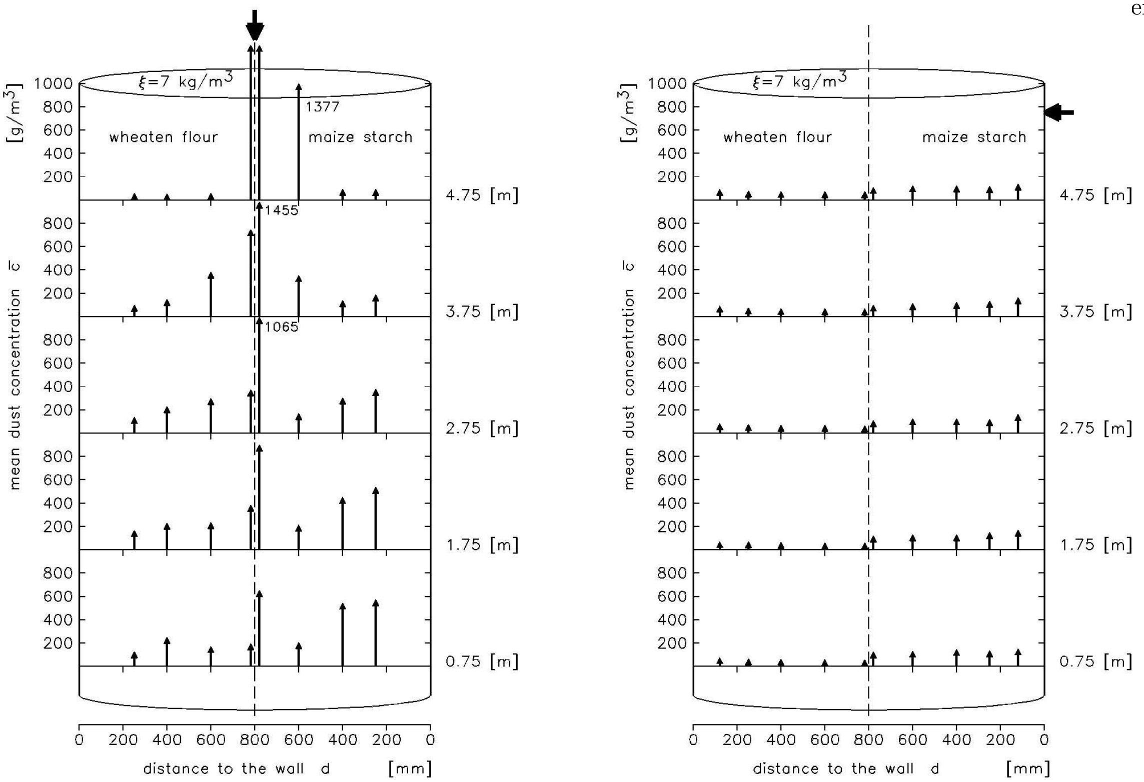


Figure 2: (a) Dust distribution filling the silo vertically for wheaten flour and corn starch at different levels using a feeding rate of ξ =7 kg/m^3 .
(b) Dust distribution filling the silo tangentially. Most of the dust is circulating in a small layer near the silo wall.

Table 1: Results of the explosion tests for different ignition positions and vent areas for a ring nozzle. Additional the turbulence measurements are shown.

vent area	K_{St}	p_{red}	igniter	turbulence
A=0.5 m^2	100 bar m/s	0.34 bar	bottom	
		0.22 bar	middle	
	200 bar m/s	0.86 bar	bottom	
		0.57 bar	middle	RMS(0.85 s) =2.1 m/s
A=0.3 m^2	100 bar m/s	0.79 bar	bottom	RMS(1.3 s) =1.3 m/s
		0.46 bar	middle	
	200 bar m/s	1.54 bar	bottom	
		0.97 bar	middle	

(a) vertical feeding | (b) tangential feeding

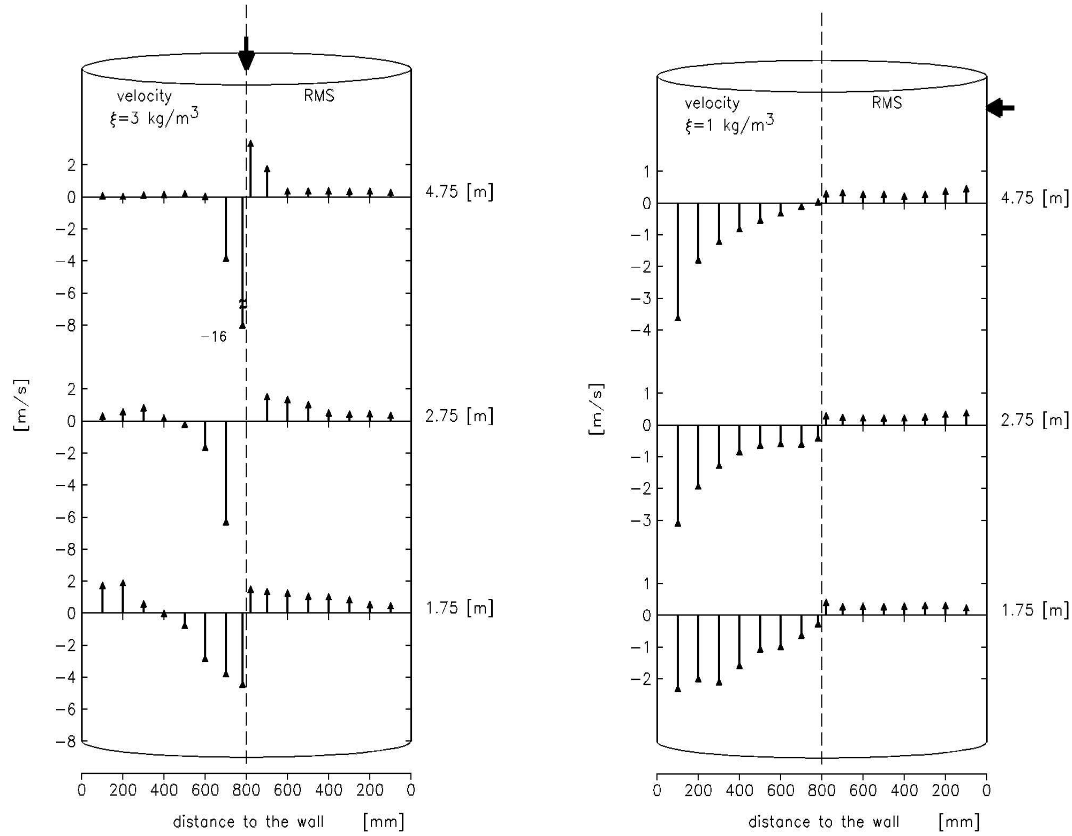


Figure 4: (a) The left side shows the flow velocity, the right side shows the RMS turbulence velocity of the component in z-direction at a feeding rate of 3 kg/m^3 and vertical filling (v_c=max).
(b) horizontal components of the flow velocity and the RMS turbulence velocity for tangential filling (1 kg/m^3, v_c=max).

3.3 Reduced explosion pressure

3.3.1 Ring nozzle

The following table shows the results of the explosion tests for different ignition positions and the turbulence measurements (according to Figure 3). The K_{St}–value is adjusted by means of the ignition delay time.

Figure 6 shows the pressure–vent area diagram for a K_{St} of 100 bar m/s.

3.3.2 Pneumatical vertical feeding

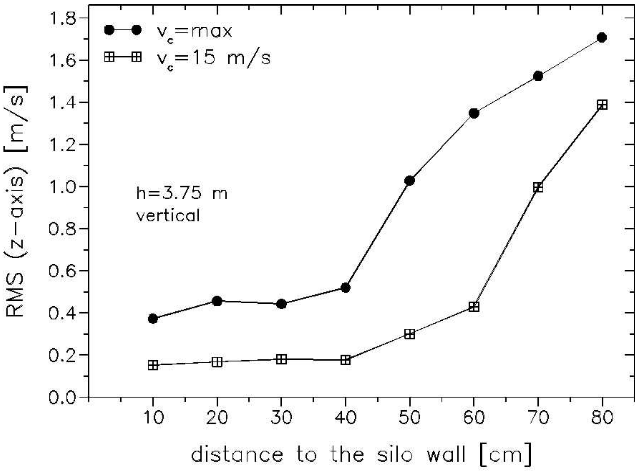
The measurement of the dust distribution shows that according to VDI 3673 the vent area has to be calculated for a inhomogeneous distribution. The table gives the values of p_{red} for different vent areas and ignition positions (v_c=max). Additional the pre-ignition RMS turbulence velocity is shown for the two ignition positions. The pressure–time–history shows, that the maximum overpressure and pressure rise depends strongly on the position of the ignition source.

vent area	p_{red}	igniter	turbulence
A=0.5m^2	0.35 bar	bottom	
	0.25 bar	middle	RMS(bottom) =1.5$\frac{m}{s}$
A=0.3m^2	0.7 bar	bottom	RMS(middle) =2 $\frac{m}{s}$
	0.36 bar	middle	

Figure 7 shows the resulting pressure in detail. No unambiguous maximum can be determined, but the optimum dust load is between 3 and 5 kg/m^3 under the used conditions. The maximum pressure rise as a function of the dust load is shown in Figure 8.

3.3.3 Pneumatical tangential feeding

The measurements of the dust distribution show (Figure 2) that according to VDI 3673 the vent area has to be calculated for a inhomogeneous distribution. The following table gives the values of p_{red} for different ignition positions. Additional the pre-ignition RMS turbulence velocity is shown for the two ignition positions.



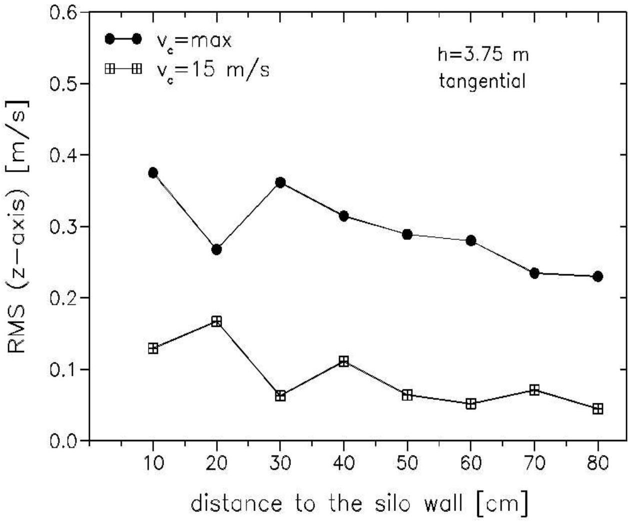


Figure 5: Influence of the conveying velocity on the RMS turbulent velocity of the particles filling the silo vertically (top) and tangentially (bottom) ξ=3 kg/m^3.

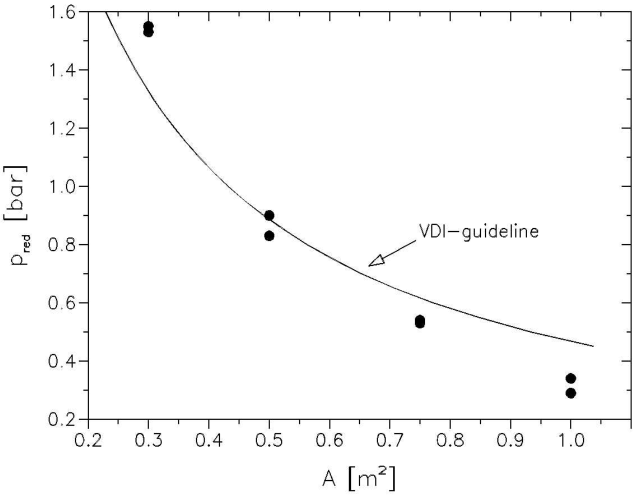


Figure 6: Reduced explosion-pressure measured as a function of the vent area for a ignition delay time of t_v=0.85 s that is K_{St}=200 bar m/s. The curve gives the results of the VDI–guideline 3673 for a homogeneous dust/air mixture.

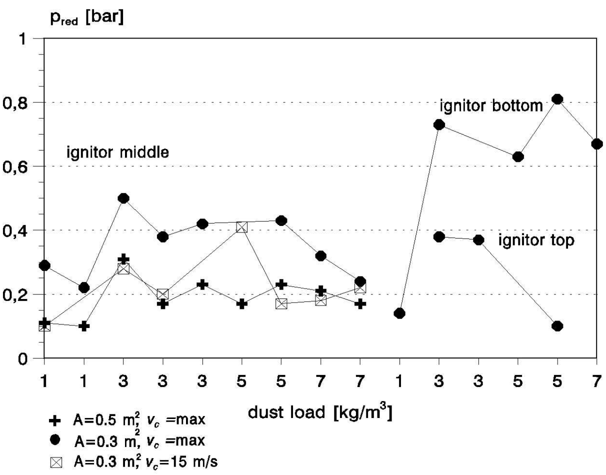


Figure 7: Reduced explosion-pressure after ignition filling the 9.4 m^3-silo pneumatically vertically with corn starch for two vent sizes and conveying velocities. The igniter was located at three different positions.

vent area	p_{red}	igniter	turbulence
A=0.3 m^2	0.14 bar or no ignition	bottom	RMS(bot.)=0.4$\frac{m}{s}$
	0.1 bar or no ignition	middle	RMS(mid.)=0.4$\frac{m}{s}$

Figure 9 gives a survey of the number of ignitions at the different levels. At a level of 3.75 m the dust/air mixture was not ignited in three trials.

Figure 10 compares the predictions of the VDI-guideline for homogeneous and inhomogeneous dust distributions with the results of the explosion tests.

4 Discussion and Conclusion

The influence of turbulence on the pressure rate or maximum explosion pressure could not be demonstrated by the variation of the position of the ignitor. Although the turbulence is changed at different levels the behavior of the pressure is reversal, that is p_{red} is increasing moving the igniter to the bottom, while the turbulence is decreasing. The reason for that are effects like compression of unburned dust, which are covering the turbulence effects. The radial turbulence variation at a given level has no influence due to the large spatial extension of the chemical igniter. On the other hand the change of the conveying velocity to about half has also affected the turbulence intensity, which could now be correlated with the explosion characteristics. The pressure and the pressure rise is reduced to the half value, while the turbulence is decreased stronger.

The present experimental results demonstrate that the RMS turbulence velocity is similar using a homogeneous distribution by generating the dust cloud with ring nozzles and a inhomogeneous distribution filling the silo pneumatically axially downwards. The same turbulence was measured regardless whether the type of dust or the dust feeding rate is changed. Feeding the silo tangentially the

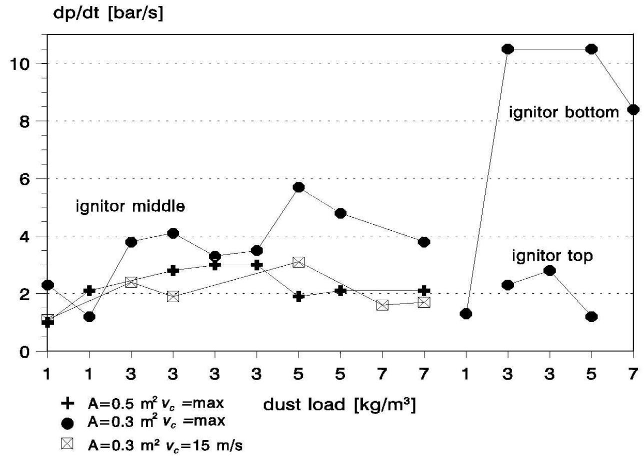


Figure 8: Pressure rate filling the silo pneumatically vertically with corn starch for two vent sizes and conveying velocities.

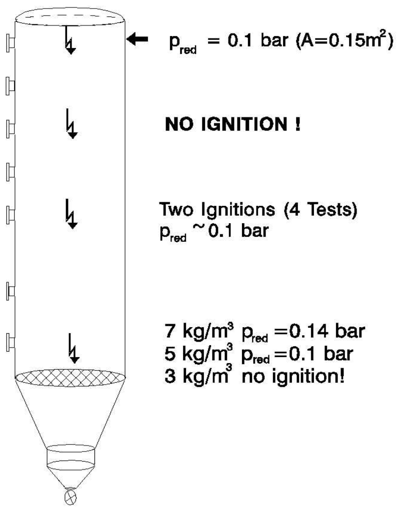


Figure 9: Survey of the single results at the different ignition positions using tangentially pneumatically filling. At a level of 3.75 m no ignition of the dust/air mixture was possible.

RMS-value is reduced strongly.
The resulting maximum reduced explosion pressure is reduced filling the silo pneumatically vertically to about 70 % of the measured values for homogeneous distributions. However, according to the equations of the VDI 3673 guideline for inhomogeneous dust/air mixture the vent area is calculated to small and the resulting reduced pressure is underestimated using our experimental approach. It must be taken into account, that this silo is also used in process industries. Therefore, the equation for the homogeneous dust distributions should normally be used, otherwise dust explosion experts for calculating vent areas should be consulted.

However, for tangentially filling ignition was only possible using high dust loads (7 kg/m^3), where the resulting pressure nevertheless was quite low.

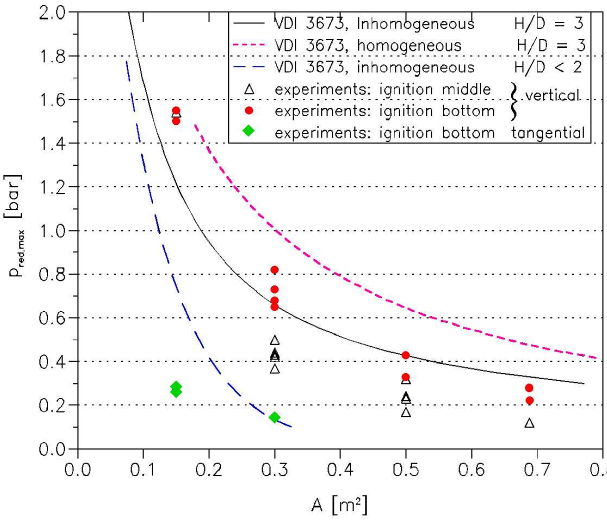


Figure 10: Comparison of the pressure–vent area course of the VDI 3673 guideline and our experimental results. The VDI-curves are calculated for a K_{St} of 140 bar m/s and p_{max}=9 bar. The experimental data are only for a feeding rate of 3 and 5 kg/m^3 (maximum).

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