ABSTRACT
Investigation of explosion characteristics of coal dust was undertaken as a part of regular research program at CSIR-CBRI, Roorkee, India, for designing explosion safety measures for coal dust handling installations. Potential explosion hazard of coal dust cloud is characterized by maximum explosion pressure, maximum rate of pressure rise and explosibility index. Study aimed at review and analysis of existing data on explosion parameters of coals and creating new sufficient quantitative explosibility data for safe design and operation of plants handling some specific selected coals. Various aspects covered are: determination of minimum exploisable dust concentration; maximum explosion pressures and maximum rate of pressure rise; limiting oxygen concentration; and influence of oxygen mass fraction, coal volatility and particle size on explosion violence data. This paper presents results of detailed experimental work on determination of explosion violence characteristics over a wide range of dust concentration (80-4500 g/m$^3$) of two types of coals (volatile matter 27.18% and 19.69%) from Jharia coalfield of India determined at ambient conditions with 20-L Spherical Vessel (similar to Siwek 20-L sphere) established at CSIR-CBRI. Data presented will be used for risk assessment of explosive atmosphere and for designing explosion safety measures for installations handling pulverized coal with similar nature.

KEYWORDS: Dust; Explosion; Coal.

INTRODUCTION
The production processes managing with coal are power plants, coal mines, cement manufacturing plants and other related activities. Handling of pulverized coal suspension in these industries is associated with the risk of coal-dust explosions. These hazards are well recognized for coal mines and there are a number of scientific works aimed at minimizing the dust explosion hazards in mines during the last century. The current environmental regulations have modified the methods for transportation and storage of pulverized coal leading to confined or partially confined systems resulting in increase in the probability of coal dust explosions. Such installations should conform to relevant regulations related to explosive atmosphere which needs the evaluation of explosion parameters for safety, hazard analysis and for designing appropriate explosion safety measures. Dust explosion hazards in atmospheric pressure bins and handling equipment are usually provided for by arranging the discharge of explosion pressure through explosion discs or relief vents and by using explosion suppression systems. The design phase of these safety measures require input data on safety-technical properties- viz. explosion parameters of fuels mixtures created in experimental activities.

An accurate knowledge of explosion parameters of coals is essential for realistic appraisal of fire and explosion hazards involved in their mining, transportation, storage, use, handling, and for efficient prevention of dust explosions and mitigation of their disastrous effects. The explosion preventive measures- good housekeeping and safe design of plant and building, inerting of plant and machinery with nitrogen or other inerts, ignition source elimination - require data on explosibility limits for dust, maximum permissible oxygen concentration, minimum ignition temperature and minimum ignition energy for dust clouds. The design of explosion protective measures- explosion-resistant construction, explosion relief venting, automatic isolation of interconnected spaces and explosion suppression- and risk assessment, are done using maximum explosion pressure and rate of pressure rise data [1-4]. Safety measures to prevent dust explosions or to protect humans and equipment from its effects are designed for different circumstances under which explosions are likely to occur depending on the particular technological application. The explosion parameters related to dust, required in most design procedures, are usually determined in laboratory-scale apparatus wherein their experimental evaluation is strongly affected by dust dispersion degree, initial turbulence level and particle size distribution. The experimental variables are desired to be carefully controlled in order to assure accuracy of experimental data and interpretation of data for industrial application.

Despite the vast amount of data accumulated on explosion parameters for various dusts, there exists no consensus. Even a brief study of the literature reveals wide discrepancies and lack of reproducibility which clearly reflects the experimental difficulties in obtaining accurate and reproducible data for dust-air mixture. Historically, the evaluation of the explosion parameters -maximum explosion pressure and maximum rate of pressure rise- has been done using a 1.2-L Hartmann Apparatus [5] and up to 1970s explosion safety measures like vent sizing were being performed with these data [6] which proved often inadequate as it underestimates explosion severity due to various reasons - Hartmann bomb is much too small to produce representative explosions and the underlying idea that in dust clouds the combustion was more or less volumetric, as in a well-stirred reactor was wrong [7], non-uniform dust dispersion, lack of agreement with large scale tests for rates of pressure rise, and the inadequacy of the spark ignition source for many dusts [8]. This technique was therefore judged inadequate and use of data obtained from the test method in the design of explosion protection systems was not recommended [8]. For solving those problems, European researchers developed several larger spherical test chambers. A 1 m$^3$ chamber designed by Bartknecht [9,10] recommended in west Germany became standard in much of Europe for measuring pressures and rates of pressure rise for dust explosions. Although the use of the 1m$^3$ vessel seemed to give consistent results to be worldwide accepted [11,12],
there were continuous efforts to minimize the size of vessel so as to ease the tests and enable them to be performed in laboratory which resulted in acceptance of a 20-L Sphere designed by Siwek as the minimum size giving comparable data for rates of pressure rise [13] which is more adiabatic with respect to the classical Hartmann apparatus. It is an internationally accepted laboratory apparatus providing a level of control for the significant experimental variables and resolves the many uncertainties and contradictions of the past data and appears in the latest standards as an alternative to the 1 m³ vessel [14-16]. It can be used with much higher ignition energy, thus allowing testing of hardly ignitable dusts which would not explode in a Hartmann apparatus. The well established ‘cubic law’ correlates data obtained in vessels of volume of 1 m³ and this 20-L Sphere [16]. CSIR-CBRI, Roorkee, India, has established a 20-L Spherical Vessel (similar to that designed by Siwek) for studying explosion parameters of gases, vapours and dusts.  

As a part of research program on determination of explosion characteristics of various dusts an exhaustive investigation was undertaken on coal dust explosibility data using CSIR-CBRI 20-L Spherical Vessel which covered a comprehensive review and analysis of existing data on explosion parameters of coal dust and creation of new data on each identified gap.

The coal is a highly variable organic derivative and its use by industries differs in composition, volatile content, particle size distribution, etc. There is a wide range of explosibility data of coal dusts in technical literature on various aspects including: ignition energy requirements for adequate measurements of explosibility limits of coal dusts and effects of volatility on these limits, volatility model for coal dust flame propagation, effects of particle size on explosibility data, and comparison of laboratory and large scale data [17-34]. Coal dust explosibility research is subject to many complicated factors and test data have been misleading and contradictory. Mixtures of coal dust and air are inherently difficult to control and even with the same apparatus and experimental methods there may not be reproducibility from one test to the next. Early research used explosion chambers which seriously underestimated dust explosibility and are therefore considered inadequate by modern standards. Data reported on explosion violence for coals using 20-L Sphere [16,23,25,26,29,32,33] differ in particle size and composition of coals. The explosion data created in present study will be discussed with reference to these data. The systematic work on coal dust (volatile 37%, from Pittsburgh seam, USA, used for decades as a standard test dust [17, 20],) done by USBM in 20-L chamber designed by Pittsburgh Research Laboratory (PRL) is worth mentioning here [31,34]. This work resulted in Kₐ values of coal dusts which are 1/3rd of those determined by Siwek sphere as the turbulence levels in PRL 20-L chamber are lower than in Siwek Sphere and are not recommended for the sizing of vents according to various standards. The turbulence and consequently explosion data are governed by aerodynamics and combustion inside the vessel [35,36].

The study included various parameters like minimum exploisible dust concentration; maximum explosion pressures and maximum rate of pressure rise; maximum permissible oxygen concentration; and influence of oxygen mass fraction, coal volatility and particle size on explosion violence data. However this paper covers experimental evaluation of explosion violence characteristics - maximum explosion pressure (Pₘₐₓ), the maximum rate of pressure rise (dP/dtₘₐₓ and the explosibility index (Kₐ) of coals necessary for the design of protection and mitigation systems and risk assessment of explosive atmosphere. The results of explosion violence measurement experiments to obtain sufficient quantitative explosion data to design and operate plant for handling coals from Jharia coalfield of India for two bituminous coals with different characteristics for a particular size distribution determined at normal initial temperature and pressure over a wide range of dust concentration determined with CSIR-CBRI 20-L Sphere using air as the suspension media are presented and discussed here. Effects of particle size in detail, oxygen concentration, ignition source strength, etc. on explosion violence data of coal will be presented in separate publications.

The coals selected for this study are classified as coal A (volatile- 27.19%), and coal B (volatile- 19.69%). The sizes used are: size representative of those used in pulverized coal boilers (90% passing through 200 BS Mesh and nothing remaining on 52 BS Mesh), 74µm and 38µm. To the author’s knowledge, no coal dust data obtained with the 20-L Sphere for the coal samples selected have been published.  

**EXPERIMENTAL SET-UP AND PROCEDURE**

The 20-L chamber is a hollow sphere made of steel. The permissible working pressure for the sphere is 30 bar. Test pressure is 40 bar. It was designed to allow maximum flexibility in positioning of current and additional new instrumentation. The dust to be tested is dispersed from a pressurized storage chamber (0.6 l) by means of outlet valve and a perforated annular nozzle using compressed air supply at 20 bar. Schematic diagram for instrumentation of 20-L Spherical Vessel is shown in Fig. 1. Chamber top is hinged and opens across the full chamber diameter allowing easy access to the interior for positioning instruments and for cleaning. During routine operation at two to four tests per hour, the thick walls of the chamber provide sufficient heat sink for the post explosion gases and particles to cool to room temperature without the need for water cooling of the
chamber. There are several ports in the chamber for vacuum creation, gas/dust system introduction, installing various instruments for measuring pressures, etc. The vacuum creation and dust introduction and dispersion system were optimized based on a number of preliminary experimental trials. Ignition source installation system was designed to accommodate different types of ignition sources viz. spark discharge and pyrotechnic igniter. The dynamic pressure during explosion is measured using piezoelectric and strain gauge type pressure transducers provided at two ports. The strain gauge pressure transducers measure the explosion pressure and can also be used during partial evacuation of the chamber prior to dispersion and for adding gases to the chamber by partial pressures since it is an absolute pressure gauge. The pressure time curve is recorded by storage oscilloscope or high speed chart recorder.

For experiments to measure explosion data, first the known quantity of dust sample is placed at the bottom of the dispersion nozzle and igniters are placed in centre of 20-L Sphere, firing in the horizontal plane and in opposite directions. The upper half of the vessel is bolted on. The vessel is partially evacuated to 0.4 bar(a) prior to dispersing the dust. This evacuation of the 20-L Vessel by 0.4 bar together with air in storage chamber (+ 20 bar; 0.6 l), results in the desired starting initial pressure (1 bar) for the experiment. The ignition source is two pyrotechnic igniters (total energy 10 kJ) initiated by a 1A electric fuse head. Each ignitor contains 1.2 g of a pyrotechnic composition (40 % zirconium, 30 % barium nitrate and 30 % barium peroxide). The degree of turbulence in the explosion chamber is mainly a function of the ignition delay time - time between the onset of dust dispersion and the activation of the ignition source- standardized to 60 ± 5 ms to maintain a moderate level of turbulence at the time of ignition of dust cloud.

The experiments for explosion violence determination are conducted over a wide range of dust concentration. As per standard procedure [16] an initial concentration of 250 g/m³ (5 g/20 litre) is tested which may be systematically increased by an equivalent of 250 g/m³ (e.g. 500, 750,1000 g/m³, etc.) until curves are obtained for both maximum explosion pressure, Pₚₑₓ and (dP/dt)ₑₓ that clearly indicate an optimum value has been reached. Two additional test series are run at the concentrations where the maximum were found and that at one concentration on each side of the maximum. If it is indicated that the optimum concentrations for (dP/dt)ₑₓ or Pₚₑₓ is less than 250 g/m³, the tested concentration may be halved (e.g. 125, 60,30 g/m³) until the optimum value is obtained. If the maximum values for the pressure and the rate of pressure rise are not observed in the first test series, experiments are continued with higher dust concentrations (> 1500 g/m³) until these maximum values have been clearly seen. The tests for range of dust concentrations giving maximum values of explosion data are repeated in two further test series. For calculating Pₚₑₓ and (dP/dt)ₑₓ the means from maximum values of each series are taken. Kₑₓ is calculated from the above means by use of cubic law.

Typical pressure-time curve recorded during dust explosion violence measurement experiments is as shown in Fig. 2. The pressure trace starts at the partially evacuated value of 0.4 bar(a). The blast of air that disperses the dust starts at 40 ms and ends at 90 ms on the pressure-time trace. The ignitor is activated at 100 ms at a chamber pressure of 1.0 bar(a). Pₚₑₓ is the maximum explosion pressure (above the pressure in the vessel at the time of ignition). The value of Pₑₓ for a test at a given concentration, is the highest deflagration pressure (absolute) minus the pressure at ignition (normally 1 bar). (dP/dt)ₑₓ is the maximum rate of pressure rise reached during the course of a single explosion experiment. Pₑₓ is the maximum pressure (above pressure in the vessel at the time of ignition) and (dP/dt)ₑₓ is the maximum value for the rate of pressure increase per unit time reached during the course of explosion for the optimum concentration of the dust tested and equals maximum slope of a tangent through the point of inflexion in the rising portion of the pressure vs. time curve. The values for Pₑₓ and (dP/dt)ₑₓ are the averages of the highest values (over the range of dust concentrations). The explosibility dust constant, Kₑₓ, characterizes the explosibility of the material. Kₑₓ is maximum (dP/dt) normalized to a 1.0 m³ volume measured at the optimum dust concentration and defined in accordance with the following cubic relationship [9]:

\[ Kₑₓ = \left( \frac{dP}{dt} \right)ₑₓ^{1/3} \]  

(1)

Where,

\[ P \] - Pressure, bar  
\[ T \] - Time, s  
\[ V \] - Vessel volume, m³  
\[ Kₑₓ \] - Explosibility dust constant, bar.m/s

Kₑₓ values rounded to the nearest integer are used. The dust are classified as St 0 (non-explosive) for Kₑₓ < 0; St 1 (explosive) for Kₑₓ 0-200 bar.m/s; St 2 (strongly explosive) for Kₑₓ 200-300 bar.m/s; and St 3 (extremely explosive) for Kₑₓ > 300 bar.m/s.

The 20-L Sphere and the test procedure have been designed in such a way that the results are commensurate with those from the 1 m³ explosion vessel that is standardized in the ISO standard [11] and VDI guidelines. Because of the cooling effect from the walls of the 20-L sphere, the values for Pₑₓ > 5.5 bar are slightly lower than in the 1 m³ vessel. To obtain results equivalent to 1 m³ vessel, this Pₑₓ value may be corrected using equation 2 based on numerous correlation tests between 1 m³ vessel and 20-L Sphere [16]:

\[ Pₑₓ = 0.775 Pₑₓ^{0.15} \]  

(2)

Where,

\[ Pₑₓ \] - Corrected explosion pressure, bar  
\[ Pₑₓ \] - Maximum explosion pressure for a tested dust concentration, bar

When ignited, the igniters produce a dense cloud of very hot particles and little gas. Some experiments were conducted to measure the pressures generated by 10 kJ igniters used in this study. It was found that these igniters produce pressure rises of about 0.5 bar in the 20-L chamber. Due to the small test volume, the pressure effect caused by the pyrotechnic igniters have been taken into account in the range Pₑₓ < 5.5 bar [16]. A blind test, with pyrotechnic ignitor alone, will give a pressure of approximately 1 bar if 10 kJ ignitor are used. But during a dust deflagration, with rising Pₑₓ, the influence of the pyrotechnic igniters will be minimized by the pressure effect of the deflagration
The equation used for this correction is given below [16]:

\[ P_{m} = 5.5 \times \frac{P_{ex} - P_{CI}}{5.5 - P_{CI}} \text{ bar} \]  

(3)

Where,

- \( P_{m} \): Corrected explosion pressure, bar
- \( P_{CI} \): Pressure due to chemical igniters = 1.6(IE/10000), bar
- IE: Ignition energy, J

The criteria for significant flame propagation in the 20-L chamber are that the maximum explosion pressure, \( P_{ex} \geq 2 \text{ bar} \) (a) and that the volume normalized rate of pressure rise \( (dP/dt)^{1/3} \geq 1.5 \text{ bar. m/s} \) as used by USBM studies [27, 28].

To prepare suitable dust samples of coal A and coal B for explosion tests it was decided to mill and sieve the coal to a particle size representative of those used in pulverized coal boilers (90% passing through 200 BS Mesh and nothing remaining on 52 BS Mesh) and dry them to a moisture content of less than 5%. The particle size distribution was determined by normal sieving procedure. The method of mechanical sieving was evaluated by sieving a number of coals for 10, 15, 20 minutes. The results suggest a minimum sieving time of 15 minutes.

![Figure 2. Typical pressure-versus-time trace during a dust explosion experiment in 20-L Spherical Vessel](image)

Experiments were started with an initial dust concentration 250 g/m³ for coal A and coal B dusts. The dust concentration was increased by 250 g/m³ repeated thrice. For calculating \( P_{max} \) and \( (dP/dt)_{max} \), the means from the maximum values of each series are taken. Further experiments were conducted to cover the entire expected explosible range of dust cloud between reported minimum explosible limit and maximum explosible range for coal dusts. The minimum value of dust concentrations was taken lower than the reported minimum explosible limit for Pittsburgh high volatile coal dust i.e. ~ 80 g/m³ [34]. The maximum value of dust concentration for experiments was 4500 g/m³ which is closer to an apparent explosible dust concentration of 4000 g/m³ reported for coal as an ignitability limit using an electric spark ignition source (much weaker than pyrotechnic igniters) [18]. For most practical purposes dusts can be considered to have no rich limit of explosibility [39]. Data from experiments to determine explosion severity were collected as shown in Fig. 2. From a set of such experimental curves, the maximum values for a particular dust concentration was determined. All the results of experiments were collected, analysed and predicted data were presented in various figures showing explosion violence data against dust concentrations.

**RESULTS & DISCUSSIONS**

The experimental pressure-time curves similar to Fig. 2 were recorded for the dust concentrations for coal A and coal B during many experiments of series conducted for concentration ranges 250-4500 g/m³ (increment- 250 g/m³), 300-950 g/m³ (increment- 50 g/m³) and 200-50 g/m³ (decrement-50 g/m³) for particle sizes- 90% passing through 200 BS mesh and nothing remaining on 52 BS Mesh, 74µm, and 38µm. Each experiment was repeated thrice. The experimental curves were analysed and values of \( P_{ex} \), \( (dP/dt)_{ex} \) and \( (dP/dt)^{1/3} \) were estimated for each experiment as per procedure explained above. Correction for effect of vessel size for \( P_{max} > 5.5 \text{ bar} \) is done using equation (2) and that of ignitor for \( P_{max} < 5.5 \text{ bar} \) is done using equation (3).

![Figure 3. Particle size distribution of coals](image)

**Table 1. Proximate Analysis and Calorific Values for Coals**

<table>
<thead>
<tr>
<th>Property</th>
<th>Coal A</th>
<th>Coal B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (%)</td>
<td>3.92</td>
<td>3.80</td>
</tr>
<tr>
<td>Volatility (%)</td>
<td>27.18</td>
<td>19.69</td>
</tr>
<tr>
<td>Fixed Carbon (%)</td>
<td>50.70</td>
<td>40.72</td>
</tr>
<tr>
<td>Ashes (%)</td>
<td>18.20</td>
<td>35.79</td>
</tr>
<tr>
<td>Calorific value, cal/g</td>
<td>6011.76</td>
<td>3684.91</td>
</tr>
</tbody>
</table>

The particle size distributions of coals are shown in Fig. 3. The proximate analysis data and calorific values of coals determined as per standard procedures [37, 38] are given in Table 1. For experiments with other particle sizes, samples of sizes 74µm and 38 µm were prepared for both the coals. Experiments were carried out for coals with various dust concentrations discussed in next section as per procedure described above. Each experiment was repeated thrice, and the means from the maximum values of each series are taken. Further experiments were conducted to cover the entire expected explosible range of dust cloud between reported minimum explosible limit and maximum explosible range for coal dusts. The minimum value of dust concentrations was taken lower than the reported minimum explosible limit for Pittsburgh high volatile coal dust i.e. ~ 80 g/m³ [34]. The maximum value of dust concentration for experiments was 4500 g/m³ which is closer to an apparent explosible dust concentration of 4000 g/m³ reported for coal as an ignitability limit using an electric spark ignition source (much weaker than pyrotechnic igniters) [18]. For most practical purposes dusts can be considered to have no rich limit of explosibility [39]. Data from experiments to determine explosion severity were collected as shown in Fig. 2. From a set of such experimental curves, the maximum values for a particular dust concentration was determined. All the results of experiments were collected, analysed and predicted data were presented in various figures showing explosion violence data against dust concentrations.
upto 1500 g/m$^3$. Thus initially experiments were conducted at dust concentrations- 250, 500, 750, 1000, 1250 and 1500 g/m$^3$. The experimental results are presented in Fig. 4. The top portion of the graph shows the maximum absolute explosion pressure, $P_{ex}$, plotted against dust concentration. The lower portion shows the maximum rate of pressure rise, normalized by the cube root of chamber volume ($dP/dt.V^{1/3}$ i.e. $K_{St}$. The maximum value of $K_{St}$ for coal dust is 158 bar.m/s for coal A and 140 bar.m/s for coal B and is proportional to the maximum flame speed [20,40]. The maximum explosion pressures for coal A is 6.8 bar(a) and coal B is 6.2 bar(a). The maximum explosion data occurs at a dust concentration 500 g/m$^3$ for both the coals.

As the difference between two concentrations tested on either side of the dust concentration corresponding to maximum explosion data was 250 g/m$^3$, further experiments were conducted for concentration interval of 50 g/m$^3$ on either side of this concentration to determine accurate value of explosion data and optimum dust concentration at which these maxima are obtained. The dust concentrations selected for this test series are 300, 350, 450, 550, 600, 650, 700 and 750 g/m$^3$. The resultant explosion data are presented in Fig. 5 which confirms the optimum dust concentrations for both the coals as 500 g/m$^3$ and maximum values of explosion data as indicated above.

There are several locations in plants where low levels of dust concentrations are expected leading to weaker dust explosions. Experiments were conducted for dust concentrations 200, 150, 100, 90, 80, 70, 60 and 50 g/m$^3$. Explosions could be observed up to a dust concentration 80 g/m$^3$ for coal A and 100 g/m$^3$ for coal B. These dust concentrations are equal to the minimum explosible concentrations (MEC) for these coals determined in the same experimental set-up using 10kJ ignitor and are in agreement to that reported for Pulverized Pittsburgh coal in 1 m$^3$ chamber using 10kJ ignitor [27,28]. The estimated $P_{ex}$ and $(dP/dt)_{ex}V^{1/3}$ for these experiments are presented in Fig. 6.

In order to study the overall explosibility characteristics of a dust, tests must be made over a range of concentrations to determine the ‘worst case’. Hence, experiments at higher dust concentrations were also conducted. In practice it is very difficult to measure the upper explosibility limits for dusts owing to the difficulty in obtaining a uniform dust concentration throughout the vessel. Agglomeration of the dust inhibits dispersion, whilst turbulence results in concentration stratification. Therefore, the upper explosibility limit in case of dusts is regarded as a guide and not an absolute measurement. Explosions have been observed in coal dust at very high concentrations e.g. 4000 g/m$^3$ for Pittsburgh coal (37 % volatiles, moisture 1.2 %) [34], 7000 g/m$^3$ for Morewell Victorian brown coal (volatiles 49.5 %, 14.1% moisture) and 10,000 g/m$^3$ for moisture free sample of the same coal [23]. Similar observations were made in the present study. The author qualified these results and indicated that they are a guide only due to the difficulty in obtaining uniform dust concentration in the chamber, largely because of agglomeration and turbulence effects.
The dust concentration for this series are: 1750, 2000, 2250, 2750, 3000, 3250, 3500, 3750, 4000, 4250 and 4500 g/m$^3$. The values of $P_{exp}$ and $(dP/dt)_{exp}$ $V^{1/3}$ for these concentrations are shown in Fig.7. The summary of experimental results for dust concentration range 80-4500 g/m$^3$ is presented in Fig.8.

A quantitative model of the combustion process in a coal dust explosion is beyond the scope of this study. However the following sequence of events in a coal dust explosion, which is based on a model proposed by Hertzberg [22] will be used to rationalize the results obtained in this study: (i) removal of adsorbed water from surface,(ii) devolatilization of the particles, (iii) mixing of volatiles with air, (iv) combustion of air/volatiles mixture, (v) oxidation of char substrate. The processes which quench flame propagation are a combination of convective, conductive and radiative heat transfer from the burnt products to the unburnt particles and the surrounding gases.

Variation of explosion data with dust concentration is a complex phenomenon which can be explained by the importance of devolatilization and the availability of volatile combustible gases in the explosion chamber. At concentrations below minimum explosible concentration (MEC) - 80 g/m$^3$ and 100 g/m$^3$ for the coal A and coal B- the heat liberated from the combustion of the particles near the ignition source is not sufficient to ignite adjacent particles; consequently flame propagation does not occur. The $P_{exp}$ and $(dP/dt)_{exp}$ are quite low at MEC due to the fact that at very low dust concentration, the dispersed particles are devolatilized very rapidly and the concentration of combustible volatile components comes very close to its upper explosive limit value. At this stage, the availability of oxygen becomes the limiting factor for the oxidation reaction. Consequently, the energy released is not sufficient to give explosion pressures in higher range. Once the dust concentration exceeds MEC value, flame propagation is favoured and flame speed increases with coal dust concentration. However there is minimal effect on explosibility data until the stoichiometric concentration is reached. The explosion severity peaks at a dust concentration ($C_{ex}$) of 500 g/m$^3$(Fig.4). The stoichiometric ratios of total fuel/oxygen and volatile matter/oxygen are much lower than this value ~150 and 200 g/m$^3$, respectively, indicating that a significant quantity of dust is not consumed in the explosion. With gas mixtures, which are homogeneous at a molecular level, the explosion severity peaks at the stoichiometric ratio. However, for the two-phase dust dispersion the rate of oxidation is limited by the rate at which the particles are heated and devolatilized, thus $C_{ex}$ occurs at a concentration above the stoichiometric ratio. The optimum dust concentration was ~ 3 times greater than the stoichiometric value in all cases confirming that dust combustion is largely incomplete in the condition of maximum reactivity for the system. The optimum dust concentration at ambient pressure ranged from 375 to 750 g/m$^3$ for the data reported in literature for coals [23,25,26,32,33,34].

The process of reduced devolatilization continues with further increase of dust concentration. At dust concentration above $C_{ex}$ the severity of the explosion decreases since the excess fuel acts as a heat sink and reduces the maximum temperature rise. The quenching effect of the excess fuel increases as the dust concentration increases until at the upper explosible limit no flame propagation occurs. At the higher dust concentrations as shown in Fig 7, although the mixtures are normally fuel-rich, the pressures nevertheless remain constant. There is an increased uncertainty in the dust dispersion effectiveness at these very high concentrations. The decrease in pressure at higher concentrations may be due to the increased heat sink of the very large dust concentrations and decrease in rate of rise of explosion pressure may be due to the increased heat sink effect and to the possible decrease in turbulence due to the large mass of dust. At even higher dust concentrations, although the mixtures are nominally fuel rich, the pressure, nevertheless remains constant. The normal rich limit observed for hydrocarbons such as CH$_4$ is not observed for dusts. An explanation of this effect, at least for many dusts such as coal, is that the solid-phase fuel first devolatilize before it can mix with air as explained in five step model for coal dust explosion. As soon as sufficient volatiles are generated to form a stoichiometric concentration of volatiles in air, the flame front propagates rapidly through the mixture before excess fuel volatiles can be generated. The availability of the combustible volatile matter becomes the controlling factor for the rate of oxidation, as well as heat generation. Thus the results presented above clearly indicate that the ignition mechanism based on the homogeneous reaction of volatile combustion products formed from the decomposition of coal solid particles explain the experimental observation correctly. The excessive loadings of suspended explosive dust are inhibitory to explosion propagation. There is also confirm recognition that at very high dust concentration, the excess fuel does not participate in the exothermic combustion stage of explosion and instead acts as a
heat sink. Several other workers have used part of a similar mechanism but the present study has been able to explain the ignition behaviors over a wide range of dust concentration.

The experimental results for two types of coals used in this study indicate that for similar size coal A (volatile-27.18%) have lower MEC, higher explosion pressures, and higher (dP/dt)\textsuperscript{1/3} values than low volatile coal B (volatile-19.69%). The maximum rate of pressure rise (dP/dt)\textsubscript{max} increases as the volatile content increases.

### Table 2. Explosibility Data for Coals

<table>
<thead>
<tr>
<th>Property</th>
<th>Coal A</th>
<th>Coal B</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEC, g/m\textsuperscript{3}</td>
<td>70</td>
<td>160</td>
</tr>
<tr>
<td>( \rho_{\text{max}} ), bar (a)</td>
<td>7.2</td>
<td>7.3</td>
</tr>
<tr>
<td>( K_{\text{50}} ), cm/s</td>
<td>170</td>
<td>160</td>
</tr>
</tbody>
</table>

It is clearly established from the literature that explosibility increases as the dust particle size decreases. The explosion violence data for other size distribution of coals were also investigated as the particle size is at least as important as volatility in understanding the explosion hazard and obtaining data for the hazardous industrial situations. The experimental values of explosibility data for two sizes-74 and 38 µm are given in Table 2. The explosion severity increases marginally when particle size is reduced from 74 to 38 µm. In terms of each of the parameters MEC, \( P_{\text{max}} \), and \( K_{\text{50}} \), the explosibility increased from coal B to coal A. This trend can be attributed to a combination of physic-chemical factors; however, the major factor is high volatile matter content and specific energy. This increase in explosibility with increasing volatile matter content is consistent with the literature [31] and this is the keystone to many of the postulated dust explosibility models presuming that only the volatile matter is consumed in an explosion and that the role of the less reactive material, the char, is that of a heat sink.

The data on study of particle size effect show that the required minimum explosive dust concentration increases with increase in particle diameter. This behaviour may be explained by the fact that for coal dust ignition is preceded by devolatilization which is the controlling reaction step in the process. The rate of this reaction is dependent on the exposed surface area of particles. For larger particles, the surface area per unit volume of dust is lower; hence a higher minimum dust concentration is required so that increased volatile combustible products are formed from devolatilization of a larger number of solid particles. The yield of volatiles in the combustion chamber is a complex phenomenon governed by various factors such as size of particles, concentration of dust and heat transfer mechanism. As larger particles are also commonly encountered in process industries, ignition of larger particles was also studied in the present investigation. Details on effect of particle size on coal dust explosibility data will be presented in future publications. However it was concluded that finest size of coal B have explosibility data comparable to those of the larger sizes of the coal A as coal B with size 38 µm was found to have values of \( P_{\text{max}} \) and \( K_{\text{50}} \) comparable to those of 74 µm size of coal A.

The data presented above are in reasonably good agreement with those of other researchers [16,23,25,26,29,32,33] for coals with similar volatile matter. The experimental data obtained by present study and various researchers in a 20-litre sphere similar to that of Siwek are presented in Figs 9 and 10. Comparable results should in principle be obtained by all laboratories when using the standard 20 litre procedures. The variation of the \( K_{\text{50}} \) values obtained by the laboratories reflects the difficult nature of the coal dust samples in respect of uniform test conditions. The dispersion of the dusts into the explosion vessel and the turbulence level inside the vessel at the moment of explosion greatly influences the rate of pressure rise. A substantial part of variations in the explosion data must also be ascribed the heterogeneous samples. Classification of coarse and fine particles during handling and transportation and minor changes in the moisture content during storage of the rather voluminous dust samples at different test facilities could not be avoided. A comprehensive experimental determination of explosion violence data of 8 coals (volatile matter -5.4% to 56.42% on dry basis) dust with 20-L sphere was undertaken by Continillo et al. [25,26]. The highest values are attained by lignite, which has the highest volatile content. Significant differences were measured by LOM and TNO in the 20-L Sphere for the more conventional lignite dusts [33].

In addition to the above data on coal dust explosion in 20-L Siwek type Sphere, the exhaustive work has been done by USBM for various size distributions of Pittsburgh seam high volatile bituminous coal (moisture 1%, volatility 37%) and Pocahontas seam low-volatile bituminous coal (moisture 1%, volatility 17%) over a dust concentration 80-4000 g/m\textsuperscript{3} from the experiments conducted in their 20-L vessel using 2500 and 5000 J ignitors [31,34]. The turbulence level in these tests is lower than that in Siwek 20-L Sphere as there is a total ignition delay of ~0.4 s from the start of dispersion until ignition for the standard test procedure in this study in comparison to ignition delay of ~0.06 s and a reservoir pressure of 20 bar in standard procedure for the Siwek 20-L chamber, resulting in higher level of turbulence. The explosion violence data reported by this work are useful as a relative measure of explosion hazard for comparison of different dusts and not recommended for sizing vents according to standards [1-4] which are based on the higher turbulence level of the Siwek 20-L chamber and the 1 m\textsuperscript{3} chamber. The standard Pittsburgh pulverized coal (PPC) dust used for most of the tests has 80% minus 200 mesh (<75µm) and a mass median particle diameter of 48µm. The measured values for standard pulverized Pittsburgh dust (200 mesh (100%), ignitor 2500 J) are: MEC -80 g/m\textsuperscript{3}, \( P_{\text{max}} \) -6.6 bar a (dP/dt)\textsubscript{max}V\textsuperscript{1/3} -39 bar m/s; and for Pocahontas low volatile coal (86%<75µm, median particle diameter - 27 µm) are: MEC-90 g/m\textsuperscript{3}, \( P_{\text{max}} \) -6.3 bar, (dP/dt). V\textsuperscript{1/3} -32 bar m/s. The optimum dust concentration is ~500 g/m\textsuperscript{3}. At the higher turbulence level recommended in ASTM Standard E 1226 [16] maximum (dP/dt). V\textsuperscript{1/3} data for Pittsburgh coal would be roughly three times higher. The maximum (dP/dt). V\textsuperscript{1/3} data from the present study falls in the range three times the value that reported by USBM study.
CONCLUSION

The explosion violence data - maximum explosion pressure, \( P_{\text{max}} \), maximum rate of pressure rise, \( (dP/dt)_{\text{max}} \), and explosibility index, \( K_{\text{St}} \) data for coals determined with CSIR-CBRI 20-L Sphere reported in this paper may be used in the practical design of various explosion safety measures aimed at suppressing the disastrous effects of explosion e.g. sizing explosion relief venting systems in conjunction with the nomographs published in various standards [1-4] based on the higher turbulence level of the Siwek 20-L Sphere and the 1 m\(^3\) chamber. The specifications of explosion protection systems can be worked out using these data and approved or recognized design methods by those skilled in the art. These data may also be used as elements of an explosion risk assessment as for evaluating the risk of explosion in areas/locations susceptible to have concentrations lower or higher than the optimum dust concentration taking other pertinent factors into account.

As well known, some experimental data presented in this study confirm that higher volatile coals and finer coals are more hazardous. Because of the importance of particle size, it is critical that representative samples of dusts be collected for explosibility evaluation. It is advisable to evolve the experimental values of explosion parameters of the dust in question for incorporation of explosion safety measures as per standard safety regulations.

The data show reasonably good agreement with those from tests for similar size of coals. It has been observed that for coal dust the explosion data are low at very lean concentrations (near the minimum exploisible concentration) but it increases as the dust concentration increases and reaches a maximum and decreases again after reaching a maximum as the dust concentration is further increased. The data on explosion severity together with limiting oxygen concentration and minimum exploisible concentration appear to be sufficient to characterize the protective measures. The only component of protection system design which has been addressed here is explosion severity data. The other parameters studied will be presented in future publications.

NOMENCLATURE

| IE | Ignition energy, J |
| C_{\text{ox}} | Optimum dust concentration, g/m\(^3\) |
| \( K_{\text{St}} \) | Explosibility index, bar.m/s |
| \( P \) | Pressure, bar |
| \( P_{\text{ex}} \) | Maximum explosion pressure for the dust concentration tested, bar |
| \( P_{\text{CI}} \) | Pressure due to chemical ignitors (=1.6(IE/10000)), bar |
| \( P_{\text{max}} \) | Maximum explosion pressure, bar |
| \( P_{\text{m}} \) | Corrected explosion pressure, bar |
| t | Time, s |

### Table 3. Summary of Coal Explosibility Results with 20-L Sphere - Literature Data/CSIR-CBRI Study

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Coal classification</th>
<th>Volatile matter (%)</th>
<th>Moisture (%)</th>
<th>Particle size, ( D_{50} ) (μm)</th>
<th>MEC (g/m(^3))</th>
<th>( P_{\text{ex}} ) (bar)</th>
<th>( P_{\text{m}} ) (bar.m/s)</th>
<th>( K_{\text{st}} ) (bar.m/s)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Morewet brown coal [23]</td>
<td>106</td>
<td>62</td>
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<td>22.9</td>
<td>100</td>
<td>160</td>
<td>162</td>
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<tr>
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<td>22.9</td>
<td>100</td>
<td>160</td>
<td>162</td>
</tr>
<tr>
<td>3</td>
<td>Yallourn dark litho-type coal [23]</td>
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<td>162</td>
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<tr>
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<td>0</td>
<td>22.9</td>
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<tr>
<td>5</td>
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<td>100</td>
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<tr>
<td>6</td>
<td>German lignite/LQM [33]</td>
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<td>0</td>
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<tr>
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<td>0</td>
<td>22.9</td>
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<td>160</td>
<td>162</td>
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<tr>
<td>20</td>
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<td>62</td>
<td>0</td>
<td>22.9</td>
<td>100</td>
<td>160</td>
<td>162</td>
</tr>
</tbody>
</table>

\( D_{50} \) mean particle size - mesh of the sieve dividing the fuel in two equal parts, \( *D_{50} \) mass median diameter, TNO- TNO Pneum Maurits Laboratories (TNO), The Netherlands, LQM- Laboratorio Oficial J.M. Madariaga (LQM), Spain.
REFERENCES


