Simulating Dust Explosion Venting Through Ducts

Diana Castellanos [a], Trygve Skjold [b,c], Kees van Wingerden [c], Rolf K. Eckhoff [b] & Sam Mannan [a]

[a] Texas A&M University, College Station, Texas, USA

[b] University of Bergen, Bergen, Norway

[c] GexCon AS, Bergen, Norway

1 Introduction

Venting is a widely used protective measure for reducing the consequences of dust explosions in the process industry [1]. Parts of the enclosure to be protected are designed to fail during early stages of an explosion, thus relieving destructive overpressures by allowing unreacted mixture and combustion products to escape to the surroundings. Several variables influence the reduced overpressure P_{red} inside a vented enclosure. Parameters characterizing the enclosure and venting device include vessel volume V_v, vessel shape, vent area A_v, vent position and opening pressure P_{stat}. The initial state and development of the explosive mixture are determined by the chemical composition and particle size distribution of the combustible dust, the initial flow conditions and concentration distribution in the dust cloud, the presence of accumulated dust layers, and various factors influencing the transient flow and combustion phenomena that takes place during the vented explosion. The course of events may also be significantly influenced by the position, total energy and rate of energy release associated with the ignition source.

The outflow during a vented explosion will interact with congestion inside the enclosure and flow restrictions outside the vent opening, including blockage, deflector plates and vent ducts. The purpose of a vent duct is to direct the outflow from a vented explosion to a safe location outside a building, and thereby minimizing the consequences to property and personnel. The duct may influence the venting process in several ways, and introduces additional design parameters that influence P_{red}: the length L_d, diameter D_d and internal surface roughness of the duct, and the presence of bends or obstacles along the duct. The duct itself increases the flow resistance, and jet ignition of the highly turbulent cloud inside the duct may cause secondary explosions that produce pressure loads exceeding those of the primary explosion.

Design of dust explosion protection based on vent ducts can be traced back to the 1880s [2], and several empirical correlations have been developed for predicting the effect of vent ducts on P_{red} [3-7]. Current standards include NFPA 68 [8, 9] in the US and EN 14491 [7, 10] in Europe. Other relevant guidelines include the HSL curves [11], the nomographs from VDI 3673 [12], and the methodology developed by FM Global [3, 4, 13]. The complexity of the physical phenomena and the numerous parameters involved suggest that is not straightforward to develop reliable and simple guidelines from the limited number of large-scale dust explosion experiments that have been performed with vent ducts, and the repeatability of such experiments is also limited. It may be argued that many of the experiments involve unrealistic worst-case conditions that hardly will occur in practice, resulting in

Correspondence to: dycastellanos@gmail.com

sufficiently conservative guidelines for practical applications. However, the current knowledge about transient, turbulent, particle-laden flow and turbulent multiphase combustion is probably not sufficiently developed to support this statement.

Computational fluid dynamics (CFD) represents an alternative approach that in time may overcome some of the inherent limitations associated with simplified guidelines for explosion protection in complex geometries [14]. The aim of the present study is to explore the use of the CFD tool DESC [15] for simulating a series of experiments performed by Health and Safety Laboratory (HSL) [5, 16]. The HSL experiments represent an important part of the empirical foundation for the guidelines mentioned above, and the simulation results are therefore also compared with predictions from guidelines. The discussion focuses on identifying weaknesses in the implemented models with respect to important physical phenomena involved in vented dust explosions, including flame acceleration and flame quenching. Of particular interest is the degree of details that should be modeled in order to yield reliable predictions for the consequences of realistic dust explosion scenarios in the process industry.

2 Experiments

Fig. 1a illustrates the explosion vessel used in the HSL experiments with vent ducts [5, 16]. The volume of the vessel was 18.5 m^3 and the aspect ratio 1.7. The vessel was equipped with a dispersion system consisting of three 16 liter dust reservoirs, initially pressurized with air to 20 barg, and discharged through fast-acting valves and pepper pot nozzles. The dispersed dust clouds were ignited by 30 g of black powder, fired 760 ms after onset of dispersion. The ignition source was located in the rear, centre or front of the vessel. The vent area could be modified by installing orifice plates, from 0.95 m^2 down to 0.64, 0.38 and 0.20 m^2. Vent ducts of equal or larger cross section than the vent openings, and lengths 1, 6, 11 or 16 m, could be attached to the vessel. The vents were open during the entire experiments, i.e. P_{stat} equal to 0. Coal dust with K_{St} 144 bar-m s^{-1} and P_{max} 7.5 barg, and nominal dust concentration 500 g m^{-3}, was used in all experiments considered here. The pressure was recorded with pressure transducers inside the vessel and along the vent duct.

3 Simulations

Fig. 1b illustrates the geometry model implemented in DESC. Cubical grid cells of size 0.10 meter were used in most of the simulations. The laminar burning velocity S_L and fraction of burnable fuel λ were estimated from experiments in a 20 liter vessel for a coal dust with K_{St} = 150 bar-m s^{-1} and P_{max} = 8.6 barg [15]. The dispersion system was modeled as three transient jets impinging on porous panels in order to imitate the actual dispersion nozzles. The ignition delay was 760 ms.

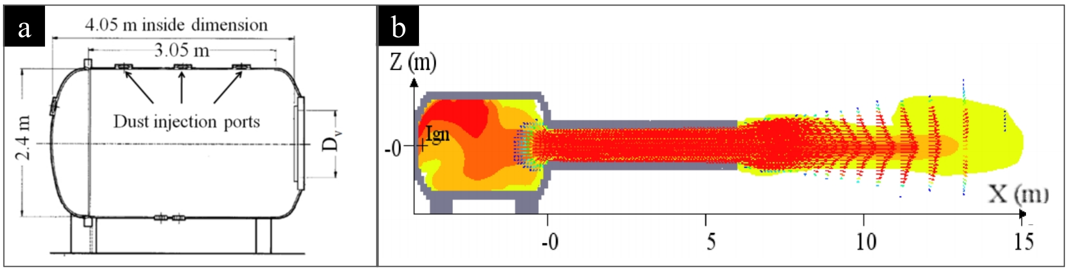

Figure 1. *a)* Schematic of the 18.5 m^3 vessel [16]; *b)* Simulated dust explosion: $D_v = D_d$ = 0.9 m and L_d = 6 m.

Previous studies indicate a relatively strong sensitivity of simulation results from DESC with respect to ignition position and the dimensionless factor C_L used for adjusting the experimentally determined values for S_L [14, 15]. The present study used C_L = 1.25, in accordance with previous results [14, 15], and included two ignition positions for each of the three original positions. It was assumed that combustion of 30 g black powder in a transient flow field results in volumetric rather than point-like ignition, and the simulated ignition positions were therefore positioned either along the center line of the vessel, or 0.4 m below. Table 1 summarizes the simulated scenarios.

Table 1: Summary of the simulated combinations of duct diameters (D_d) and vent diameters (D_v); ignition positions: rear (*R*), center (*C*) and front (*F*); duct lengths: 0, 1, 6, 11 and 16 meters.

D_d (m) / D_v (m)	0.5	0.7	0.9	1.1	A_v (m^2)
0.5	*R C F*	*R C F*	*R C F*	*R C F*	0.196
0.7	–	*R C F*	–	*R C F*	0.385
0.9	–	–	*R C F*	*R C F*	0.636
1.1	–	–	–	*R C F*	0.950

4 Results

Fig. 2a summarizes the results for configurations with $D_v = D_d$. Experimental and simulated results are in reasonable agreement, showing a systematic increase in P_{red} for increasing duct length, and the highest pressures are found for ignition in the rear end of the vessel. The simulation results are not particularly sensitive to moderate variations in the vertical position of the ignition source.

Figs. 2b and 2c illustrate the effect of duct length L_d on P_{red} when $D_d > D_v$. Although most guidelines set $D_v = D_d$ for such configurations, the experimental results show appreciable differences in P_{red}. For $A_d/A_v \leq 2$ (Fig. 2b), the simulated P_{red} decreases with increasing D_d in accordance with experimental observations [16, 17]. For $A_d/A_v > 2$ (Fig. 2c), the simulated P_{red} are not influenced by L_d, whereas the experimental results are less conclusive, suggesting highly turbulent and hence unpredictable flame propagation in the duct [16].

Fig. 2 include predictions from guidelines, but direct comparison with experiments and simulations is not straightforward since two standards require P_{stat} to be at least 0.1 barg (VDI 3673 and EN 14491), and three standards assume $D_v = D_d$ (FM Global, VDI 3673 and EN14491). Predictions by VDI 3673 and EN 14491 are not included for D_v = 0.5 m because P_{red} without duct exceeds the valid range for the models (P_{red} > 2 barg). VDI 3673 and EN 14491 define a critical length L_s beyond which a further increase in L_d has no influence on P_{red}. This phenomenon has been observed in experiments reported by Bartknecht [18], and was attributed to choked flow conditions in the duct. However, neither the experiments nor the simulations presented here seem to support this assumption. Both VDI 3673 and EN 14491 yield conservative values for P_{red} when $L_d < L_s$.

Among the guidelines, NFPA 68 yields the most accurate predictions of the effect of L_d on P_{red}. The influence of L_d increases in a similar manner as the experimental results, suggesting a reasonable selection of scaling parameters. However, it should be noted that the empirical correlations in this guideline originate from the HSL experiments [6]. The FM Global method underestimates P_{red} for the largest vent diameter (1.1 m) and rear ignition, but yields more conservative results for smaller duct diameters. Previous research on both gas and dust explosions have shown that the pressure developed during vented explosions depend more strongly on A_v than on A_d [19], justifying the conservative results obtained when assuming $D_d = D_v$ (Figs. 2b and 2c).

4.1 Sensitivity of P_{red} with respect to ignition position

Effects of the ignition position on P_{red} was analyzed by moving the point of ignition along the center line of the vessel (*x*–axis). The analysis was performed for a single scenario, $D_v = D_d$ = 1.1 m and L_d = 16 m, by changing the ignition position in steps of 0.5 m. Fig. 3a. shows a systematic increase in P_{red} of about 17 % as the ignition position is moved towards the rear wall. These results indicate an inherent limitation in current prediction methods, since the ignition position is not taken into account, and center ignition is generally considered as the worst case scenario.

4.2 Sensitivity of P_{red} with respect to reactivity and homogeneity

The effect of reactivity and homogeneity of the dust cloud on P_{red} is summarized in Fig 3b. The reactivity was modified by varying the correction factor, C_L [14, 15]. The effect of the cloud homogeneity was analyzed by creating an ideal cloud with uniform concentration through the entire vessel. Simulations with the more reactive mixture (C_L = 1.5), or homogeneous dust clouds led overestimation of P_{red} relative to experimental values. On the other hand, simulations with C_L equal to unity lead to underestimation. In accordance with previous studies [14, 15], the recommended value for the constant C_L is about 1.25.

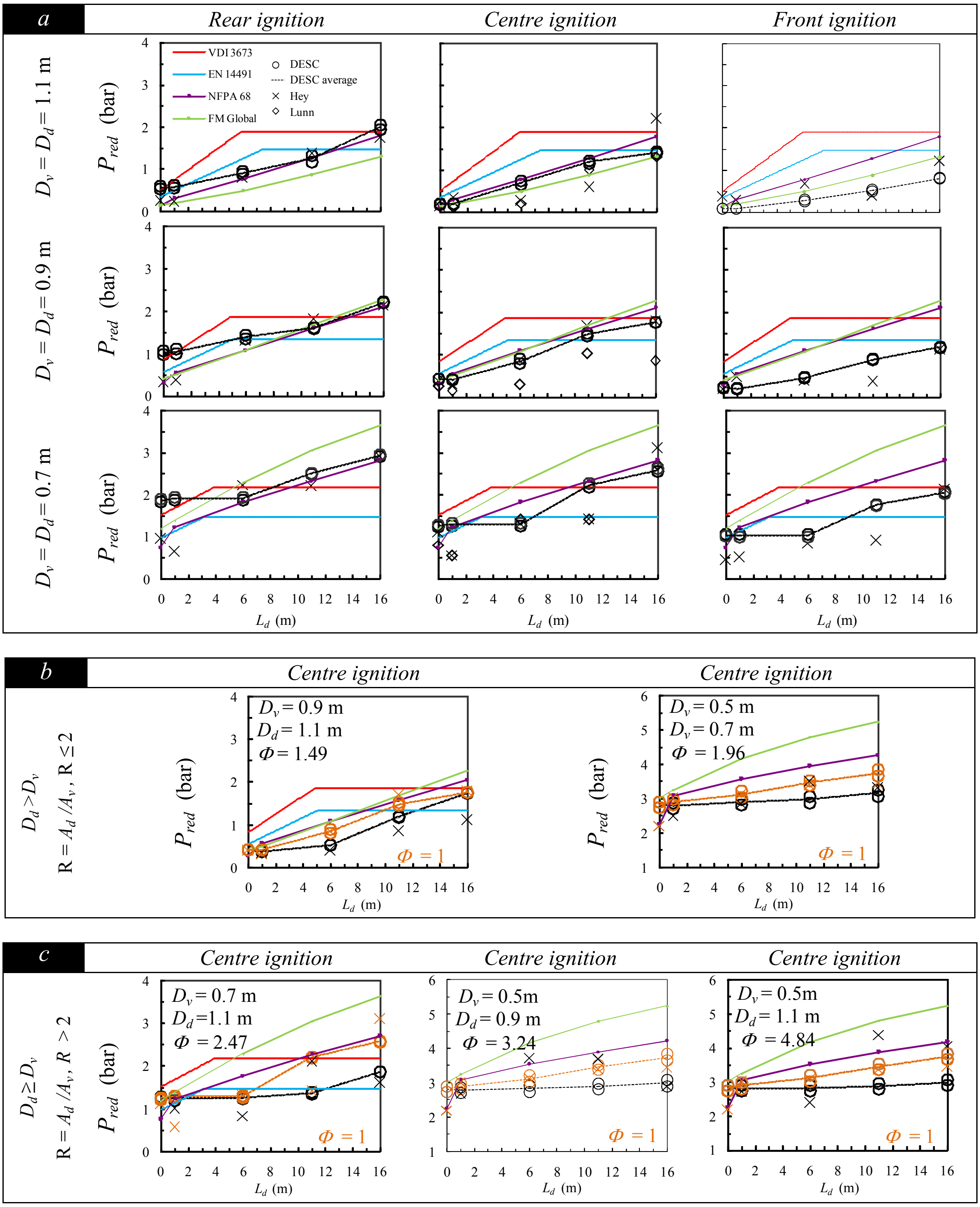

Figure 2. Effect of ignition position (center, rear, front), duct diameter D_d and duct length L_d on P_{red} for coal dust explosions in a 18.5 m^3 vessel. Experiments reported by Hey (×) [16] and Lunn (◊) [5], simulations with DESC

1.0 (○), and average simulation results (---). *a)* $D_v = D_d$, *b)* $D_d > D_v$ & $A_d/A_v < 2$ (orange values correspond exclusively to $R = A_d/A_v = 1$), and *c)* $D_d > D_v$ & $A_d/A_v \geq 2$. Orange values correspond exclusively to scenarios where the vent area A_v is equal to the cross section A_d of the duct: $\Phi = A_d/A_v = 1$.

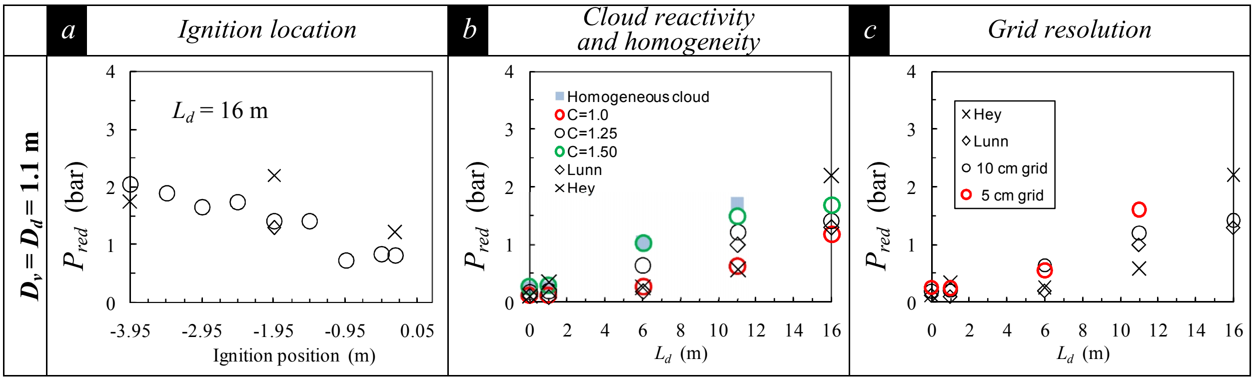

Figure 3. Effect of duct diameter D_d and duct length L_d on P_{red} for coal dust explosions in a 18.5 m^3 vessel. Experiments reported by Hey (×) [16] and Lunn (◊) [5], simulations with DESC 1.0 (○). Simulations with center ignition positions unless otherwise specified.

4.3 Sensitivity of P_{red} with respect to grid resolution

Fig 3c. illustrate the effect of grid resolution on P_{red} for 0.05 m and 0.10 m cubical grid cells. The results are similar for $L_d < 11$ m, but the finer grid yields more conservative results for longer vent ducts.

5 Discussion

Fig. 4 summarizes the results from all the base-case simulations. Although there is significant scatter in the results, the predictions obtained with DESC are generally in good agreement with experimental data for different ignition locations and duct sizes.

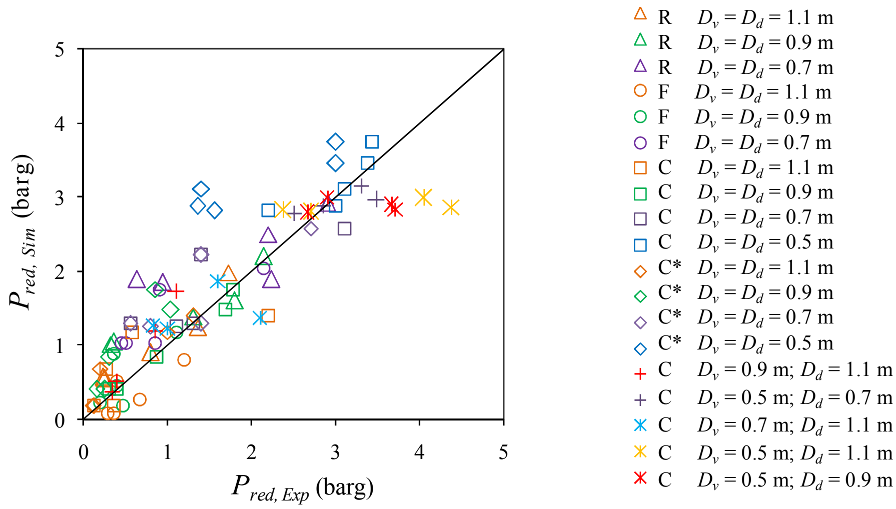

Figure 4. Comparison of simulated ($P_{red,\ Sim}$) and experimental ($P_{red,\ Exp}$) results for experiments reported by Hey [16] for rear (R), center (C) and front (F) ignition, and by Lunn [5] for center (C*) ignition.

The simulations over-predict P_{red} for certain scenarios with small vent areas (D_v = 0.5 m). The simulated results are similar to results obtained by Hey [16], but up to a factor two higher than data from Lunn for the same experimental conditions [5]. Hey reports typical variations in measured P_{red}

values of about 0.3 bar for a given scenario, whereas results from Hey and Lunn may differ with more than one bar for the same experimental configuration.

The limited repeatability of the experimental series may have several explanations, such as delayed opening of valves, differences in dispersion nozzles or ignition sources, variations in the particle size distribution, humidity or volatile content of the coal dust samples, and jet ignition or quenching effects taking place in the duct. Future experimental campaigns should therefore aim at more detailed documentation of the experimental procedures and measurements of other variables than pressure, such as flame arrival times, dust concentrations and turbulence [14].

The simulations significantly under-predict P_{red} for a few scenarios with area ratio $A_d/A_v \geq 2$. Clark *et al* [20] proposed a model for coal flame acceleration where an increase in duct diameter increases the turbulent Reynolds number and leads to enhanced flame accelerations. Kasmani *et al.* [17] applied this explanation to justify a significant increase in pressure for certain vented gas explosions with rear ignition and $A_d/A_v = 3.8$. It is possible that the relatively simple combustion model in DESC [15] yields somewhat low combustion rates for the highly turbulent flow conditions during secondary explosions in the duct. However, it is also possible that inherent limitations in the modeling of particle-laden flows result in an improper representation of the turbulent dust cloud inside the vent duct at the time the turbulent flame from the vessel enters the duct. Hence, it is not straightforward to reach a conclusion based on the selection of single-point data available from the experiments.

Further simulation work will focus on other dust explosion experiments with vent ducts, including experiments with bends in the duct, in order to identify future model improvements in the CFD code. A more realistic representation of particle-laden flow and flame propagation in dust clouds may improve the results, but the poor repeatability of many large-scale dust explosion experiments represents inherent limitations with respect to validation. Current experiments in a specially designed flame acceleration tube for dust explosions may prove useful for identifying model improvements [21, 22].

6 Conclusions

Vented dust explosions in an 18.5 m^3 vessel equipped with vent ducts of varying length and diameter were simulated with the CFD code DESC. Most of the simulated results are in good agreement with experimental data for different ignition locations and vent duct sizes. However, the simulations under-predict the explosion pressure for certain configurations involving vent ducts with significantly larger diameter than the vent opening. These discrepancies may be caused by inherent limitations in the model, such as the representation of particle-laden flow or the correlations used for describing turbulent combustion. Relatively poor repeatability of the experiments and limited access to detailed experimental data complicates the analysis of the results.

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