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Literature survey by

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On the topic:

Explosion characteristics of hybrid mixtures with two or more components.

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ABSTRACT

Explosions involving flammable gases or combustible dusts, or a mixture of both are a major subject of concern for industries than handle or process dusts, gases or solvents. The aim of this literature survey is to understand the characteristics of explosion of hybrid mixtures containing two or more than two components. This report particularly focusses on the calculation of minimum explosion concentration (MEC) of dusts, explosion overpressure (P_{ex}) and rate of pressure rise during an explosion $(dp/dt)_{ex}$. Investigations of explosion hybrid mixture using standard 20L spherical combustion chambers have been studied in detail. It has been found that when one combustible gas or dust is mixed with another combustible dust or gas, even small amounts have increased the likelihood of an explosion, with a higher explosion pressure and at a high rate of pressure rise, which otherwise would not be considered if the component were in its pure form. It has also been found that standard empirical models of Le Chatlier's line and bratknecht's curve used to determine the lower explosion limit (LEL) of a single gas or solvent are not sufficient when it comes to hybrid mixtures with two or more components. More research has to be done with respect to standardization of safety parameters for commonly encountered hybrid mixture components.

1. INTRODUCTION

Explosion is a exothermic chemical reaction involving a rapid chemical oxidation resulting in an increase in temperature or pressure or both together [1]. Explosions mainly involving flammable gases or combustible dusts or a hybrid mixture of both are a main subject of concern for the industries that either work with or process dusts and gases or solvents. Hybrid mixture explosions occur when two or more combustible substances with different states of aggregation are mixed [2] [3]. Hybrid mixtures are found in various process industries such as mining industry (coal dust and methane), paint factories (pigments and solvents), pharmaceutical industries (solid active principles or excipients and volatile organic vapour) and textile manufacturing industries. The gases formed from overheating of smouldering products can also form hybrid mixtures [4]. Dust Gas explosion is largely influenced by the gas or dust concentrations or the particle size [5]. Accidents caused these explosions are not minor (1994 – Groβ-Umstadt, Germany) (1906 - Courrières, France: methane explosion leading to secondary coal dusts explosions: 1100 fatalities) (Data from [6]).

2. STATE OF ART

In 1885, Engler was the first one to observe that a hazardous environment having a potential of a severe explosion with enormous release of heat could be produced if a non-explosible amount of coal dust (i.e. below its minimum explosible concentration (MEC)) is mixed with methane at a concentration below its lower explosion limit (LEL) [4] [7]. Since Engler's first experiment in 1885, a lot of research has been carried out on behaviour of hybrid mixtures with the aim of reducing the consequences or either preventing its occurrence. Some of the researches are listed below.

In 2007, Denkevits et al. studied the explosibility of hydrogen – graphite dust hybrid mixtures. Standard 20L sphere was used to measure the explosion of 4 µm fine graphite dust in lean hydrogen/air mixture (25-300 g/m^3 and 8-18 vol% respectively). It is possible to induces an explosion with hydrogen having concentration as low as 10%. As the concentration increases to 12 vol% or higher, dust is also involved in the explosion with a minimum tested concentration of 25 g/m^3. At 10-12 vol%, the explosion proceeds in two stages: fast hydrogen explosion stage and slow dust explosion stage. The maximum explosion pressure is much higher but the rate of pressure rise is lower compared to that of pure hydrogen. At higher concentration of 16-18 vol% hydrogen, the graphite dust/hydrogen mixture explodes together as a monofuel. The maximum pressure and the pressure rise rate, both are much higher compared to the corresponding hydrogen/air mixture [8].

In 2008, Dufaud et al. studied the influence of mixing pharmaceutical dusts with various solvents (ethanol, di-isopropyl ether, and toluene). They primarily studied the changes in maximum explosion pressure P_{max} and maximum rate of pressure rise $(dp/dt)_{max}$. They state that the influence of vapour injection on the MEC of a comnustible dust cloud or introduction of dust on the LEL of a vapour atmosphere is noticeable. The hybrid mixtures are combustible even when the vapours are below their LELs or dusts are lower than their MECs.

In 2011, Khalili et al. proposed a simplified model to estimate the ignition sensitivity of gas or vapour/dust mixture explosions. They used a 20L sphere and a Hartmann tube to calculate the explosion sensitivities of various gas or vapour/dust mixtures. The minimum ignition energy is significantly reduced with the introduction of gas/vapours as low as 1 vol%. They also confirm that a hybrid mixture explosion is possible even when the dust concentration is lower than its minimum explosible concentration and vapour is below its lower explosion limit. They also compared their experimental result with classical models of Bartknecht and Le Chatelier [9].

In 2015, Addai et al. carried out experimental investigations of hybrid mixtures of combustible dusts and gases to validate the existing mathematical formulae used for calculation of lower explosions limits of hybrid mixtures. They used a standard 20 L sphere and a permanent spark with ignition energy of 10 J was used as an ignition source. They found that the existing mathematical formulae for calculation of LELs are not safe enough for some combinations of dust and gas [10].

In 2015, Addai et al. studied the explosion behaviour of a mixture containing three flammable components and air. They confirm that a hybrid mixture explosion is possible even when the gas, vapour and dust are below their LELs and MEC respectively [1].

In 2016, Addai et al. experimentally investigated the lower explosion limits of three phase hybrid mixtures of six combustible dusts (corn starch, lycopodium, high density polyethylene [HDPE], toner, wood dust, and CN4), three gases (methane, hydrogen, and propane) and four solvents (ethanol, toluene, isopropanol, and hexane) using a Godbert-Greenwald furnace. The experiment results showed major decrease in the explosion limits of dust, gas or solvent and a significant increase in the likelihood of an explosion when a small amount of gas or solvent was mixed with dust or viceversa [3].

In 2016, Addai et al. studied the minimum ignition energy (MIE) of hybrid mixtures of two gases (methane and propane) and eight burnable dusts (wheat flour, starch, protein, polyethylene, peat, dextrin, wood coal and brown coal) in a modified Hartmann apparatus. The MIE was determined for different concentrations of gases below their LEL by adding them to a pressurized air to generate a dust cloud. The result show that when a small amount of gas below its LEL is added, the MIE of dust decreased which results in an increase of likelihood of an explosion [2].

In 2018, Addai et al. carried out an experimental investigation to calculate the limiting oxygen concentration (LOC) of fifteen combustible dusts and methane gas and two solvents (ethanol and isopropanol) hybrid mixtures. A standard 20L explosion chamber along with three different ignition energies (10J, 2kJ and 10kJ) was used. The results states that 10J electric spark ignition shows higher values of limiting oxygen concentration than that of 2kJ and 10kJ. LOC values for hybrid mixtures were considerably lower than those for dust air mixtures, when a weaker igniter was used. Addai states that when a system or process having multiple substances with different states of aggregation, one cannot rely on LOC value of a single substance for the safety of the system [11].

In 2018, Song et al. studied the explosion characteristics of hybrid CH_4/coal dust mixture using a 20L combustion chamber. The results show bigger values of maximum explosion pressure and maximum rate of explosion pressure rise in the beginning, but as the concentration of coal dust or CH_4 increases, these value decrease. It also shows that maximum explosion pressure is almost directly proportional to the initial pressure of the system, similarly maximum rate of explosion pressure rise also increases with the initial pressure. The explosion likelihood of hybrid CH_4/coal dust mixture is higher than pure dust air mixture only when CH_4 concentration is high [5].

In 2019, Abbas et al. suggested a new model for theoretical calculation of LEL of hybrid mixtures, when no precise experimental data is available [4].

In 2019, Zhao et al. studied the Minimum explosible concentration (MEC) of hybrid coal dust/flammable gas mixtures in synergic explosion regions. The results state a high risk of explosion for coal dust in presence of small amount of flammable gas. Maximum explosion pressure and maximum rate of explosion pressure rise increases as the flammable gas concentration increases, or MEC of dust decreases as the flammable gas concentration increases [12].

The aim of this literature survey is to understand the explosion characteristics of hybrid mixtures. Also, to understand the procedure, analysis of experimental data and ways of presenting the data graphically, for the calculation of minimum explosible concentration (MEC) of hybrid mixtures. Parameters that influence the maximum explosion pressure P_{ex} and rate of change of maximum explosion pressure (dp/dt) have been studied. The experiments carried out by Addai et al. [1] and Zhao et al. [12] to calculate the minimum explosible concentration (MEC) have been discussed further in detail.

3. METHODS AND MATERIALS

3.1 Experimental Materials

Addai et al. [1] used starch with particle size distribution of 95% below 50 µm and moisture content with less than 2% in mass. Table 1 shows the elemental analysis of starch and Table 2 shows the properties of methane and acetone (Data from [1]).

Table 1 – Elemental analysis of starch in mass.

Element	w/w%
Carbon	44.64
Hydrogen	6.43
Oxygen	48.93

Table 1: Elemental analysis of starch (Data from [1]).

Table 2 – Properties of methane and acetone.

Properties	Methane	Acetone
Formula	CH_4	C_3H_6O
Molecular weight ($g\,mol^{-1}$)	16.04	58.08
Exposable range (vol.%) (Brandes and Möller, 2003)	4.4–17.0	2.3–14.0
Laminar burning velocity (cm/s) (Nazaroff and Harley, 2007)	40	54
Vapor pressure at kPa (25 °C) (Brandes and Möller, 2003)	–	30.6
Flash point °C (Brandes and Möller, 2003)	−188	−20
Specific heat capacity (J/molK) (Nazaroff and Harley, 2007)	35.6	126.3
Boiling point (Brandes and Möller, 2003)	−161	57
Heat of combustion at 25 °C MJ/g (Standard thermodynamic, 2000)	54.00	28.55

Table 2: Properties of methane and acetone (Data from [1]).

Zhao et al. [12] used methane, hydrogen and carbon monoxide as the combustible gases and bituminous coal and anthracite coal as dust. Using eq 1 the concentration of gas in gas cylinder is converted to the concentration of gas participating in the reaction.

$$C_{chamber} = \frac{\Delta P1 \times \Delta P2}{P1 \times P2} \times C_{cylinder} \tag{1}$$

Where ΔP_1 is the pressure difference before and after the compressed gas is injected in the dust container. P_1 is the pressure after compressed gas is injected in the dust container. ΔP_2 is the pressure difference before and after gas from dust container is injected into the chamber, P_2 is the pressure in the chamber before ignition. $C_{cylinder}$ is the mole fraction in the 40L cylinder and $C_{chanber}$ is the mole fraction participating gas in the explosion chamber. The concentrations of the combustible gases used in the experiment were calculated according to eq 1 are shown in Table 3 (Data from [12]).

Concentration of the flammable gases.

Concentration	CH_4			H_2			CO		
$C_{cylinder}$ (vol. %)	1	2	3	1	2	2.5	1	2	3
$C_{chamber}$ (vol. %)	0.57	1.14	1.71	0.57	1.14	1.43	0.57	1.14	1.71

Table 3: Concentration of the flammable gases used in the experiment (Data from [12]).

3.2 Experimental Description

Addai et al. [1] used a standardized 20L test chamber shown in Figure 1. A fixed time delay (time interval from beginning of air/gas mixture blasts to ignition) of 60 ms was considered for all test repetitions in this work. All the test were repeated three times and the average value was taken, the explosion pressure was recorded as a function of time. Determination is according to DIN EN 14034 1-4 [1].

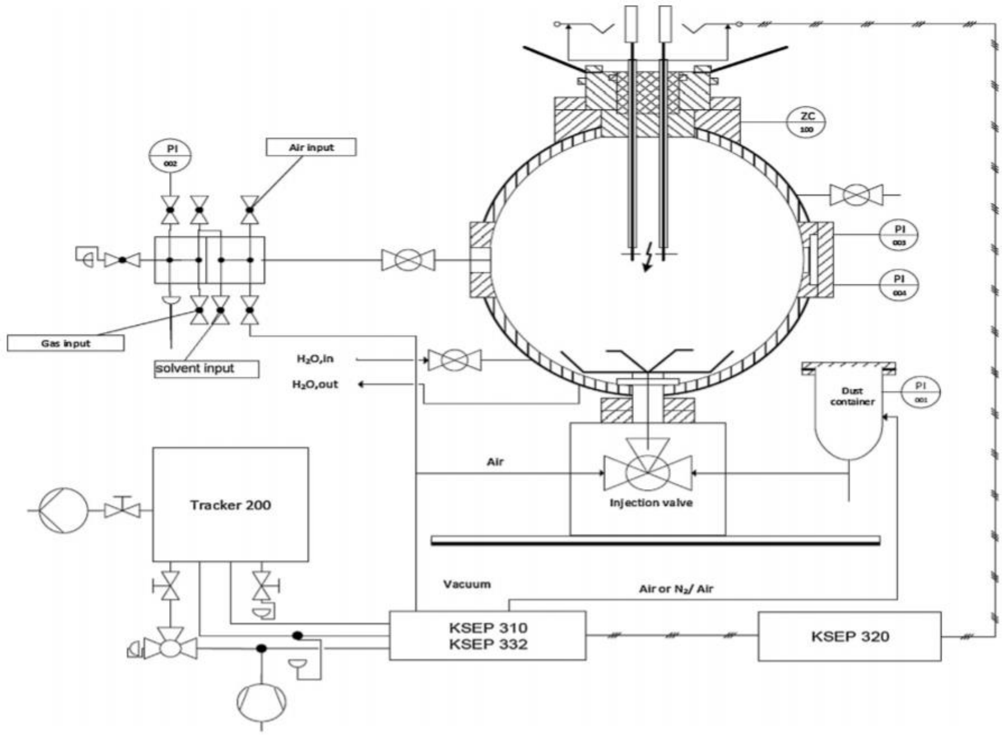


Figure 1: Technical diagram of a 20L spherical chamber with measurement and control devices, supply panel (Data from [1]).

3.2.1 Single Substance experiments (only dust, only gas or solvent)

The dust was weighed with a deviation of 0.05 g. 10J electric discharge was used as an ignition source. The dust was discharged into the storage container, filled with air at 20bar pressure to disperse the dust into the combustion sphere. The sphere was then evacuated to 0.4bar following the dispersion of dust into the sphere. The pressure changes were measured by piezoelectric sensors during the test.

In case of gas the same principle of dust was followed, only difference was, at beginning of each experiment the sphere was evacuated to 0.3bar and required amount of gas was filled through the gas panel, and afterwards the pressure was adjusted to 0.4bar.

For solvent, the same principle was used, just in place of gas panel, the solvent is filled with the solvent reservoir [1].

3.2.2 Two component mixture experiments (dust-gas, dust-solvent, solvent-gas)

For hybrid mixture, the gas was added to the explosion sphere after the evacuation, hence the pressure in the sphere ha to be less than 0.4bar so as to allow the combustible gas to enter the sphere. For example, for methane concentration of 10%, partial pressure of methane was 0.1bar, hence the evacuation pressure had to be 0.3bar. 10J was the ignition energy of the mixture.

In case of solvent and dust, it was similar procedure to only solvent and dust. Principle used for gas and dust was followed for solvent and dust. In case of gas and solvent, it was similar procedure to only gas and solvent. Principle used for dust and solvent was followed [1].

3.2.3 Three component mixture experiment (dust, gas and solvent)

Principle used for hybrid mixture of two components and hybrid mixture of three components was the same. The spherical chamber was modified to allow input of liquid. For feeding acetone to the sphere, first the sphere was evacuated to 0.2bar, and then desired amount of acetone stored in solvent reservoir was introduced in explosion sphere by solvent input valve. Later, methane was introduced with the same procedure for dust and gas hybrid mixture, lastly before the dispersion of dust in the sphere, the sphere was adjusted to 0.4bar with air. Table 4 shows various compositions of all three components [1].

Table 3 – The various concentrations of each component for the three components mixtures experiment.

Dust (g/m^3)	Methane (vol.%)	Acetone (vol.%)
5, 10, 20, 30, 60, 125, 250, 375, 500, 750, 1000	1, 2, 3, 4	0.5, 1, 1.5, 2, 2.3

Table 4: Various concentrations of all three components for three components mixture (Data from [1]).

Zhao et al. used two methods to determine MEC, overpressure and combustion duration time of dust explosion. But major focus was given on combustion duration time of explosion. According to Zhao, a maximal time is required at the MEC for the flame to propagate from ignited spots to entire volume of the sphere. t_c is the corresponding combustion duration time which is defined as time interval between ignition and moment combustion reaction completion, can be obtained from pressure-time curves. For E.g., MEC can be determined as 10 g/m^3 with the maximum t_c of 105 ms for bituminous coal dust in air with 1.14% CH_4 concentration which is consistent with the determination based on overpressure method (0.03MPa) as shown in figure 2. When dust concentration increased from 10 g/m^3 to 30 g/m^3, t_c decreased. But when dust concentration was decreased to 5 g/m^3, a self-sustained flame could not propagate in 20L sphere, which showed no explosion [12].

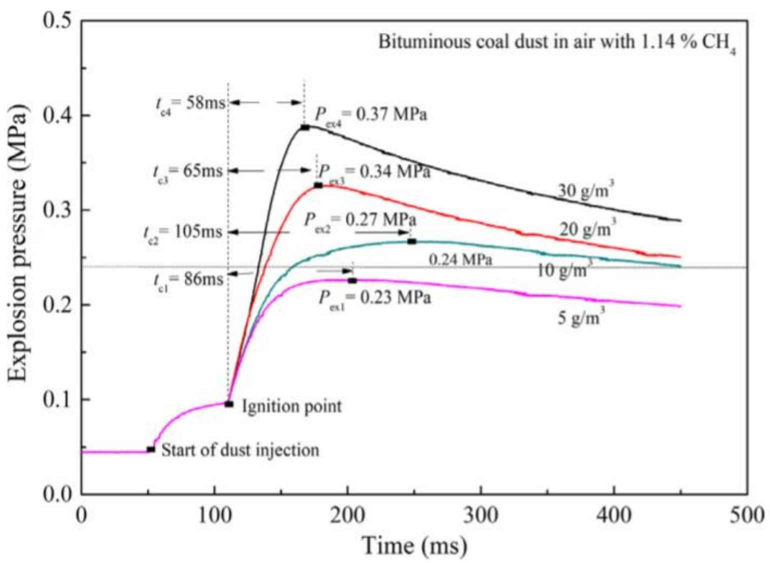


Figure 2: Combustion duration time (t_c) for bituminous coal at various concentrations (Data from [12]).

4. RESULTS AND DISCUSSION

Addai et al. [1] found that there was a noticeable increase in the likelihood of an explosion and increase in explosion severity when a small amount of gas or solvent (below their LEL) were mixed with dust. The results obtained by Addai et al. are shown below [1].

4.1 Test with single substance experiments (only dust, only gas or solvent)

For dust air explosion, the test was carried out using two different igniters, chemical igniter and electrical igniter to note the change in the readings. The maximum overpressure (P_m) was almost the same for both, but for pressure rise with time there was a big difference of 196 g/m^3 in the pressure rise rate of chemical and electrical igniter. The explosion limits obtained in the tests with chemical igniter were lower than electrical igniter with values of 125 g/m^3 and 250 g/m^3 respectively. This was because of the energy released by chemical igniter was higher than electrical igniter. Hence, a difference in maximum explosion pressure was also seen for these two igniters with values of 750 g/m^3 for chemical igniter and 1250 g/m^3 for electrical igniter. Due to these behaviours, all other experiments were carried out with electrical igniters. Figure 3 shows results for starch dust.

The next single substances tested were methane and acetone, maximum over pressures and pressure rise rates for methane and acetone are shown in figure 4. Both components almost show the same trends for maximum overpressures (P_m), pressure rise rates (dp/dt). At vol% of 10-12% both methane and acetone developed a maximum pressure of almost 8bar. The maximum rate of pressure rise at this concentration was 1300 g/m^3 [1].

4.2 Two component mixture experiments (dust-gas, dust-solvent, solvent-gas)

Figure 5 (Data from [1]) shows the results of two component explosion of methane and acetone. The results showed that, after addition of small amount of acetone, the LEL of methane decreased. The LEL value of methane shifted to left as the amount of added acetone increased, even though the concentration of acetone was below its individual LEL. This shows the explosion severity of methane acetone mixture was higher than for individual methane explosion [1].

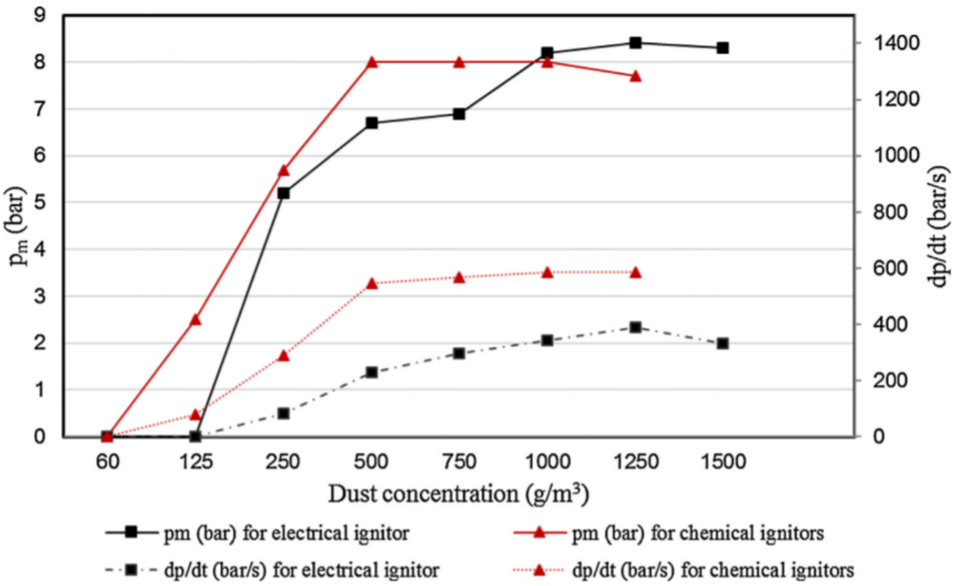


Figure 3: Maximum explosion pressure and rate of pressure rise in dependence on the starch dust concentration (Data from [1]).

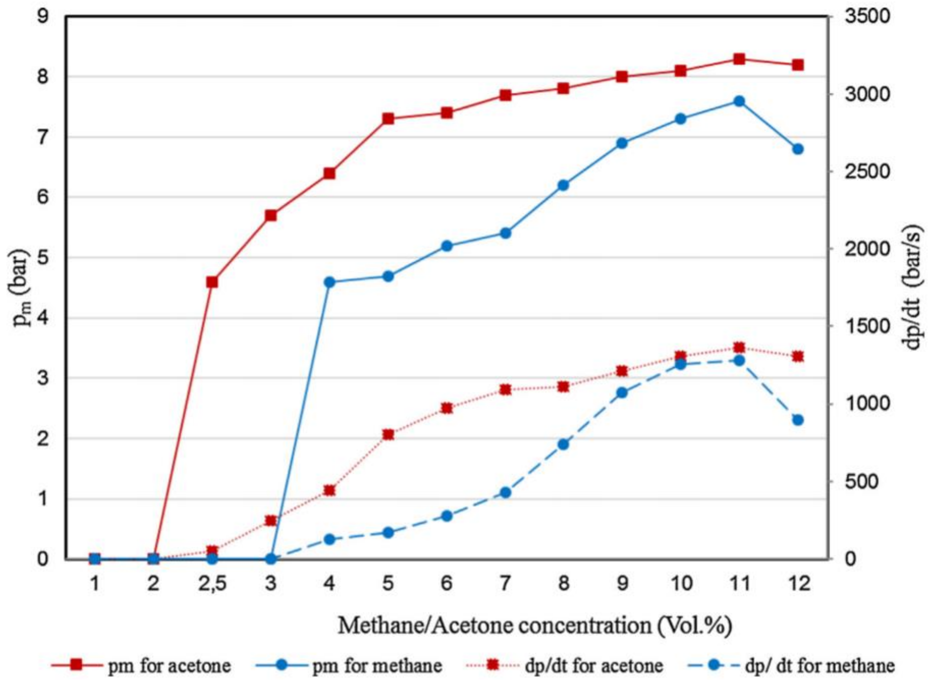


Figure 4: Maximum explosion pressure and rate of pressure rise for both methane and acetone in dependence on both acetone and methane concentration (Data from [1]).

Figure 6 (Data from [1]) shows the results of starch and acetone mixture explosion. The concentration of acetone below its individual LEL were considered in this test. On addition of small amount of acetone, the MEC of starch decreased, it kept on shifting towards left or lowered step by step as the concentration of added acetone was increasing [1].

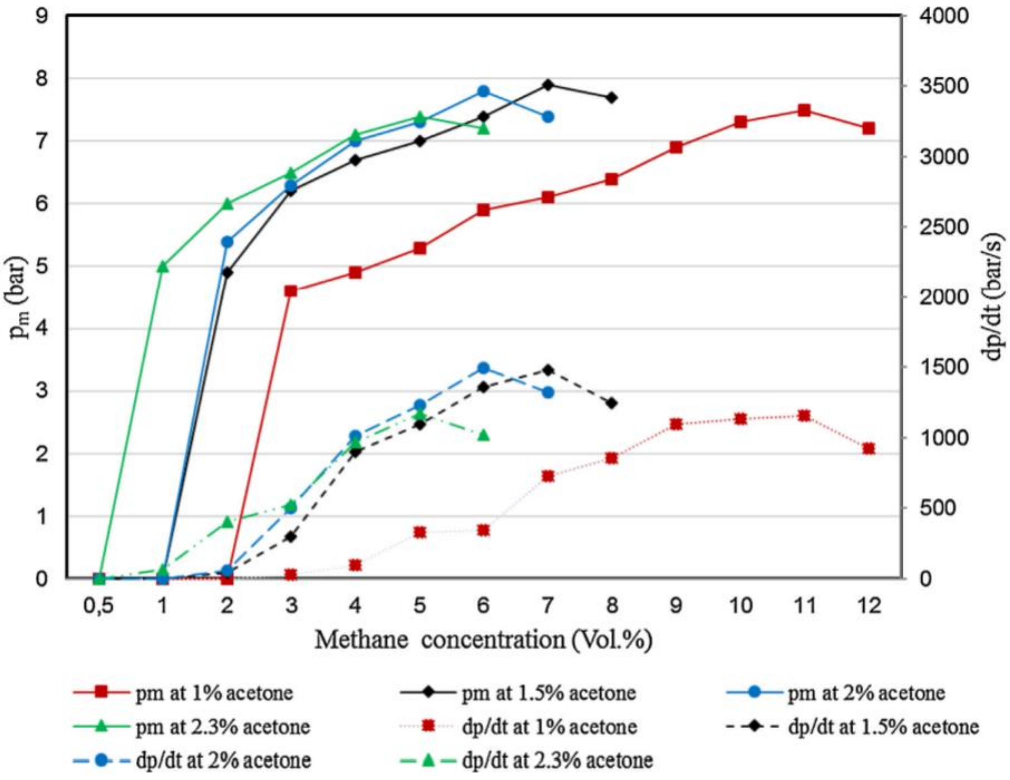


Figure 5: Maximum explosion pressure and rate of pressure rise of a mixture of acetone and methane in dependence on the methane concentration (Data from [1]).

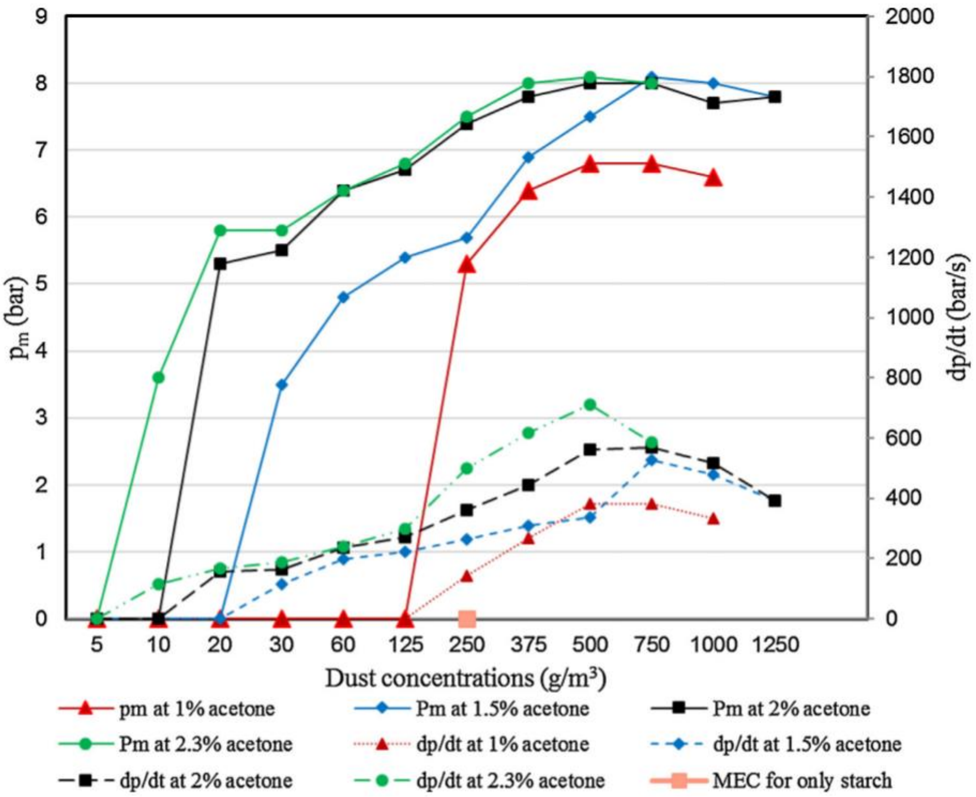


Figure 6: Maximum explosion pressure and rate of pressure rise of mixtures of acetone and starch in dependence on the dust concentration (Data from [1]).

Figure 7 (Data from [1]) shows the results from starch and methane mixture explosion. The concentration of methane was kept below its LEL and the concentration of starch were varied. Same influence as of acetone starch mixture were seen on methane starch mixture. The MEC of starch kept on decreasing with increase in concentration of methane. The explosion severity for this mixture was found lower than that for methane, but higher than that for starch alone [1].

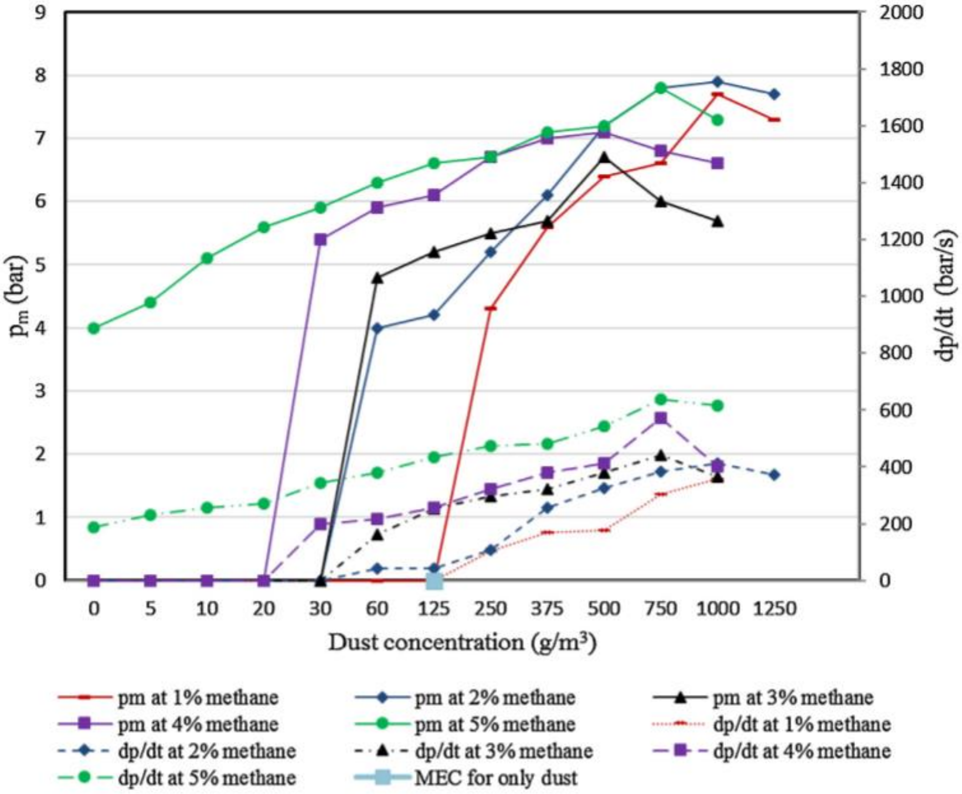


Figure 7: Maximum explosion pressure and rate of pressure rise of mixtures of starch and methane in dependence on the dust concentration (Data from [1]).

4.3 Three component mixture experiment (dust, gas and solvent)

The acetone concentration is kept constant for all the results. Concentrations of 1.0, 1.5, 2.0 and 2.3 vol% were considered. But due to similarities in the results, results with only 1 vol% and 2 vol% are represented graphically.

Figure 8 (Data from [1]) shows results for 1% acetone and varied concentrations of methane and starch. This shows that MEC of the dust can decrease to as low as 5 g/m^3 with 1 vol% acetone and the concentration of methane is increased from 1 vol% up to 4 vol%. The MEC decreased sharply as methane concentration increased. It was also seen that the combinations with were non ignitable in two mixture explosions became explosible when a third component in a low concentration was added. For example, considering the various mixtures, 1 vol% Ch_4 – 60 g/m^3 starch, 2 vol% CH_4 – 20 g/m^3 starch and 3-4 vol% CH_4 – 5 g/m^3 starch, which were not initially ignitable. On addition of 1.0 vol% acetone, all of them became ignitable [1].

Figure 9 (Data from [1]) shows when the acetone concentration is doubled from 1 vol% to 2 vol%, the MEC of dusts decrease further. For E.g. mixture with 1 vol% methane and 20 g/m^3 starch became explosible. Explosion severity of three phase mixtures was same a that of two phase mixtures, but not higher than single dust explosion [1].

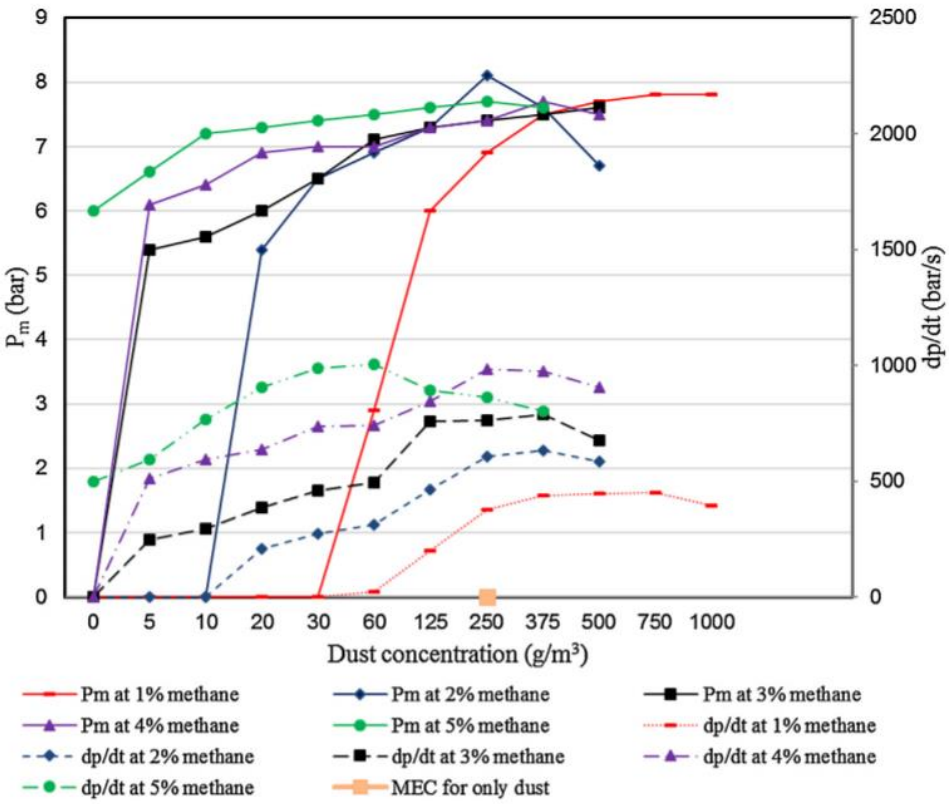


Figure 8: Maximum explosion pressure and rate of pressure rise of mixtures of dust, methane and 1.0 vol.% acetone in dependence on the dust concentration (Data from [1]).

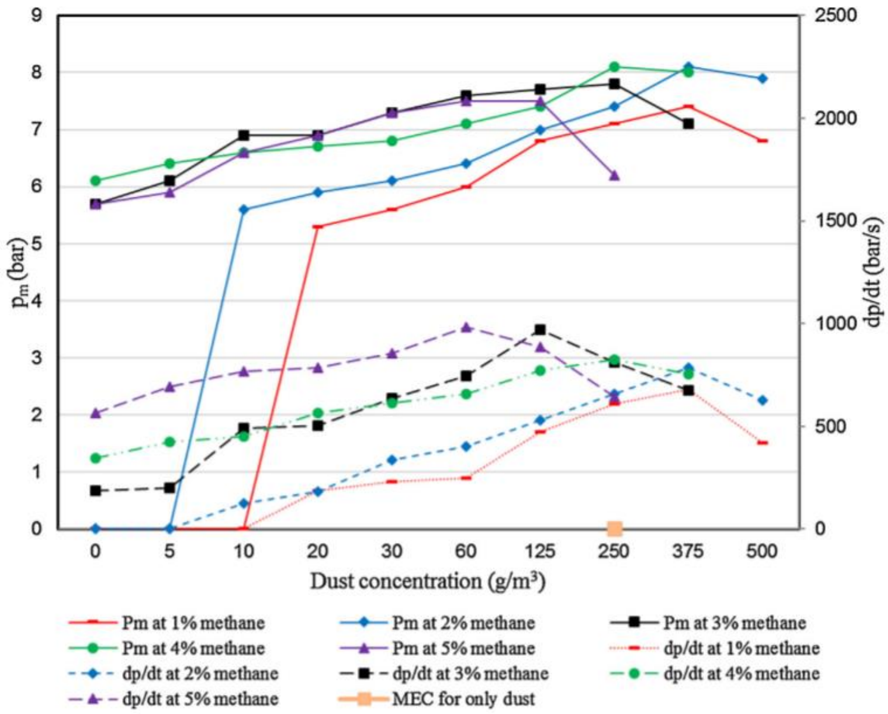


Figure 9: Maximum explosion pressure and rate of pressure rise of a mixture of dust, methane and 2 vol.% acetone in dependence on the dust concentration (Data from [1]).

Table 5 shows the summary of experimental results for two component mixture and three component hybrid mixture explosion performed (Data from [1]).

Hybrid mixtures Two component			Hybrid mixtures Three component		
Mixtures	Based on starch		Mixtures	Based on starch	
	MEC (g/m^3)	dp/dt-max (bar/s)		MEC (g/m^3)	dp/dt-max (bar/s)
ST + 1%AC	250	383	ST + 1%ME + 1%AC	60	452
ST + 1.5%AC	30	527	ST + 2%ME + 1%AC	20	631
ST + 2%AC	20	569	ST + 3%ME + 1%AC	5	787
ST + 2.3%AC	10	709	ST + 4%ME + 1%AC	5	982
			ST + 5%ME + 1%AC	0	1006
ST + 1%ME	250	358			
ST + 2%ME	60	412	ST + 1%ME + 1.5%AC	20	647
ST + 3%ME	60	440	ST + 2%ME + 1.5%AC	10	711
ST + 4%ME	60	571	ST + 3%ME + 1.5%AC	5	831
ST + 5%ME	0	637	ST + 4%ME + 1.5%AC	0	893
			ST + 5%ME + 1.5%AC	0	1027
ME + 1%AC	3	1364	ST + 1%ME + 2%AC	20	681
ME + 1.5%AC	2	1478	ST + 2%ME + 2%AC	10	785
ME + 2%AC	2	1499	ST + 3%ME + 2%AC	0	971
ME + 2.3%AC	1	1173	ST + 4%ME + 2%AC	0	825
			ST + 5%ME + 2%AC	0	983
			ST + 1%ME + 2.3%AC	10	598
			ST + 2%ME + 2.3%AC	5	597
			ST + 3%ME + 2.3%AC	0	583
			ST + 4%ME + 2.3%AC	0	652
			ST + 5%ME + 2.3%AC	0	738

Zhao et al. [12] studied the MEC of coal dust and methane hybrid mixture, in the synergic regions. The results presented by Zhao are discussed below.

4.4 Effects of small concentration of flammable gas on MEC

As shown in figure 10 (Data from [12]) it is clearly understood that presence of small amount of methane reduces the MEC of coal dust. Concentration of methane as low as 0.57 vol% can ignite bituminous coal dust of 20 g/m^3. When the methane concentration is increased from 0.57 vol% to 1.71 vol%, both the explosion overpressure (P_{ex}) and pressure rise rate (dp/dt) increase.

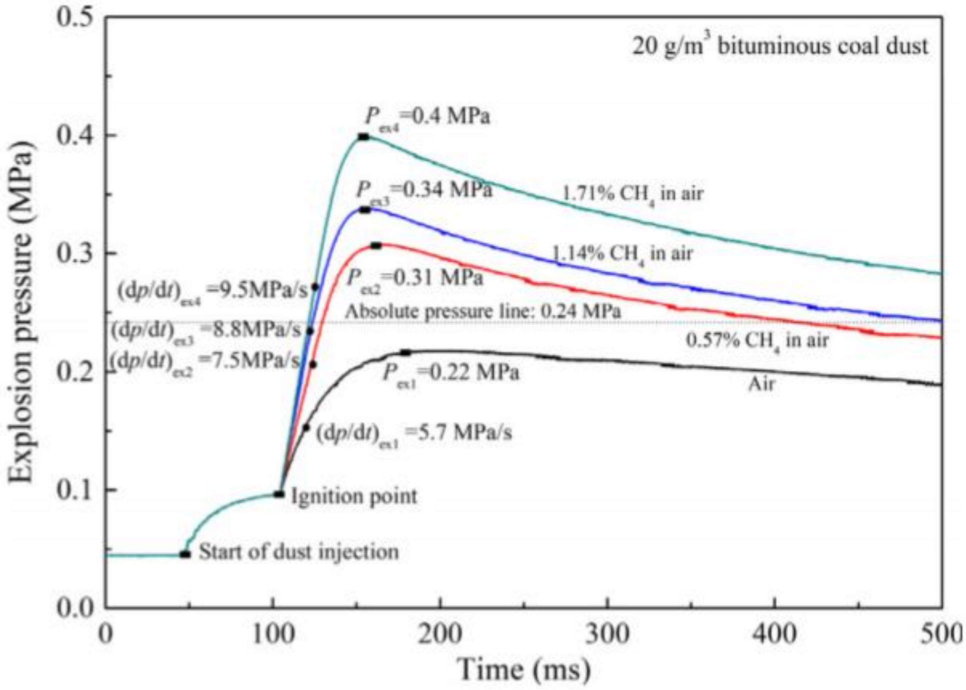


Figure 10: The effect of small amount of CH4 on the explosion process of 20 g/m3 bituminous coal dust (Data from [12]).

Figures 11 a and b (Data from [12]) clearly shows an increase in P_{ex} from 0.2MPa to 0.38 MPa and 0.222 to 0.34 MPa for bituminous coal and anthracite coal respectively. The addition of flammable gas decreases the MEC and increases the P_{ex}, as there is low concentration of dust and abundance of oxygen, its results in more heat release.

CH_4 > H_2 > CO was a general trend seen with respect to the promotion effect of the gases.

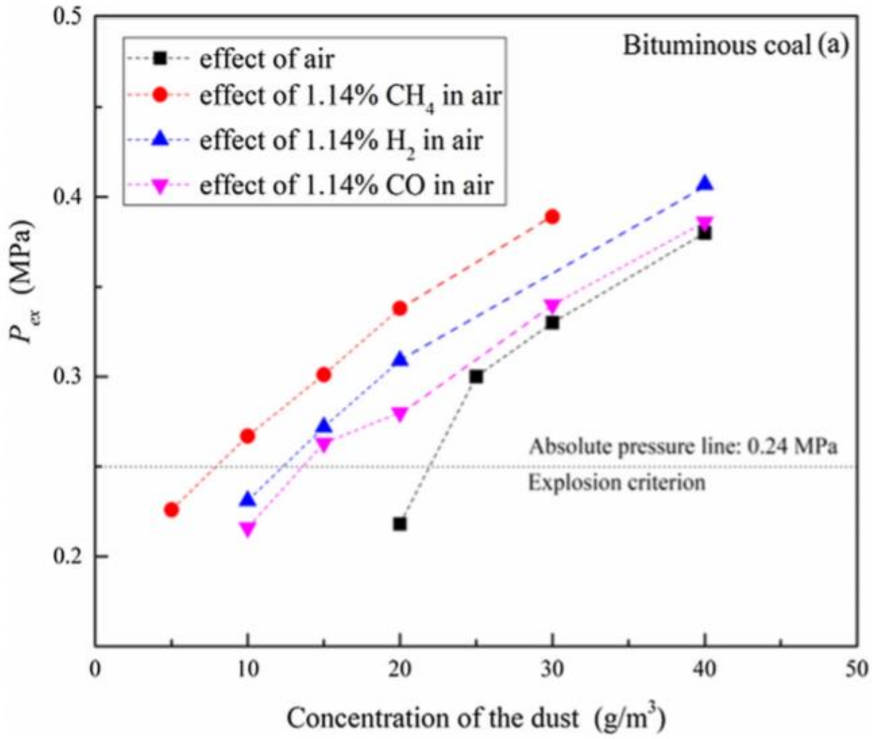


Figure 11(a)

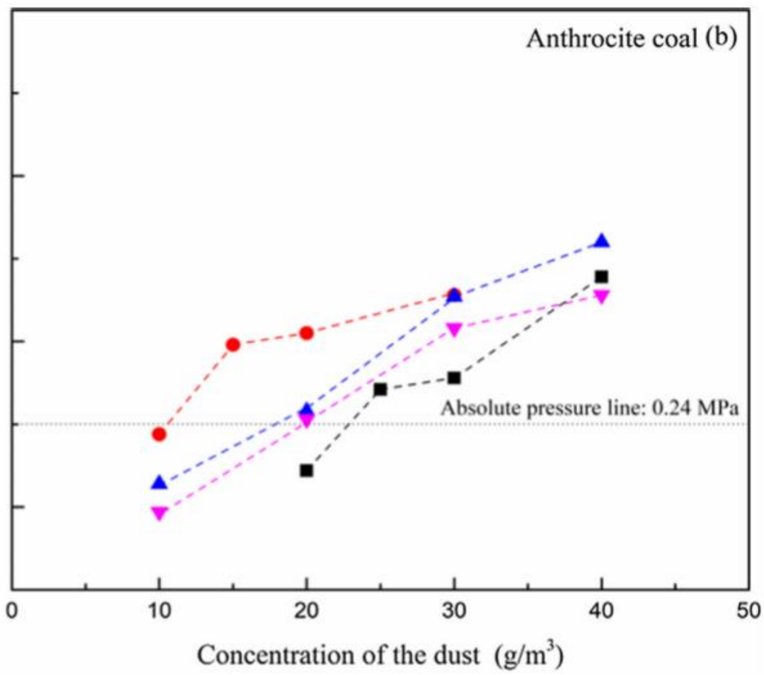


Figure 11(b)

Figure 11: The effect of flammable gas and dust concentration on P_{ex} and MEC of dust samples: (a) bituminous coal and (b) anthracite coal (Data from [12]).

4.5 Results of hybrid mixture with bituminous coal

In the following three figures shown, the X axis represents the ratio of flammable gas concentration in the hybrid mixture to LEL of gas in air. Y axis represents ratio of dust concentration in hybrid mixture to MEC of dust in the air. The grey circles represent the value of P_{ex} for pure substances. Black circles represent stage of no explosion, circles with number inside them or besides them represent ignited mixtures and those values are their corresponding values of P_{ex}. Also, Le Chatelier's line and Barknecht's curve have been plotted.

Figures 12 13 and 14 show the explosion regimes of hybrid mixtures of bituminous coal with methane, hydrogen and carbon monoxide respectively. In figure 12 it can be seen that the explosion occurred even when both the components of hybrid mixture were below their MEC and LEL of pure form. There are some clear explosions near the Le Chatelier's line and Barknecht's curve such as, at 0.114 $LELCH_4$/0.8 MEC_{dust}, 0.114 $LELCH_4$/0.6 MEC_{dust}, 0.228 $LELCH_4$/0.6 MEC_{dust}, 0.228 $LELCH_4$/0.4 MEC_{dust} and 0.341 $LELCH_4$/0.4 MEC_{dust}. With low methane concentrations, when the coal dust concentration is increased, the explosion pressure of hybrid mixture P_{ex} increases gradually. We can also see that as the increase in flammable gas from 0 to 0.342 $LELCH_4$, the explosion point of pure MEC dust decreases from MEC_{dust} to 0.2 MEC_{dust}. This proves a significant promotion effect of presence of flammable gases in the dust explosion [12].

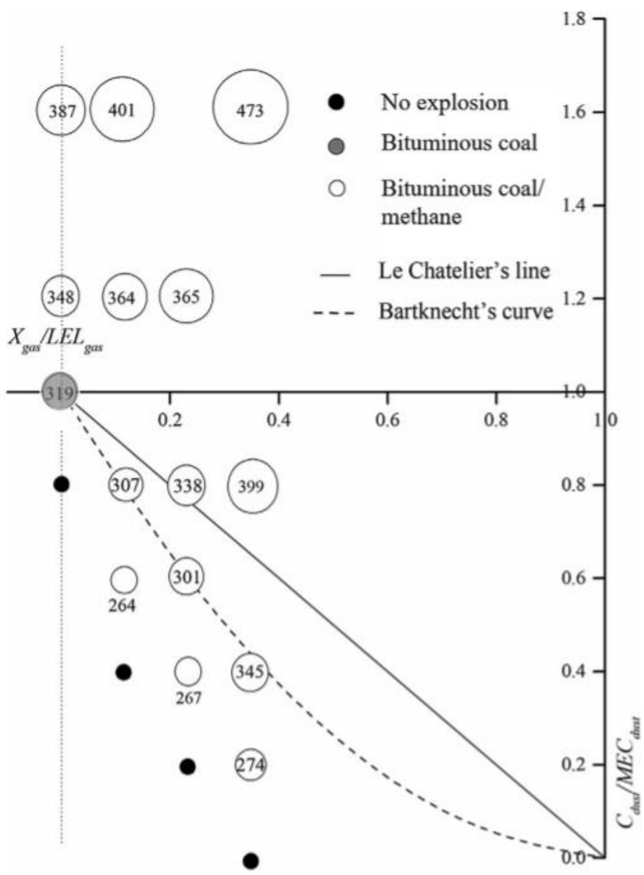


Figure 12: Explosion regimes of bituminous coal and methane (Data from [12]).

Figure 13 shows the explosion regimes of hybrid mixture of bituminous coal and hydrogen.

Similar to figure 12, it shows some explosion points that are outside the Le Chatelier's line and Barknecht's curve, such as 0.14 LELH_2/0.8 MEC_{dust}, 0.14 LELH_2/0.6 MEC_{dust}, 0.29 LELH_2/0.6 MEC_{dust}, 0.36 LELH_2/0.6 MEC_{dust}. P_{ex} at certain gas atmosphere concentration increases as the coal dust concentration increases [12].

Figure 14 shows the explosion regimes of hybrid mixture of bituminous coal and carbon monoxide. In this case, all the tested points are outside the restricted area by Le Chatelier's line, some points such as 0.045 LELCO/0.8 MEC_{dust}, 0.09 LELCO/0.8 MEC_{dust}, 0.09 LELCO/0.6 MEC_{dust}, 0.14 LELCO/0.6 MEC_{dust} are even outside the Barknecht's curve. Zhao found that P_{ex} has a large dependence on the mole fraction of CO. The MEC values of coal dusts are even smaller than those in its pure form [12].

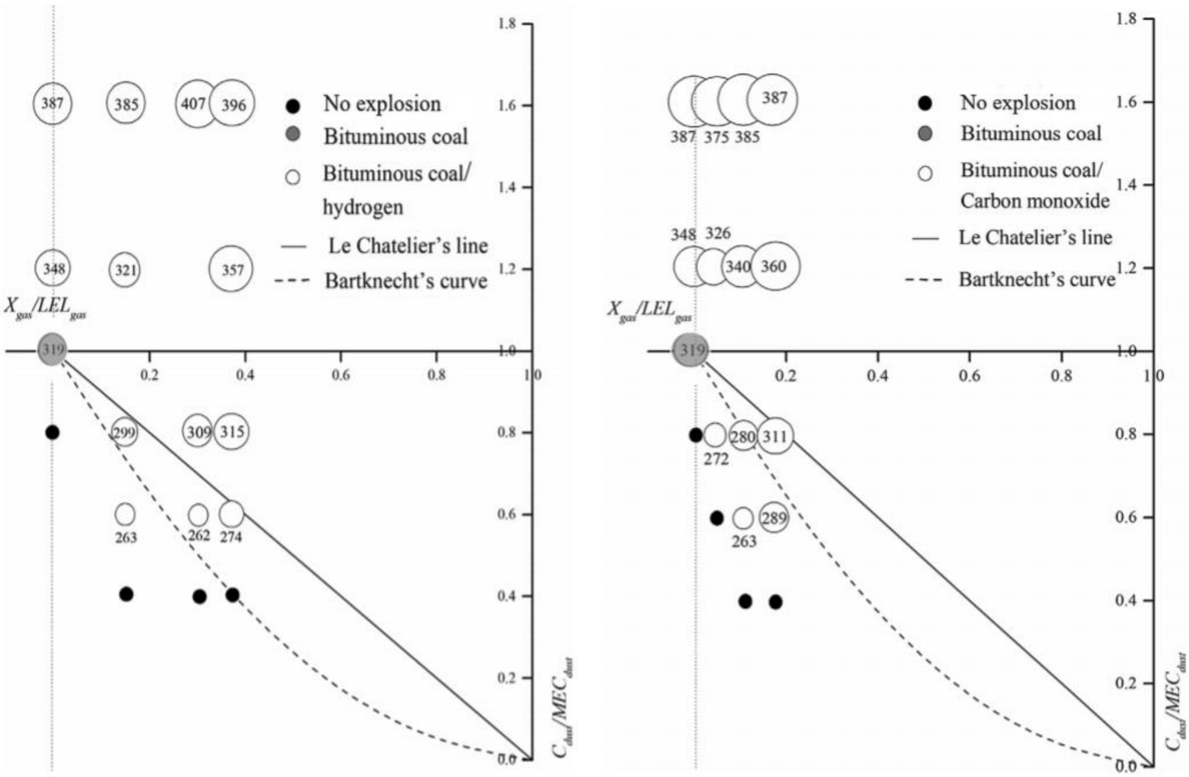
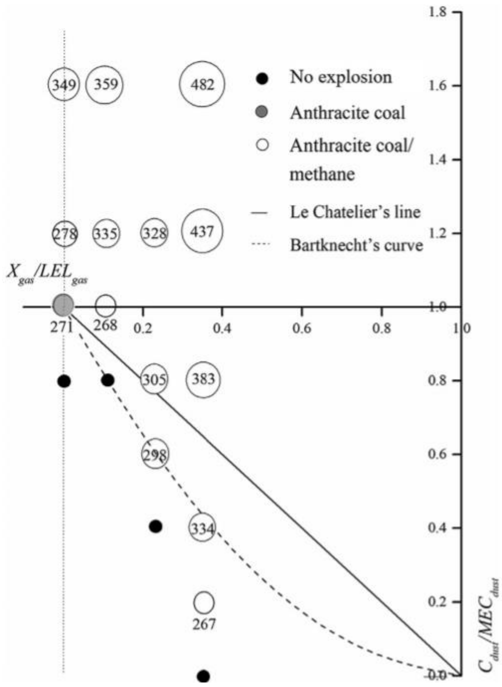


Figure 13: Explosion regimes of hybrid mixture of bituminous coal and hydrogen (L). Figure 14: Explosion regimes of hybrid mixtures of bituminous coal and carbon monoxide (R) (Data from [12]).

4.6 Results of hybrid mixture with anthracite coal

These figures 15-17 representing different results are similar to the previous section 4.5. Figure 15 shows explosion regimes of anthracite coal dust with methane. Comparing the values of anthracite coal with bituminous coal, it is clearly seen that values of P_{ex} for anthracite coal are smaller and there are les explosion points outside the Le Chatlier's line. We can conclude, that small ampunts of flammable gas have a significant effect on bituminous coal dust. Explosion risk of bituminous coal dusts is a higher than anthracite coal dust, this statement is supported by the trends shown in figures 16 and 17. Explosions took place in series only when concentration of anthracite coal dust was 80% MEC_{dust} with H_2 or CO, while for bituminous dust this value was 60% MEC_{dust} as shown in figure 11.



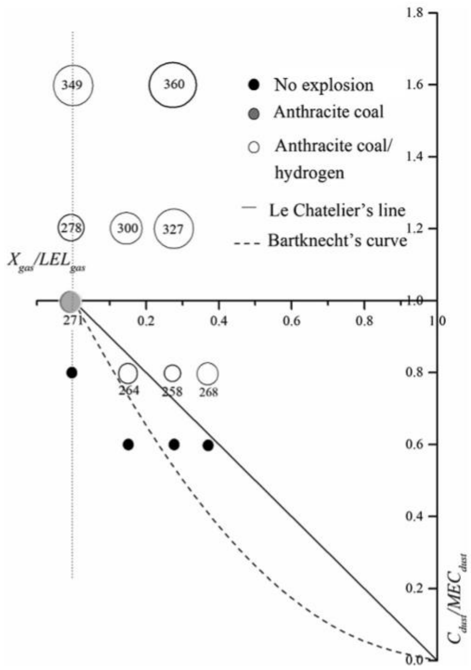


Figure 15: Explosion regimes of anthracite and methane (L). Figure 16: Explosion regimes of anthracite and hydrogen (R) (Data from [12]).

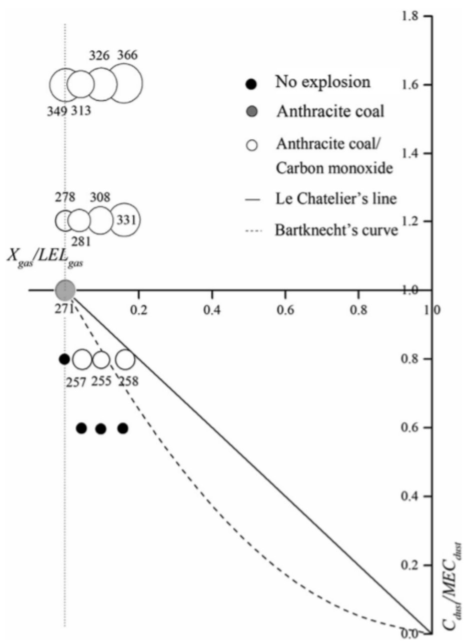


Figure 17: Explosion regimes of anthracite and carbon monoxide (Data from [12]).

5. CONCLUSION

Hybrid mixture formations can occur in industries or some industrial processes. No specific safety related characteristic data is available on hybrid mixtures of combustible substances. From the articles studied, it can be said that to avoid the likelihood of explosion or to reduce the explosion severity, the safety parameters of any substance in its pure form are not reliable when the same substance is mixed with one or more than one combustible substance.

Addai et al. concluded that, when dust is considered as a primary component, the results showed that if gas concentration as low as 1 vol% is added to the dust, it can be ignited resulting in higher explosion pressure. For instance, pure starch with MEC of 250 g/m^3 can also be ignited at a concentration of 10 g/m^3 if small amount of combustible gas or vapour is mixed with the dust. On the other hand, if dust is added to a gas which is below its LEL, the probability of an explosion increases significantly. Hybrid mixtures can not only explode at low concentrations but can also have very large explosion pressure with higher rates of pressure rise, which otherwise is not accountable in case of pure form of components [1].

Zhao et al. also concluded the same result as compared to Addai. It has been found that the presence of small concentration flammable gas increases the chances of an explosion for coal dust below their MEC. The explosion overpressure and the rate of pressure rise both increase as the flammable gas concentration increases, which results in decrease of minimum explosible concentration of dust. This also increases the explosion severity of hybrid mixture explosion. Zhao added that the principle for Le Chatlier’s line and bartknecht’s curve are insufficient for the safety consideration of explosion of hybrid mixtures [12].

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