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Venting as a means of mitigating explosions: The need to revised European and USA (NFPA68) guidance for explosion venting

Ismaila, A[a]., Andrews, G.E.[b], Abdullahi, I.[c], Nasiru, R[a]., and Abdullahi, Y.A[d]

[a] Department of Physics, Ahmadu Bello University, P.M.B 1044, Zaria, Nigeria
[b] Energy Resources Research Institute, University of Leeds, Leeds LS2 9JT, UK
[c] Ahmadu Bello University, School of Basic and Remedial Studies, Funtua, Nigeria
[d] Center for Energy Research and Training, Ahmadu Bello University, Zaria

ABSTRACT

The aim of the present work is to compare the Bartknecht correlations for gas and dust explosion venting that are used in NFPA 68 and in European Guidance on vent design with experimental data published in various literatures and see how well (reliable) the correlation predicts experimental results. The published experimental data for vented explosions from various gases and dusts-air mixture were compared with data computed using the Bartknecht correlations. Separately, the data for different gas reactivity (K_G) for same venting geometry were compared. The influence of volume, V, vents static burst pressure, P_{stat}, vent area, Av and length to diameter ration, L/D of vessel on explosion over-pressure have been determined. Analysis of the experimental data and computed results have shown that Bartknecht correlations grossly over-predicted vented explosion overpressure, P_{red} for gas explosion. Some over-predictions were observed to be in the order of 10 and have implication of designing a vent area than required and this can substantially led to the increase in design costs. Reverse was the case for dust explosion with the majority of the experimental data under-predicted and this is not safe for vent design as P_{red} has to be lower than the vessel design strength. Therefore, as the Bartknecht equations does not safely predict experimental results, US NFPA 68 and Draft EU Guidance on gas and dust venting design cannot be use with confidence and there a need for more experimental research that will actually address the reason for the overprediction and underprediction of vent area required for small volumes for gas and dust explosion venting respectively.

Key words: Explosion, Venting, overpressure, Over-prediction, Under-prediction.

INTRODUCTION

An explosion is defined as the sudden generation and expansion of gases associated with an increase in temperature and pressure capable of causing structural damage [8]. The effect of an explosion depends on a number of factors, such as maximum pressure, duration of shock wave interaction with structures, etc. These factors in turn depend on a number of variables such as Fuel type, Stoichiometry of fuel, Ignition source type and location, Confinement and venting (location and size),Initial turbulence level in the plant, Blockage ratios Size, shape and location of obstacles, Number of obstacles (for a given blockage ratio) and Scale of experiment/plant [7].

For some time it has been standard practice to attempt to limit the pressure in gas phase explosions in chemical plants by the use of vents, the provision of which requires knowledge of the explosibility of the inflammable mixture under consideration and the strength of the vessel to be vented [6]. The most convenient and economical explosion protection technique is explosion relief venting and it should always be considered as the first option [12]. Venting is an explosion control technique where by the pressure generated in the vessel by explosion is release by the prompt opening of an aperture covered by weak vent panel that burst at a defined overpressure-P_{stat}. In the process burning and/or un-burnt material and combustion products are released and the overpressure inside the enclosure is reduced.

The vent area is the most important parameter in determining the value of maximum reduced explosion overpressure ($P_{red,max}$) generated inside the vessel by the vented explosion. The key design requirement in calculating a suitable vent area includes the design pressure of the enclosure, static activation overpressure, explosion characteristics of the dust/gas as characterized by the K_G value (bar m/s), the shape and size of the enclosure, the condition of the dust cloud, the strength of the equipment, the turbulence of the vessel at the beginning or during the explosion would have to be determined and other characteristics of the vent enclosure (Lunn et al, 1988). To design a vent that can withstand explosion, maximum explosion over-pressure ($P_{red\ ,max}$) should be set less than the vessel design strength. It is essential that the vent area is large enough to prevent the explosion within the vessel from exceeding its design strength. It is equally important for practical and financial reasons that the vent is not unnecessarily large (Field, 1984). An explosion vent is designed to be the weakest part of the external structure. As the explosion vent experiences the pressure rise, it opens quickly allowing the rapidly expanding heated gases to be released to the outside. By doing so, the internal walls, floor, and ceiling are spared from the damaging overpressure experienced during a deflagration. To successfully limit damage to the vented area, vent design and the pressure resistant structure must be according to recommended guidelines.

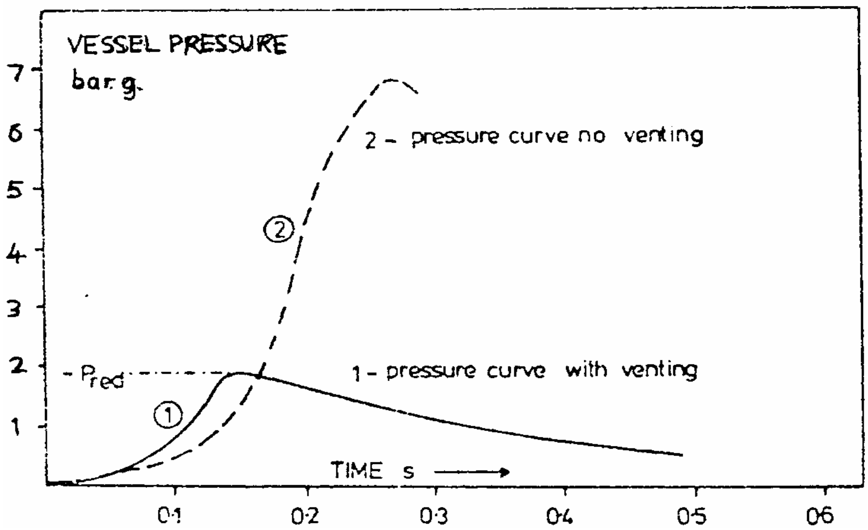

Figure 1.0: Explosion in a vessel with and without explosion vent for propane-air mixture

Figure 1.0 below shows an explosion in a vessel with and without explosion vent for propane air mixture. The highest pressure attained in a vented explosion is known as the reduced explosion pressure, P_{red} and is much less than the explosion pressure generated in an enclosed vessel. When the explosion relief is properly designed, P_{red} is not high enough to cause damage to the plant.

Various correlations for vent design have been postulated over the time by many researchers however, the current gas explosion vent standards in the USA (as stated in NFPA 68) and in Europe (as stated in Draft Gas Venting Guidance, 2004) rely on the vent correlations first published by Bartknecht in 1993 and highlighted in the review of explosion venting by Siwek in 1995.

The form of Bartknecht overall vent design correlation for dust and gas is given in equation 1.0 and 3.0 respectively.

$$A_v = [3.264x10^{-5}\ P_{red}^{-0.569} P_m K_{st} + 0.27 P_{red}^{-0.5}(P_{stat}-0.1)]\ V^{0.753} \text{.......................... (1.0)}$$

This may also be written in term of $K_v \sim V^{3/4}/A_v$

$$1/K_v = [3.264x10^{-5}\ P_{red}^{-0.569} P_m K_{st} + 0.27 P_{red}^{-0.5}(P_{stat}-0.1)] \text{................................ (2.0)}$$

$$A_v = [(0.1265 \log K_G - 0.0567) P_{red}^{-0.5817} + 0.1754 P_{red}^{-0.5722}(P_{stat}-0.1)]\ V^{2/3} \text{ ....(3.0)}$$

This may be also expressed in terms of $K_v = V^{2/3}/A_v$

$$1/K_v = (0.1265 \log K_G - 0.0567) P_{red}^{-0.5817} + 0.1754 P_{red}^{-0.5722}(P_{stat}-0.1) \text{.....................(4.0)}$$

Where, K_v is the vent coefficient (dimensionless), A_v is the vent area (m^2), V is the enclosure volume (m^3) , K_{st} and K_G is the Dust and gas or vapour characterisation factor (reactivity) respectively in (bar. m/s), P_{red} is the maximum pressure developed during venting (bar), and P_{sta} is the vent static burst pressure (bar). The correlations are apply to compact vessels, which Bartknecht defines as those with L/D<2, although the draft European standard has applied this equation for L/D<3 (Andrews, 2009). The first term of these correlations is the vent flow pressure loss term for 100mb P_{stat} and the second terms is the additional influence of P_{stat}. It is also observed that the above correlations are valid for maximum explosion constant (characterization factor): 50mb/s $\leq K_{max} \leq$500mb/s, maximum reduced explosion overpressure: 0.1 bar $\leq P_{red} \leq$2 bar, maximum explosion overpressure: 6.8 < P_{max} < 7.6 bar, P_{stat} = 100mb, Height diameter ratio: L/D < 2, vessel sizes: $1.0m^3 \leq V \leq 1000\ m^3$, Ignition of the fuel – air mixture at zero turbulence (Siwek, 1996, Andrews, 2009).

The present work is aim to compare experimental results from methane – air mixtures, pentane – air mixtures, hydrogen – air mixtures, and acetone – air mixtures with Bartknecht correlation. For dusts explosion, an experimental results from grain dust, coal dusts, aluminum dust and corn starch dust will be compared with Bartknecht correlation to see how reliable these correlations can be used for gas and dust explosion venting design. The paper is divided in to two sections. The first section compared the Bartknecht correlations for gas explosion with experimental data and second section compared the Bartknecht correlation for dust with the experimental data.

2.0 Comparison of bartknecht correlation for gas explosion venting and experimental data

Bartknecht (1993) correlated his experimental venting data in a vessel of different volumes, V for different vent areas, A_v. He found that for fixed mixture reactivity and fixed volume the experimental result can be correlated with the equation 3.0 for a given mixture of gases. He shows that for P_{max}=6.8-7.6 bar, P_{sta}=0.1bar, ignition source (E=10J), Gas reactivities (K_G) are obtained for different gases as: K_G=55 for methane, 100 for propane, 104 for pentane, 140 for stadgas, 550 for Hydrogen etc. Experimental data set for methane/ air mixture obtained from Bartknecht vented explosion has been tabulated in Table 2.0 below. The data was replicated from Andrews lecture note on explosion prediction and mitigation with some modifications. Maximum explosion over-pressure $P_{red,max}$ in Table 2.0 was calculated from the Bartknecht correlation equation (equation 4.0). Plotted graph of experimental P_{red} (bar) and predicted P_{red} (bar) against different values of inverse of vent coefficients, I/K_v for different volumes produced a graph of the form shown in Figure 2.0. It is clearly seen that the use of Bartknecht correlation equation over predicted maximum peak pressure P_{red} when compared with actual experimental data for a higher number of points. The over prediction here is reasonable since the difference is quite small. In addition, for some few points his correlation under-predicted the maximum P_{red} which is not safe.

The data for P_{red} experimental seems to be the same for different volumes say 1m^3 and 60m^3 for example and implies that the same vent area is required irrespective of the volume which cannot be correct as the volume of the vessel has an influence on overpressure. The same effect was observed for predicted overpressure P_{pred}. The self acceleration for flame was suggested to be the caused for the increase of overpressure from 1-10m^3 but the decrease in overpressure at high volume was not explained. This means that independent volume effect shown by the result is not correlated by the K_v parameter (Andrews, 2010).

Table 2.0: Bartknecht experimental results for methane-air

Parameters	Values	V (m^3)	$V^{2/3}$(m^2)	A_V (m^2)	K_V(-)	1/K_V (-)	Experimental P_{red} (bar)	Predicted P_{red} (bar)
K_G(bar m/s)	55	1.0	1.000	0.1	10	0.1	1.2	2.320
P_{stat} (bar)	0.1	60	15.33	1.533	10	0.1	1.2	2.320
V (m^3)	2.0	30	9.655	0.966	10	0.1	1.7	2.320
1/K_V	0.1	10	4.642	0.464	10	0.1	2.0	2.320
$P_{red,max}$ (bar)	2.32	2.0	1.587	0.159	10	0.1	2.2	2.320
		60	15.33	3.066	5	0.2	0.5	0.710
		1.0	1.000	0.2	5	0.2	0.6	0.710
		2.0	1.587	0.317	5	0.2	0.8	0.710
		30	9.655	1.931	5	0.2	0.8	0.710
		10	4.642	0.928	5	0.2	1.0	0.710
		2.0	1.587	0.635	2.5	0.4	0.18	0.220
		1.0	1.000	0.4	2.5	0.4	0.2	0.220
		30	9.655	3.862	2.5	0.4	0.2	0.220
		10	4.642	1.857	2.5	0.4	0.3	0.220

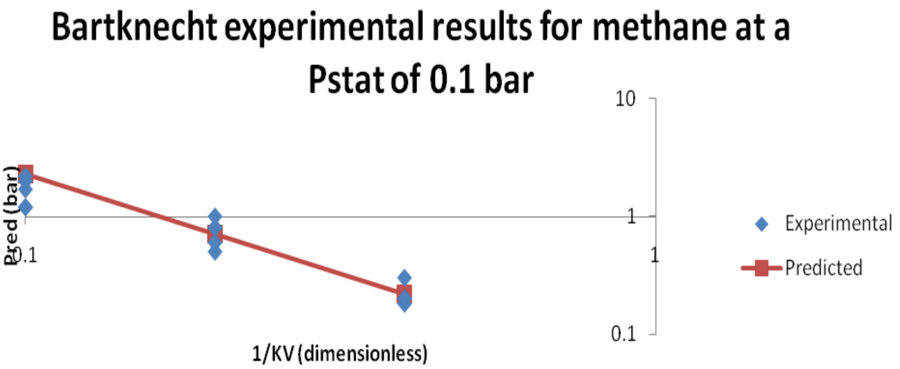

Figure 2.0: Bartknecht Experimental results for methane-air

Burgoyne and Wilson (1960) carried out an experiment to determine explosion of pentane-air mixture using cylindrical chamber of diameter 1.37m, length=1.45m, p_v = 0, w=0 and 1.7m^3 vessel volume. The experimental results obtained from a general review on venting gas and dust explosion with slight modification shows a poor disagreement with the Bartknecht correlation. Table 2.1 indicates the figures in which the comparisons are demonstrated. It was noted from this Table that the Bartknecht correlation over predicts the vented explosion overpressures P_{red} at various vent areas, A_V. Figure 2.1 shows that there is no good agreement between calculated and experimental results.

Table 2.1: Bartknecht predictions for pentane-air mixture in a1.7 m^3 vessel.

Parameters	
K_G (bar m/s) =	104
P_{stat} (bar) =	0
V (m^3) =	1.7
$1/K_v$ =	0.013193
$P_{red,max}$ (bar) =	84.04456
A_v(of chamber end)=1.267m^2	

K_v	$1/K_v$	Measured P_{red} (experimental) (bar)	Predicted P_{red} (bar)
5.1	0.196	0.14	0.87
9	0.111	1.93	2.30
20.2	0.050	4.77	9.17
75.8	0.013	5.60	84.04

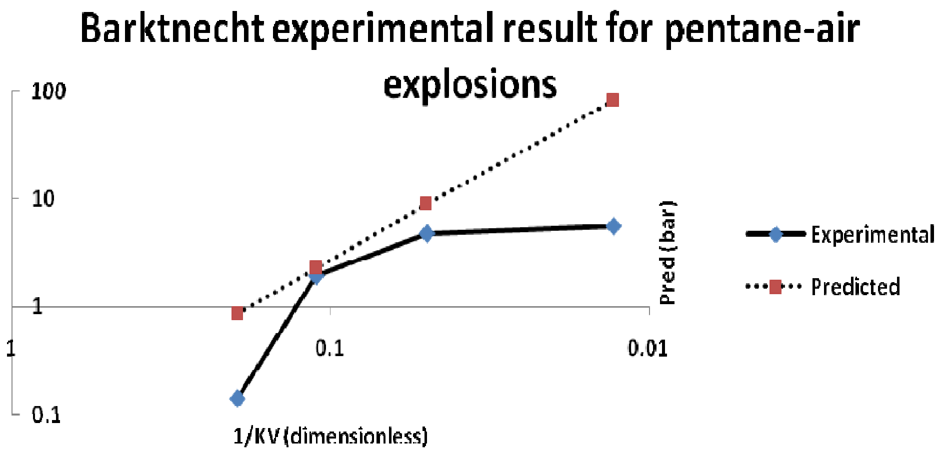

Figure 2.1: Graph of experimental result and predicted P_{red} versus $1/K_V$

2.1 Influence of vessel L/D

Bartknecht correlations for gas and dust venting are shown to be only true for a compact or spherical vessel with L/D<2 or L/D<3 and P_{sta} =0.1 mb. However, if vessel shape is substantially different from a cube or the L/D >~2 then the flame touches the wall before there has been a significant pressure rise and spherical flame propagation cannot be used to model the explosion. The result of this is that explosion protection design is a function of the vessel shape. Cousins and Cotton (1951) conducted an experiment on 40% Hydrogen-60% Air mixtures in closed vessels of different L/D. In the experiment, they used K_G=550bar m/s for propane instead of 104 used by Bartkchnet and P_{stat}=15psi (1.03 bar). Their results presented on table 2.2 are reproduced from Review on venting Gas and Dust Explosions with modifications. Figure 2.2 shows the comparisons. Comparison of the experimental results by Cousins and Cotton shows that the empirical method by Bartknecht over-estimate usually by a large amount, the explosion overpressures at static vent pressures higher than 100mbar. The main cause of this might be assigned to small vent areas and volumes. The Bartknecht correlation over predicts the vent explosion pressure to a factor of more than 10 in most of the data points but it was observed that this decreases with increase in L/D. Over prediction by factor of 10 would not be acceptable elsewhere in engineering design but should be acceptable here due to the fact that Bartkchnet used the average pipe diameter for most industrial application to validate his data and measurement of gas reactivity parameter K_G (a fundamental gas property) is based on the size of vessel and the investigator. In addition, over-prediction of measured maximum reduced pressure does not have much problems as it only increase cost, but under-predicted vent maximum reduced pressure lead to unsafe conclusion.

Table 2.2: Cousin and Cotton Experimental Data on 40% Hydrogen and 60% Air

Parameters	
K_G (bar m/s) =	550
P_{stat} (bar) =	5.418
V (m^3) =	0.492
$1/K_v$ =	0.021
P_{red} (bar) =	1150.804
A_V =	0.000336

V (m^3)	Vessel	L/D	P_{stat} (bar)	K_v	$1/K_v$	Measured P_{red} (bar)	Predicted P_{red} (bar)
0.215	Drum	1.44	1.133	8.34	0.120	1.633	11
0.215	Drum	1.44	2.357	15.08	0.066	2.857	58
0.215	Drum	1.44	3.922	39.2	0.026	4.422	506
0.215	Drum	1.44	6.303	392	0.003	6.803	27416
0.085	Tank	2.30	0.656	4.77	0.210	1.156	3
0.085	Tank	2.30	1.949	13.26	0.075	2.449	38
0.085	Tank	2.30	2.493	21.7	0.046	2.993	116
0.085	Tank	2.30	4.670	358	0.003	5.170	21550
0.492	Pipe	22.10	0.861	0.64	1.563	1.361	0
0.492	Pipe	22.10	1.813	2.07	0.483	2.313	1
0.492	Pipe	22.10	2.629	5.94	0.168	3.129	13
0.492	Pipe	22.10	3.310	11.88	0.084	3.810	55
0.492	Pipe	22.10	5.418	47.5	0.021	5.918	1151

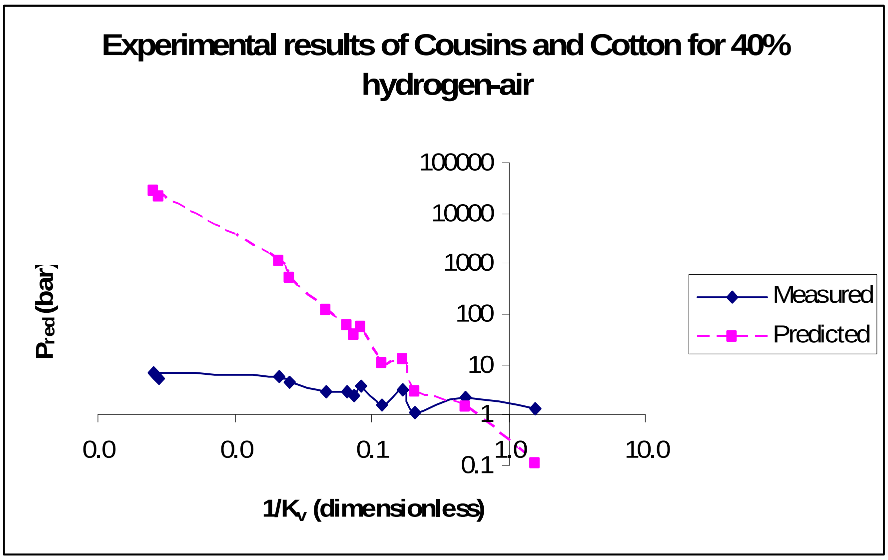

Figure 2.2 Plot of measured and predicted peak pressures against $1/K_v$

2.2 Influence of vent static burst pressure

Pressure and blast effects external to a vent do arise from pressure generated by the cloud explosion inside the plant and the explosion of the dust cloud in the area outside the vent. Vent can only be safe if the design strength of the vessel to be protected is greater than vent static burst pressure. The vent static burst pressure must be set less than the material design strength and the vent area designed such that P_{red} is less than the vessel design strength. The larger the vent area, the lower the vent maximum overpressure,P_{red} (Andrews, 2010).

The influence of the vent static burst pressure was investigated by Bartknecht at 100, 200 and 500 mb using 1 m^3 vessel and it is stated to apply up to V=1000 m^3. Experimental result by Chippett for 10 high initial pressure vented explosions for 10% methane – air where two vessels of V= 1.9 m^3 (d= 1.536 m) and V= 3.8 m^3 (d= 1.936 m) were used, the modified data is presented in Table 2.3 and shown in figure 2.3. The comparison shows no agreement between the computed and experimental results of Chippett. Bartknecht under-predicted vent explosion over-pressures greater than 100mbar. Therefore, these are not safe predictions for design purposes as the under-prediction can lead to wrong vent design.

Table: 2.3: Experimental results of Chippett using 10% methane air- mixture

Parameters	Values	P_{stat}(bar)	V (m^3)	$V^{2/3}$ (m^3)	A_V (m^2)	K_V(-)	$1/K_V$ (-)	Experimental P_{red} (bar)	Predicted P_{red} (bar)
K_G(bar m/s)	64	3.79	1.9	1.534	0.324	4.73	0.211	20.8	10.30
P_{stat} (bar)	3.79	4.00	1.9	1.534	0.324	4.73	0.211	21.4	11.10
V (m^3)	3.8	6.21	1.9	1.534	0.324	4.73	0.211	22.1	21.10
A_V (m^2)	0.993	3.93	1.9	1.534	0.993	1.55	0.645	10.3	1.590
P_{red} (bar)	3.31	5.52	1.9	1.534	0.993	1.55	0.645	11.2	2.600
1/Kv	0.408	6.97	1.9	1.534	0.993	1.55	0.645	11.0	2.930
		4.48	1.9	1.534	0.993	1.55	0.645	12.2	1.910
		3.93	3.8	2.435	0.993	2.45	0.408	16.4	3.490
		4.48	3.8	2.435	0.993	2.45	0.408	18.9	4.200
		3.79	3.8	2.435	0.993	2.45	0.408	16.8	3.310

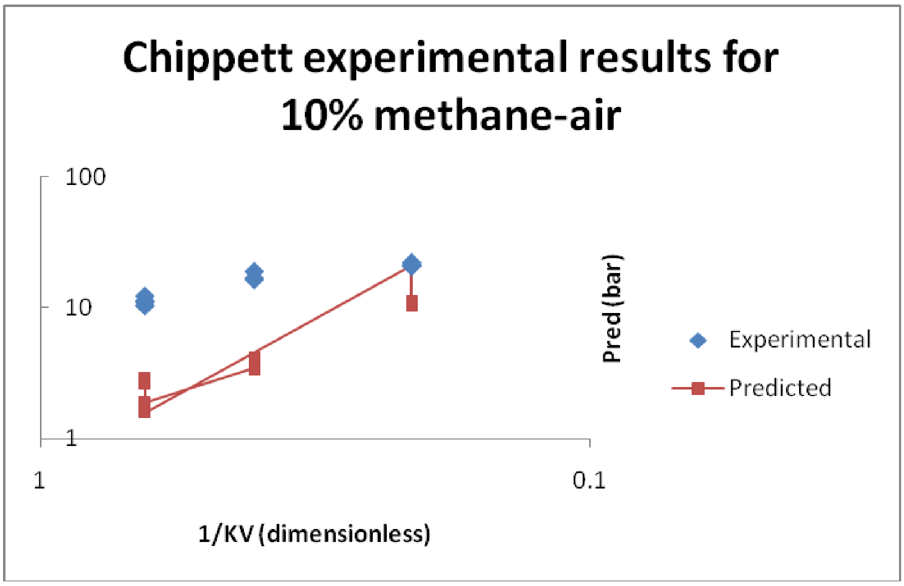

Fig 2.3: Plot of experimental and predicted reduced maximum pressure against I/K_v

2.3 Influence of gas reactivity's on explosion over-pressure

The gas reactivity parameter K_G can be considered a fundamental property of the mixture as it determines the gas explosion characteristics. Bartknecht (1993) shows in his experiment that explosion over-pressure increases with the gas reactivity K_G. He proposed the correlation below that allows P_{red} to be computed for a known A_v , V and K_G for P_{stat}=100mb.

$$P_{red} = (0.0778 \log. K_G - 0.0932)\, A_v^{-1.719} V^{1.146} \quad \text{bar where } K_G = dP/dt_{max.} V^{0.33} \quad \text{........................ (5.0)}$$

Burgoyne and Wilson (1960) conducted an experiment on pentane air mixture to determine the effect of gas reactivity parameter on explosion over-pressure. They used 1.7m^3 vessel in carrying out their experiment. The experimental results are presented in Table 2.4 and shown on figure 2.4. The comparison shows that Bartknecht correlation over-estimated much higher number of vented explosion overpressures within this set of data. Furthermore, no solid conclusion could be drawn from these predictions as a result of the fact that Burgoyne and Wilson carried out their experiment at zero vent static burst pressure (P_{sta}=0). There is still no clear explanation to why for example at 3.5% reactivity the measured explosion increases with increase in static burst pressures for some while for others it does not.

Table 2.4: Burgoyne and Wilson experimental data for pentane-air at 1.7m^3 vessel

Parameters	
K_G (bar m/s) =	104
P_{stat} (bar) =	0.4283
V (m^3) =	1.7
1/K_v =	0.12987
P_{red} (bar) =	3.187432
A_V =	0.000908

V (m^3)	P_{stat} (bar)	Reactivity (%)	K_v	1/K_v	Measured P_{red} (bar)	Predicted P_{red} (bar)
1.7	0.0345	3.25	17.4	0.057	3.869	7.433
1.7	0.0276	3.5	7.7	0.130	2.280	1.858
1.7	0	3.5	17.4	0.057	4.007	7.113
1.7	0	3.5	7.7	0.130	2.073	1.775
1.7	0.0345	3.5	17.4	0.057	2.211	7.487
1.7	0.1658	2.7	7.7	0.130	2.003	2.290
1.7	0.4283	2.7	7.7	0.130	2.003	3.187

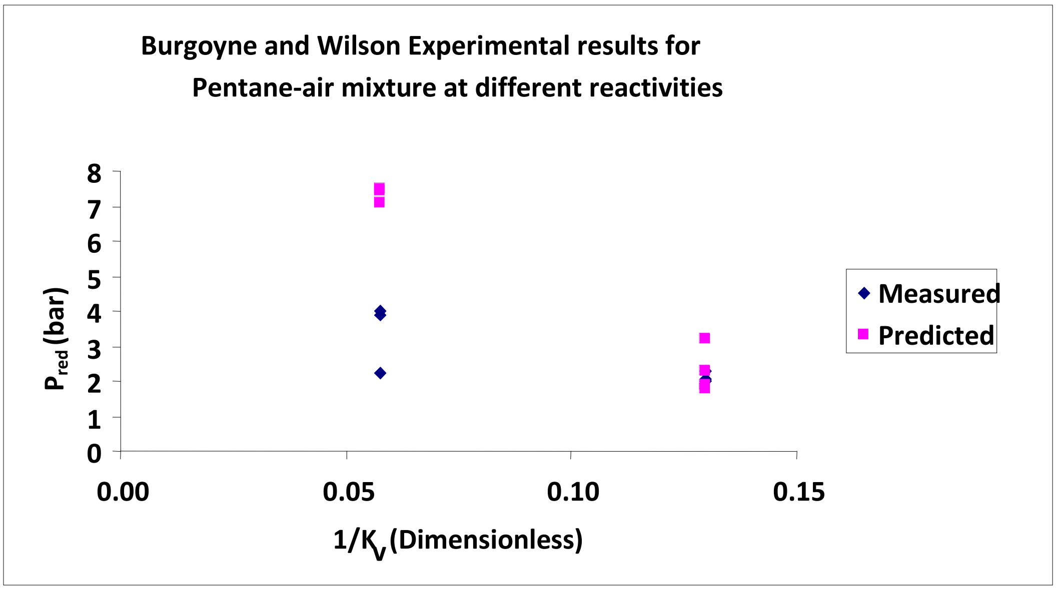

Figure 2.4: Graph of measured and predicted peak pressures versus $1/K_v$

2.4 Influence of vessel's volume

According to Molkov et al. (1993) the maximum vent overpressure occurs when the vent un-burnt gas flow rate is at a maximum and this is equal to the maximum mass burn rate at the flame front. Molkov et al. (1993) have carried out an experiment on acetone – air mixtures, experimental data obtained from ICHEME Report on the "Effects of a Duct on the Venting of Explosions". Analyses of these results presented in table 2.5 have found that Bartknecht correlation over-predicts P_{red} (experimental) with a factor greater than 10. Figure 2.5 show the comparison between the calculation and experiment for acetone-air mixture.

Table 2.5: Comparison between Molkov experiment and Bartknecht correlation

Parameters	Values		V (m^3)	P_{stat}(bar)	A_V(m^2)	K_V	1/K_V	Experimental P_{red} (bar)	Predicted P_{red} (bar)
K_G(bar m/s)	84		10.00	1.110	0.1963	23.65	0.042	5.110	40.93
P_{stat} (bar)	1.21		10.00	1.060	0.1963	23.65	0.042	3.810	39.23
V (m^3)	0.27		2.000	1.160	0.0314	50.55	0.020	5.310	152.6
A_V (m^2)	0.0019		2.000	1.160	0.0314	50.55	0.020	6.210	152.6
P_{red} (bar)	1722		2.000	1.160	0.1134	14.00	0.071	3.160	17.29
1/Kv	0.005		0.270	1.210	0.0019	212.8	0.005	6.010	1722
			0.270	2.430	0.0019	212.8	0.005	5.410	3703

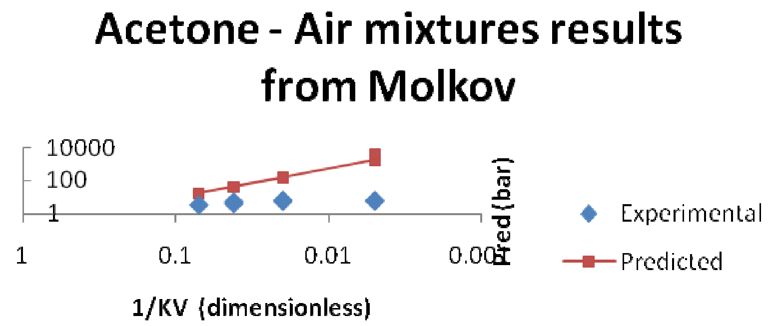

Fig 2.5: Molkov experimental results and Bartknecht correlation Vs 1/K_V.

3.0: Comparison of bartknecht correlation for dust explosion venting with experimental data

Theoretical method for calculating explosion pressure and suitable vent areas have been developed by Bartknecht in 1993 and is adopted inNFPA 68 and Draft EU standard on dust and gas explosion venting earlier shown in equation 1.0 and 3.0 respectively.

Table 3.0: Experimental data of dust test carried out with Barbara test facility

Parameters	
K_{st} (bar m/s) =	85
P_{stat} (bar g) =	0.12
V (m^3) =	8
A_v (m^2) =	0.4
P_m (bar g) =	1.184
P_{red} =	0.0138241
F(P_{red}) =	-0.000471

A_v (m^2)	K_{st} (bar m/s)	P_{stat} (bar g)	P_m (bar g)	1/K_v	Measured P_{red} (bar g)	Predicted P_{red} (bar g)
0.2	50	0.15	0.395	0.001042	0.44	0.1169
0.2	50	0.20	0.395	0.001042	0.71	0.4377
0.2	50	0.70	0.395	0.001042	1.35	15.1165
0.2	75	0.15	0.839	0.001042	0.84	0.1425
0.2	75	0.25	0.839	0.001042	1.25	1.0359
0.2	75	0.20	0.839	0.001042	1.12	0.4839
0.2	75	0.40	0.839	0.001042	1.60	3.9242
0.2	75	0.10	0.839	0.001042	0.84	0.0050
0.2	85	0.15	1.184	0.001042	1.19	0.1695
0.4	50	0.12	0.395	0.002083	0.14	0.0057
0.4	50	0.70	0.395	0.002083	0.78	3.7975
0.4	75	0.20	0.839	0.002083	0.52	0.1236
0.4	85	0.12	1.184	0.002083	0.44	0.0138

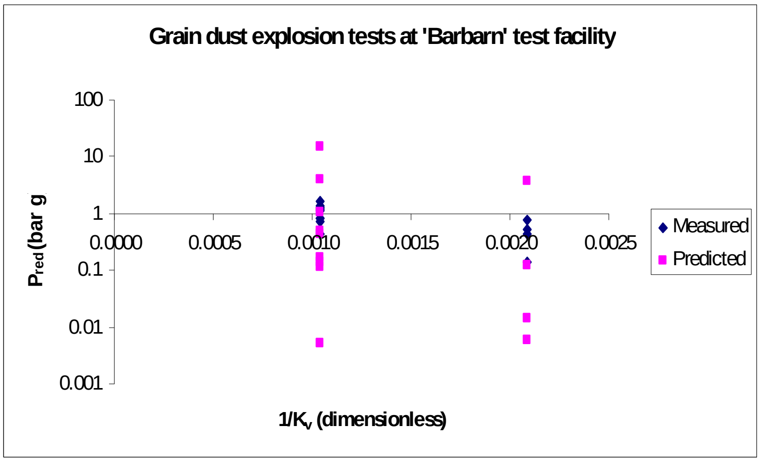

Figure 3.0: Plot of measured and predicted peak pressures against $1/K_v$

Experimental explosion test (data) produced by Barbara test facility 1n 1993 for grain dust using 8m^3 chamber for investigation of relief vent being reproduced from Andrews lecture note on "Gas Vapour and Dust Explosion Hazards" and presented in Table 3.0 with modification shows that there is poor correlation of Bartknecht result with experimental data. The plots of experimental and computed data shown in Figure 3.0 indicates that e Bartknecht correlation under-predicted P_{red} for a number of data points and some few data points matched the experimental results. The predicted maximum explosion pressure is calculated using equation 4.0.

3.1 Influence of vessel's volume

Bartknecht in his experiment to determine the actual vent correlation for gas, he produced a surprising result which shows that P_{red} is independent of the volume of vessel as the same P_{red} is observed for 1m^3 and 60m^3 and hence same vent area is required (see section 2.0). However, the results of other workers showed that vessel's volume has effect on explosion over-pressure and hence different vent area will require to control explosion. Experimental result by Donat to determine the influence of vessel for Coal dust- air explosion replicated from ICHEME Report on the "Effects of a Duct on the Venting of Explosions" with some modifications and presented in Table 3.1with some modifications. Figure 3.1 show the comparisons between calculation and experimental data. The empirical calculation method by Bartknecht under-predicted P_{red} at $1\,m^3$ and over predicts at $30\,m^3$. This is to say that vessel volume has a strong influence to the maximum explosion overpressure and P_{red} is found to increase with volume of vessels.

Table 3.1: Donat experimental results for coal-air explosion at different volumes

Parameters	
K_{st} (bar m/s) =	486
P_{stat} (bar g) =	1.43
V (m^3) =	30
A_v (m^2) =	0.500254
P_m (bar g) =	8.5
P_{red} (bar g) =	138.738159
F(P_{red}) =	0.00003698

P_{stat} (bar)	V (m^3)	A_v (m^2)	K_v	$1/K_v$	Measured P_{red} (bar)	Predicted P_{red} (bar)
0.19	1	0.40	2.5	0.400	0.21	0.04
0.20	1	0.30	3.33	0.300	0.22	0.07
0.23	1	0.20	5	0.200	0.25	0.18
0.53	1	0.10	10	0.100	0.55	2.45
1.07	1	0.05	20	0.050	1.09	33.74
0.26	30	4.01	2.41	0.415	0.28	0.37
0.29	30	3.00	3.22	0.311	0.31	0.67
0.33	30	2.00	4.82	0.207	0.35	1.56
0.55	30	1.00	9.65	0.104	0.57	9.41
1.43	30	0.50	19.3	0.052	1.45	138.74

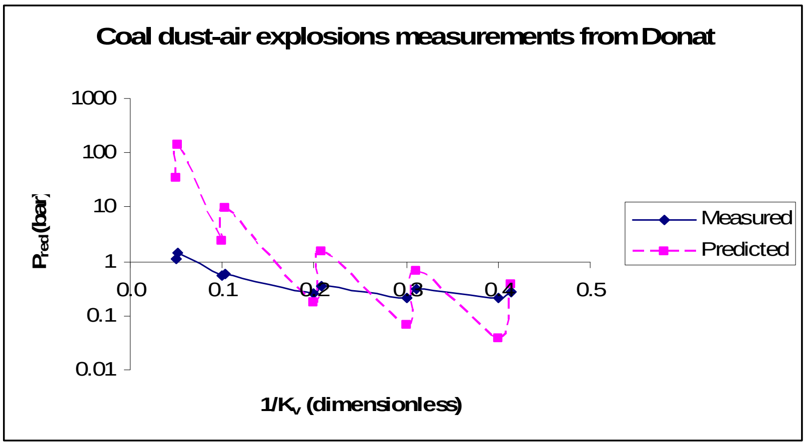

Figure 3.1: Plot of measured and predicted peak pressures against $1/K_v$

3.2 Influence of dust reactivity (K_{ST} PARAMETER)

The K_{st} parameter in dust is an empirical as it is a turbulent explosion and the turbulence level and distribution is determined by the test method and is not a property of the dust (Andrews, 2010). Donat carried out an experiment on Aluminum dust which shows the effects of reactivity parameter. He measured the maximum pressure at different values of K_{st} for $1m^3$ and $30m^3$ vessels. The result has been obtained from ICHEME Report on the "Effects of a Duct on the Venting of Explosions" with some modifications tabulated in Table 3.2 and shown on figure 3.2. The experimental data shows a poor agreement with Bartknecht equations. The Bartknecht over-predicts P_{red} irrespective of the vessel volumes. The over-prediction is quite greater than observed in coal dust possibly due to highly reactive nature of aluminum dust. Meisey et al (1965) have also shown that there is increase in P_{red} with dust reactivity for a 1.3 litre vessel with K_v = 4.3.

Table 3.2: Donat experimental result for aluminum dust

Parameters	Values	V (m^3)	P_{stat} (bar)	A_V	K_V	$1/K_V$	Experimental P_{red} (bar)	Predicted P_{red} (bar)
K_{st}(bar m/s)	1902	1	1.02	0.4	2.5	0.400	1.04	1.34
P_{stat} (bar)	2.19	1	1.02	0.3	3.33	0.300	1.04	2.30
V (m^3)	30	1	1.24	0.2	5	0.200	1.26	6.25
A_V (m^2)	2.00309	1	2.57	0.1	10	0.100	2.59	68.10
P_{red} (bar)	49.30	1	5.63	0.05	20	0.050	5.65	1055.21
P_m (bar)	11	30	0.67	4.0	2.41	0.415	0.69	5.99
		30	1.02	3.0	3.22	0.311	1.04	12.59
		30	2.19	2.0	4.82	0.207	2.21	49.30

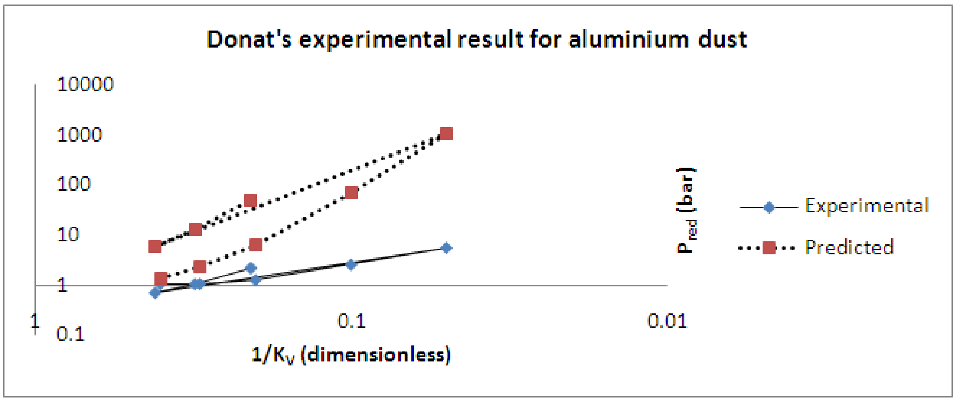

Fig 3.2: Plot of experimental and predicted P_{red} against 1/k

3.3 Influence of vent static burst pressure

A vented explosion tests was carried out on a Coal dust of concentration 0.5kg/m^3 in 18.5m^3 vessel. The data has been obtained from *Journal of Loss Prevention in the Process Industries*, and tabulated in Table 3.3 show that Bartknecht correlation over-predict P_{red} when compared with the experimental data. In each case, both experimental and predicted results showed that P_{red} increases with increase in burst static pressure P_{stat}. Figure 3.3 shows the comparison between computed and experimental data.

Table 3.3: Experimental data for coal dust at 18.5m^3

Parameters	
K_{st} (bar m/s) =	144
P_{stat} (bar g) =	0.5
V (m^3) =	18.5
A_v (m^2) =	0.196
P_m (bar g) =	8.5
P_{red} (bar g) =	40.58517
A_V=	0.00026

P_{stat} (bar)	A_V (m^2)	K_v	1/K_v	Experimental P_{red} (bar)	Bartknecht P_{red} (bar)
0.1	0.95	7.36	0.136	0.21	0.18
0.2	0.95	7.36	0.136	0.25	0.43
0.5	0.95	7.36	0.136	0.61	1.92
0.1	0.636	11	0.091	0.24	0.37
0.2	0.636	11	0.091	0.64	0.90
0.5	0.636	11	0.091	1.24	4.16
0.1	0.385	18.1	0.055	0.58	0.89
0.2	0.385	18.1	0.055	1.56	2.28
0.5	0.385	18.1	0.055	1.38	10.98
0.1	0.196	35.7	0.028	2.44	2.93
0.2	0.196	35.7	0.028	2.58	7.95
0.5	0.196	35.7	0.028	3.77	40.59

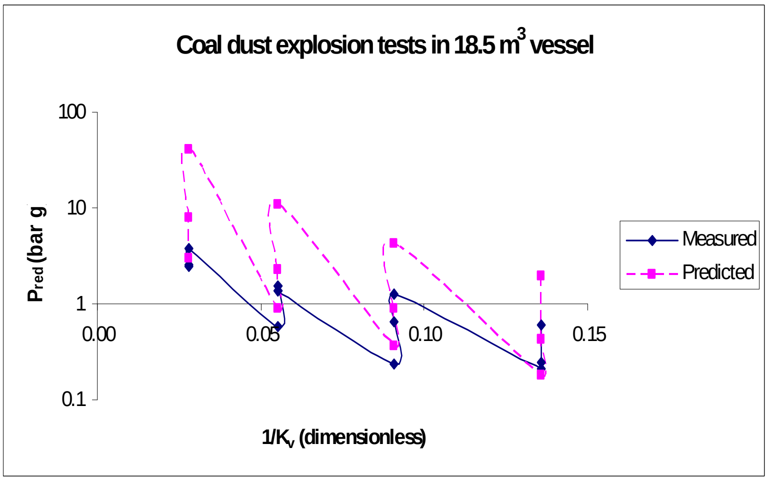

Figure 3.3: Plot of measured and predicted peak pressures against $1/K_v$

Table 3.4: Experimental data for Cornstarch- air explosion by Hartman, Cooper and Jacobs

P_{stat} (bar)	V (m^3)	A_v (m^2)	K_v	1/K_v	Experimental P_{red} (bar)	Bartknecht P_{red} (bar)
0.07	0.0283	0.013	7.17	0.139	0.09	0.005
0.10	0.0283	0.011	8.36	0.120	0.12	0.014
0.15	0.0283	0.009	10.04	0.100	0.17	0.053
0.23	0.0283	0.007	12.55	0.080	0.25	0.181
0.43	0.0283	0.006	16.74	0.060	0.45	1.386
0.07	1.81	0.833	1.784	0.561	0.09	0.018
0.10	1.81	0.714	2.08	0.481	0.12	0.029
0.15	1.81	0.594	2.5	0.400	0.17	0.053
0.23	1.81	0.476	3.12	0.321	0.25	0.119
0.43	1.81	0.338	4.4	0.227	0.45	0.500

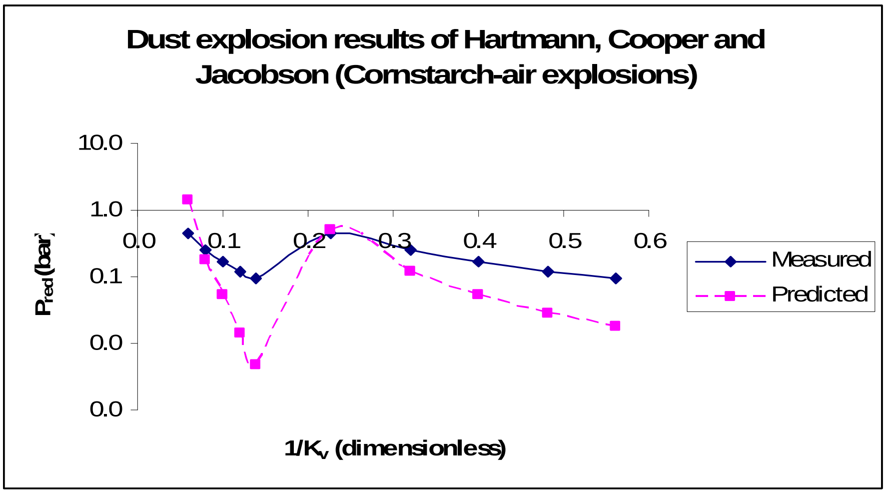

Figure 3.4: Plot of measured and predicted peak pressures against $1/K_v$

Cooper, Jacobs and Hartmann (1986) carried out an experimental explosion for a cornstarch dust in a three cubical vessel: V=0.0283m^3, 1.81m^3, 6.12m^3, data obtained from IChemE Industrial Fellowship Report and presented on Table 3.4. The result of their work shows that Bartknecht correlation under predicted a number of data points. This is not a good and safe prediction for design purpose. Figure 3.4 show the graph of P_{red} and P_{pre} Vs 1/K_v for these analyses.

CONCLUSION

Comparison of Bartknecht correlations with published experimental data for explosion venting for gas and dust were made. Separate comparison of the data for different gas reactivities for the same venting geometry and the influence of volume, V and static pressure, P_{stat} to the reduced overpressure P_{red} have been made for methane –air mixture, pentane – air, hydrogen-air, Acetone-air, Aluminum dust, Coal dust, grain dust and Corn Starch dust. From the foregoing studies, analyses and statistics on Gas and Dust explosion venting data, it is clear that Bartknecht correlations that are used in NFPA 68 and in the European Guidance on vent design cannot be used with confidence as the correlations does safely predict P_{red}. The analyses of the experimental data and computed results from Bartknecht correlations have shown that about 85% of the data points of vented explosion overpressure were over-estimated for gas explosion, and only about 10% were in good agreement with experimental results while 5% under-predicted. Some over-predictions were observed to be in the order of 10. However, reverse was the case for dust explosion with about 70% of the experimental data under-predicted, 18% over-predicted and 12% were in good agreement with correlations. It is important to note that under-predictions of overpressures is not safe for vent design as P_{red} has to be lower than the vessel design strength and over-prediction has implication of designing a vent area than required and this will significantly increase design cost.

Despite the work of Bartknecht with 1m^3 vessel which he found useful to support his correlations, the work of other researchers shows serious disagreement. It is therefore recommended that more experiments need to be done that can enable to come up with the reliable explosion venting correlation with a view to confidently draw up the conclusion. The correlating effects of enclosure volume, vent static burst pressure, reactivity parameter for gas or dust and of vessel L/D and other parameters should be carefully validated.

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