Dust explosions represent a serious hazard in the food and feed industry. Grain and flour dusts can form explosive clouds and, because, explosions from such clouds have caused some of the worst industrial accidents, it is necessary to draw public attention to this problem. This paper reviews some devastating explosions in flour mills and other facilities in grain handling installations including an incident that took place in a bakery in Turin in 1785 which motivated research in this area; analyzes conditions and causes of dust explosion in flour mills and associated facilities; and discusses explosion preventive and protective measures to avoid many injuries and deaths and material losses. The explosion parameters for wheat flour and rice flour dusts required for identifying the explosion hazards in wheat and rice flour mills and associated units and designing suitable explosion preventive and protective measures determined using CSIR-CBRI 20-L Sphere, Godbert-rice flour dusts required for identifying the explosion hazards in wheat and rice flour mills and associated units and designing suitable explosion preventive and protective measures determined using CSIR-CBRI 20-L Sphere, Godbert-Greenwald Furnace and Hartmann Apparatus are presented for specific samples along with literature data.

**KEY WORDS:** Explosion, Wheat, Rice, Dust

**INTRODUCTION**

Explosions and fires within the grain handling installations in feed and food industry are known hazards and they can have devastating and irreversible effects. Large quantities of agricultural dusts are handled during handling of food grains-wheat, rice, oats, maize, barely, etc., for bulk transport and storage. The grains are ground to fine powder for making food products like flour, cocoa, maltodextrin, cellulose, starch, artificial sweeteners, flavours and cellulose additives, etc. Dust particles from these substances, when heated, volatilize and form explosive gaseous mixtures and can explode violently when ignited in the form of dust cloud. Dust explosions in the feed and food industry have caused serious industrial accidents resulting in severe structural damage, injuries and fatalities.

There are many factors that affect the explosion violence or the sensitivity to ignition of a dust cloud such as particle size, cloud density or moisture content. Explosions can occur within a range of concentrations known as lower and upper explosion limits. The ignition energies also vary with different substances and for similar substances with differing moisture content and particle size. In order to have enough fuel for ignition approximately 25 to 500 g/m³ dust concentration is required which appears as a dense cloud in which a 100-watt light bulb would not be visible from 3 m [1], it may not possible to see one’s hand or arm’s length and it would be difficult to breath. Although such concentrations are not normally expected to be present within processing buildings, explosive dust clouds are regularly formed inside the material handling/ processing equipment i.e. flour mills, silos, bin filling/ emptying, pneumatic conveying or dust collectors in food and feed industry. A dry dust contains less than 5% moisture and the dryer it becomes the effect on ignition sensitivity and explosion violence will increase. Dry dusts of small particle size will be more easily ignited and produce more violent explosions. Moisture within or on the particle surface reduce both the flame propagation ease and rate. However, the moisture content in the range 12-18%, as found in many agricultural products, are not enough to render the dust non-flammable. The explosion data of dusts which form basis for designing various explosion safety measures are therefore sample specific. Research in dust explosion area is a specialized field of activity at CSIR-CBRI, Roorkee, India. A study was undertaken to evaluate the explosion hazard associated with grain handling installations to assess the extent and nature of the explosion problem and basis of designing the explosion safety measures. Experimental work aimed at increasing understanding of the subject was undertaken which covered review of literature data and determination of explosion parameters for range of wheat and rice flours in experimental facilities provided at CSIR-CBRI as per international standards, as wheat and rice are the most important and widely used edible commodities in India. The wheat and paddy, grown in the farm land are transported to the processing mills and industrial units to make desired products. Prior to industrialization, these raw grains used to be continuously processed at household levels or in cottage type units, mostly located in rural area in the vicinity of farm lands. However, at present, there are large number of mills engaged in processing/ milling of wheat and rice and are spread over in almost all states across the country to produce various products. These industries have inherent explosion hazards as wheat and rice which are complex carbohydrate made from glucose molecules chained together retain flammable properties of sugar.

**SOME REPORTED EXPLOSION DISASTERS IN GRAIN HANDLING INSTALLATIONS**

Heavy causality and property damage has occurred in dust explosions throughout the world. In India, information pertaining to dust explosions is almost non-existent solely because in most accidents that occur in India, the broad term 'Explosion' is used and recorded while the type of explosion goes unrecorded. Dust explosions and fires in the feed and food industry tend to be treated as rather private affairs in India and not documented properly. This situation is quite different from the one existing in developed countries where dust explosions are recognized as major industrial hazards and serious attention is paid towards their documentation, analysis, prevention, mitigation and control. As an example, an average of 10.6 agricultural grain dust explosions are reported per year in the U.S.
in 1.6 deaths, 12.6 injuries and millions of dollars in damages [2]. During the period 1970-2010, there have been 600 explosions in grain handling facilities across the United States, which have killed more than 250 people and injured more than 1000 [3]. Some of the catastrophic explosion disasters in mills/ grain handling facilities which triggered, encouraged and led to intense research on flour dust explosions aimed at looking after the causes of explosion and finding solutions to impede future accidents in similar plants, are reported below.

The first documented dust explosion occurred on Dec. 14, 1785 in a flour mill in a Bakery in Turin, Italy [4,5]. It was not the first accidental dust explosion in the history of mankind, but it may well be the first scientifically investigated and documented. The explosion was caused by the ignition of flour dust by a lamp in a bakery storeroom. Boy shoveling flour from one level to another by naked candle light had his face and arms scorched. It blew out the windows and released frames into the street. Another boy saw flames coming across the warehouse and jumped off a scaffold and broke his leg. Fortunately, the explosion did not cause any fatalities. It did lead to the realization that grain dust is a highly explosive substance that must be handled carefully. The accident was reported to be due to the dryness of the corn as there had not been any rain for the last 5-6 months in the Piedmont area.

On May 2, 1878, the Washburn ‘A’ Mill- the largest flour mill in the United States at that time, exploded when flour dust in the air inside it ignited claiming 18 lives, decimating the surrounding area, and bringing instant notoriety to Minneapolis (Figures 1 & 2). The explosion blew the mill’s concrete roof several hundred meters in the air and leveled the seven and a-half storey building. Two nearby mills were flattened by explosion, and city’s business district was destroyed. The tragic explosion led to reforms in the milling industry [6].

A mill exploded at William Primrose and Sons Ltd., Glasgow, UK, on Nov. 10, 1911, killing 5 people. Their grinding process was very dusty and had no dust collection system [7]. An explosion in the top floor of a silo building at J Bibby and Sons in Liverpool, UK in 1930, killed 11 and injured 32 people. Rice flour, sunflower seeds and soya bean meal were used in processes. Self heating of the sunflower seedcake seems to have been the cause of an initial fire, but the heat spread between silos, and initiated an explosion, when hanging dust fell, while an adjacent silo was being emptied [7].

An explosion in starch/ corn plant at Cedar Rapids, Iowa, USA, in 1919 killed 43 people and one at a similar plant in Pekin, Illinois, USA in 1924 resulted in 42 deaths [5]. Explosion at a large export grain silo plant in Corpus, Christi, TX., USA, in April 1981 resulted in nine fatalities, 30 injuries and more than 30 million dollars damage. The suspected cause of the explosion was thought to be smouldering lumps of milo grain which ignited a dust cloud in a bucket elevator [8]. A grain dust explosion in Wichita, Kansas, USA, on June 8, 1998, caused extensive damage to a half-mile-long grain elevator facility [9].

A few other explosions worth reporting here are: IL Flour Mill Explosion, March 1893 at Litchfield,UK, destroyed 40 homes and 2 blocks of local businesses, 24 million dollars damage; IA Flourmill Explosion at Davenport, UK, May 1975, killed 2 workers, caused windows to shatter 18 to 20 blocks away; LA Grain Elevator Explosion at Westwego, Louisiana, UK, in Dec. 1977, killed 36 people; and Illinois Flour Mill Silos explosion, Chester, USA, April 2010, injured 3, shook homes for miles around [3]

The past information on explosion accidents indicates that most frequent locations of primary explosions are bucket elevators, storage bins, hammer mills, dust collectors and other enclosed equipments where explosions often initiate. Most of the explosions are in grain elevators, feed mills, corn processors, flour mills and rice mills. Out of 106 reported grain dust explosions during 1988-2005, 51 were in grain elevators, and 34 were in grain milling facilities (wheat, corn, oat and rice) [2]. Most probable ignition sources identified in past explosions are welding and cutting operations, fires, overhead bearings, and electronic failures.

Apparently in India, most of the food grain processing happens in comparatively open environment and the concentration of grain dust in air does not reach the conditions required for explosion which is called minimum exploisible concentration. However, explosion hazards in flour mills and associated units can not be avoided and require systematic evaluation.
EXPLOSION HAZARD ASSESSMENT AND SAFETY MEASURES
To prevent the plant becoming the next reported or unreported subject of dust explosion or fire, it is desirable to conduct audit of a grain handling installation which begins with a hazard identification exercise based on experience of the assessor, published standards and guidelines [10-16]. A systematic approach to identifying dust explosion hazards and taking measures to ensure safety involves:

- Determining the dust cloud’s ignition sensitivity and explosion severity characteristics based on published information/data or through appropriate laboratory tests on representative dust samples.
- Identifying areas of the facility where combustible dust cloud atmospheres could exist under normal and/or abnormal conditions.
- Identifying potential ignition sources that could exist under normal and/or abnormal conditions.
- Preventing the formation of explosible dust clouds in the plant and reducing the extent and duration of any clouds that may be formed.
- Taking measures to eliminate/control ignition sources.
- Taking measures to protect against consequences of dust explosions.

Explosion preventive and protective measures are generally required in all areas/units of the grain handling installations, where flammable dust clouds can exist. Explosion protection measures include explosion relief venting, explosion suppression, and explosion containment and explosion isolation. Where practical, application of inert gas to prevent the combustion process may be considered. The probable ignition sources and dust explosion data – Minimum Explosible Concentration (MEC), Minimum Ignition Temperature (MIT), Minimum Ignition Energy (MIE), explosion violence characteristics (maximum explosion pressure, $P_{\text{max}}$ and dust deflagration index, $K_{\text{St}}$) and Limiting Oxygen Concentration (LOC) – regarded as essential safety critical information for designing explosion safety measures are summarized in Table 1.

Table 1. Data and Test Required for Compliance of Safety Standards

<table>
<thead>
<tr>
<th>Ignition Source for Dust Cloud Ignition</th>
<th>Property/Test</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot surface</td>
<td>MIT for dust clouds</td>
<td>Specifying equipment surface temperature limits, including safety margin.</td>
</tr>
<tr>
<td>Electrostatic spark</td>
<td>MIE</td>
<td>Predicts the ease and likelihood of ignition of a dispersed dust cloud. Influences the choice of plant materials (conductors/ non-conductors), earthing, bonding and personnel antistatic precautions.</td>
</tr>
<tr>
<td>Dust control</td>
<td>MEC</td>
<td>Measures the minimum amount of dust dispersed in air required to spread an explosion. Operating plant with low level of dust present.</td>
</tr>
<tr>
<td>Oxygen control</td>
<td>LOC</td>
<td>Operating plant under an inert gas nitrogen. An operational safety margin is required, based upon the inert gas control system and plant layout.</td>
</tr>
</tbody>
</table>

Explosion Prevention

<table>
<thead>
<tr>
<th>Ignition Source for Dust Cloud Ignition</th>
<th>Property/Test</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explosion venting</td>
<td>Explosion indices- $K_{\text{St}}$ and $P_{\text{max}}$</td>
<td>Design and verification of adequacy of vent design for the material being handled.</td>
</tr>
<tr>
<td>Explosion suppression</td>
<td>Explosion indices- $K_{\text{St}}$ and $P_{\text{max}}$</td>
<td>Design and verification of adequacy of suppression design for the materials being handled.</td>
</tr>
<tr>
<td>Explosion containment</td>
<td>Explosion indices- $K_{\text{St}}$ and $P_{\text{max}}$</td>
<td>Verification of adequacy of explosion containment and explosion isolation design for the materials being handled.</td>
</tr>
</tbody>
</table>

Managing changes to new equipment, new processes and additional raw materials that may be combustible, administrative controls such as training and educating employees and monitoring processes, cleaning practices, work area inspections and dust accumulation, etc., are required to be considered. As identified by past accidents, the hazard analysis exercise also indicates that all equipment and areas like bucket elevators, grain bins, dust collectors, flour mills, flour rooms, flour silos and air conveyance systems tend to have the higher dust concentrations in grain handling installation and may lead to explosions in presence of ignition source of sufficient intensity. A primary explosion originating in equipment causes other static dust which typically comes from the overhead structures, other equipment, false ceilings, walls, floors, etc., to become airborne and the primary explosion becomes the source of ignition for the secondary and more destructive explosion. Good housekeeping and proper facility design is important. Application of safety measures in different areas described below will assist to operate process plant suitable for whole grains such as wheat, rice, oats, maize, barely, etc. and all exploisible flours, safely and to meet the requirements of standards [10-16].

Storage and Handling
The grain handling plant is desired to be located in the open air or in strong steel framed building with lightweight panel walls, so that the roof and wall cladding panels can if necessary lift and act as explosion relief. Within older brick/stone built premises, maximum possible area of explosion relief is provided so as is reasonably practicable based on standards depending on explosion characteristics of material handled. To prevent injury from flying debris relief panels need to be displaced to a safe place or adequately tied. Joints and leakage points around flour handling systems are to be sealed to prevent escape and
accumulation of dust in the building and onto surrounding plant items. Cleanliness is required using fully earthed, centralized pipes vacuum cleaning system. Use of sweeping brushes and compressed air is not recommended. Slight negative pressure on storage vessels such as bins and silos by use of extraction systems is desired. Adequate arrangements for separating powder from its transporting air (e.g. cyclones and bag filters) when pneumatic systems are used are to be provided.

Silos or bins are fitted with explosion relief vented to an unoccupied place safely, preferably outside the building. The venting system is designed to an acceptable standard [13,15] based on explosion parameters of flour handled. Dust collecting silos are provided with appropriately designed explosion relief and rotary valves at the base to act as an explosion choke. Open bag dust collecting filter units fitted with explosion relief are desired to be totally enclosed. Use of effective permit-to-work systems to control hot work is required for welding. All explosion relief vents are to be equipped with index switches to close down the plant in the event of explosion relief being activated to prevent the downward transmission of burning material.

**Solid Processing - Grinding, Bulk Tank Deliveries and Fabric Silo**

Grinding operation in mills is the first point of danger in processing grains as grain is ground into the fine particles of dust-like size, and flammable concentrations cannot be avoided. Two types of wheat flour milling processes- dry and wet are in use. The dry type wheat flour making process comprises of two sections- cleaning and milling. In cleaning section wheat is thoroughly cleaned to remove all impurities including the dust adhered to the surface of wheat grain. Small pieces of sticks, stones, sand, straw etc, are removed by scouring. It is passed through magnetic separator for separation of iron particles. Aspiration system is used as a cleaning means as air currents act as a vacuum to remove dust and lighter impurities. De-stoner is used to remove heavier particles like stone. Then wheat is conditioned by dampening. Conditioned wheat is stored in a silo for 24 hours and then sent to milling section. The wet type flour mills comprise of a cleaning section, washing section and milling section. The processes in the cleaning and milling sections are similar to that in dry type mills. In washing section, the cleaned wheat is washed with water and dampened prior to milling. Grinding is 24 hrs continuously running process in large capacity installations wherein finished products such as wheat flour (maida, soooji, atta, dalia, etc.) are produced. Mills of any type (wheat, rice, oats, maize, barely, etc.) are subject to additional dust explosion hazards in comparison to that in grain elevators in some accidents reported above, because of actual grinding of grain. Usually, a hammer or roller mill is used for grinding, where explosions can occur for two reasons - ingestion of tramp metal or stones can produce sparks sufficient to ignite the ground material or the moving parts of the mill can break and produce spark. Even if such events do not cause an explosion in the mill, they can ignite the ground material which is transported to a point where a primary explosion can occur.

Although feed mills, flour mills, and grain elevators differ substantially from one another, they share, in varying degrees, the same dust explosion hazard. The emphasis for hazard reduction in each type of facility is therefore on dust control and it is recommended that the hammer mills, other grinding equipment, and their dust collection systems be isolated physically and pneumatically from the main facility and should be outside the structure containing the general work area.

Feed stocks are now very commonly treated by screening, de-stoning, pneumatic separation and magnets to remove foreign bodies to prevent impact sparks from milling operations. Hammer mills are often engineered to be strong enough to contain a dust explosion, but sparks or smoldering particles may spread from mill to other more vulnerable equipment. Associated cyclone/ dust collector units are not as strongly constructed and should be equipped with explosion relief and a rotary valve at the discharge. Some fires and minor explosions have occurred involving the pneumatic blower unit on the discharging vehicle. Product may enter the blower fan causing frictional heat or blinding of clean air intake filter or both, resulting in ignition of filter material. Non-return valves downstream of the blower may be ineffective, particularly if the driver switches off the blower and relies on residual pressure within the bulk tank to discharge the last of the product. This may cause product to enter the blower.

The main fire and explosion risk is involved in an external fire resulting in melting and burning of the fabric of silos used for storage of flour and the release of large quantities of flour which could form an explosible dust cloud. Where open-air location is not practicable, preferably the silo is to be sited in a room that has adequate fire separation from the remaining premises and is itself fitted with explosion relief.

Further processing in most cases involves treatment with water in some form either liquid or steam. The explosion hazard at this point is remote except for one factor. Material that escapes from the processing equipment settles on floors, walls, beams, etc., and, if not removed, eventually dries to form a dangerous layer of dust and potentially an explosion hazard. Operations such as flour production that do not involve wet process are extremely hazardous.

**Pneumatic Conveying Systems**

After the grinding operation the material is usually moved to the next processing point by pneumatic conveyors similar to those used in dust collecting systems. These systems are often equipped with under and over pressure sensors to close down the system. An under pressure would occur downstream of any substantial leak which developed. An overpressure would be caused if someone tried to overfill a receiving vessel. To prevent discharges due to static electricity all metalwork of powder handling systems, including delivery tankers, should be electrically bonded together and earthed. Ducting and pipe work should be electrically conductive.

Because of the prevalent use of pneumatic conveyance in mills, suppression devices assume an important role in explosion prevention and systems.
involving pneumatic conveying of large amount of explosive dusts in high concentrations should always be protected using these and relevant standards must be referred.

**EXPERIMENTAL STUDIES ON EXPLOSION DATA OF WHEAT & RICE FLOUR DUSTS AT CSIR-CBRI**

Design of explosion safety measures requires information on explosion parameters of dusts under the conditions prevailing in a plant. In spite of the long term awareness of dust explosion hazard in food and feed industry, until the late 1980s relatively little had been published on the explosibility properties of flours. The data which was in the public arena was generic and unspecific both in terms of substance and test methodology. However, some studies have been conducted using relevant experimental facilities during past three decades and there exist some data in literature for wheat and rice flours (Table 2) which are for specific samples and very important variations can be found from different information sources [4,12,17-21]. This is due to the strong dependence of the explosibility parameters on physical and chemical properties of the product particularly, moisture content and particle size. Various explosion parameters required for designing fire and explosion safety measures were experimentally determined for wheat and rice flours covering the range of particle sizes that may be found in the grain handling mills. Samples of sizes 147, 74 and 38 µm were prepared for both the flours by screen analysis. Nominal size of particles was considered to be that of screen opening they passed through, to be retained by next smaller mesh. The explosion parameters MEC, MIE, MIT, P_{max} & K_{50}, and LOC were determined for all the samples in experimental set-ups established at CSIR-CBRI [22, 23].

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Dust</th>
<th>Moisture, %</th>
<th>Median Particle Size, µm</th>
<th>MEC, g/m³</th>
<th>MIT, °C</th>
<th>MIE, ml</th>
<th>P_{max}, bar</th>
<th>K_{50}, bar·m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wheat flour [4]</td>
<td>50</td>
<td>57</td>
<td>60</td>
<td>560</td>
<td>420</td>
<td>8.3</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>Rice flour [4]</td>
<td>&lt;63</td>
<td>60</td>
<td>360</td>
<td>&gt;100</td>
<td>7.4</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Wheat flour [12]</td>
<td>12.9</td>
<td>65</td>
<td>74</td>
<td>200</td>
<td>9.0</td>
<td>139</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rice flour [12]</td>
<td>60</td>
<td>74</td>
<td>9.0</td>
<td>60</td>
<td>7.4</td>
<td>57</td>
<td></td>
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<tr>
<td>3</td>
<td>Fine wheat flour [17]</td>
<td>8</td>
<td>52.7</td>
<td>70-80</td>
<td>420</td>
<td>30-60</td>
<td>6.8</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>Super wheat flour [17]</td>
<td>6.8</td>
<td>55.2</td>
<td>80-90</td>
<td>420</td>
<td>30-45</td>
<td>6.3</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>Rice flour [17]</td>
<td>8.2</td>
<td>58.2</td>
<td>50-60</td>
<td>400</td>
<td>27-35</td>
<td>7.8</td>
<td>72</td>
</tr>
<tr>
<td>4</td>
<td>Wheat flour [18]</td>
<td>No.0222</td>
<td>30</td>
<td>125</td>
<td>480</td>
<td>&gt;300</td>
<td>8.8</td>
<td>70</td>
</tr>
<tr>
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<td>No.0223</td>
<td>43</td>
<td></td>
<td></td>
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<td>7.0</td>
<td>31</td>
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<td>7.4</td>
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<td>Rice flour [18]</td>
<td>No.3130</td>
<td>105</td>
<td>60</td>
<td>370</td>
<td>&gt;100</td>
<td>6.7</td>
<td>40</td>
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<td></td>
<td>No.2066</td>
<td>85</td>
<td>60</td>
<td>360</td>
<td>&gt;100</td>
<td>7.4</td>
<td>57</td>
<td></td>
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<tr>
<td></td>
<td>No.3359</td>
<td>&lt;63</td>
<td>380</td>
<td></td>
<td></td>
<td>6.7</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Wheat flour [20]</td>
<td>71</td>
<td>400</td>
<td></td>
<td></td>
<td>9.7</td>
<td>63</td>
<td></td>
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<tr>
<td>7</td>
<td>Wheat flour [21]</td>
<td>C_{f}=250g/m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.6</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>C_{p}=500g/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.1</td>
<td>153</td>
</tr>
</tbody>
</table>

**Experimental Techniques**

The MEC, P_{max} & K_{50}, and LOC were determined in 20-L chamber which is a hollow sphere made of steel. The permissible working pressure for the sphere is 30 bar. 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 Figure 3. 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. Ignition source installation system was designed to accommodate different types of ignition sources viz. spark discharge and pyrotechnic ignitor.
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. 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. 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 pyrotechnic ignitors (10 kJ for explosion violence and 2 kJ for MEC experiments and 2.5 kJ for LOC experiments) 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 apparatus consists of oxygen measuring system and a system to create inert gas/air mixture.

The experiments for explosion violence determination are conducted over a wide range of dust concentration. As per standard procedure [24-26] 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, P_ex, 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)_max or P_max 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 P_max and (dP/dt)_max the means from maximum values of each series are taken. K_St 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 Figure 4. 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). P_ex is the maximum explosion pressure (above the pressure in the vessel at the time of ignition). The value of P_ex, 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. P_max is the maximum pressure (above pressure in the vessel at the time of ignition) and (dP/dt)_max 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 P_max and (dP/dt)_max are the averages of the highest values (over the range of dust concentrations). The explosibility dust constant, K_St, characterizes the explosibility of the material. K_St 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 [27]:

\[
K_{St} = \left( \frac{dP}{dt} \right)_{max} V^{1/3} \]

Where,
- P - Pressure, bar
- T - Time, s
- V - Vessel volume, m³
- K_St- Dust deflagration index, bar.m/s
- (dP/dt)_max values rounded to the nearest integer are used.
- The dust are classified as St 0 (non-explosive) for K_St < 200-300 bar.m/s; St 1 (explosive) for K_St = 0-200 bar.m/s; St 2 (strongly explosive) for K_St = 200-300 bar.m/s; and St 3 (extremely explosive) for K_St > 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 and VDI guidelines [25,13]. Because of the cooling effect from the walls of the 20-L sphere, the values for P_ex >5.5 bar are slightly lower than in the 1m³ vessel. To obtain results equivalent to 1 m³ vessel, this P_ex value may be corrected using equation 2 based on numerous correlation tests between 1 m³ vessel and 20-L Sphere [26]:

\[
P_{ex} = 0.775P_{max}^{1.15} \]

Where,
- P_{ex} - Corrected explosion pressure, bar
- P_max - 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 ignitors 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 $P_{ex} < 5.5$ bar. During a dust deflagration, with rising $P_{ex}$, the influence of the pyrotechnic igniters will be minimized by the pressure effect of the deflagration itself. The equation used for this correction is given below [26]:

$$P_x = \frac{5.5xP_{ex} - P_{ci}}{5.5} \text{ bar} \quad (3)$$

Where,
- $P_x$ - Corrected explosion pressure, bar
- $P_{ex}$ - Pressure due to chemical igniters = $1.6(IE/10000)$, bar
- $IE$ - Ignition energy, J

The experiments for determining MEC were carried out in 20-L Sphere as per standard procedure [28, 29]. A test series is undertaken with a systematic decrease of the dust concentration until no ignition of the dust/air mixture is observed. An ignition is deemed to have occurred if the maximum explosion pressure is at or above 0.5 bar. The final test is repeated to ensure no ignition is found in three consecutive tests and confirm the minimum exploisable concentration has been reached.

The LOC was determined in 20-L Sphere by experiments conducted at various oxygen levels over a wide range of dust concentration as per standard procedure [30]. The experiments are started with an oxygen concentration of 21% to determine the most severe explosion and for measurement of explosion data at ambient conditions. Further tests are carried out at reduced oxygen concentrations for which 20-L Sphere is filled with an air/inert gas (nitrogen in the present study) mixture of the desired $O_2$ concentration measured using an oxygen analyzer. The gas storage chamber for dust dispersion is pressurized to desired pressure with air/inert gas mixture having the same $O_2$ concentration as in 20-L Sphere. The oxygen concentration is lowered in steps of 3% initially and 1% when it came closer to LOC. At the commencement of dust dispersion the pressure in 20-L chamber is atmospheric. The pressure-time data for each test is recorded as a function of time. An ignition/explosion of dust is considered to have taken place, when the measured overpressure (influence of chemical igniters included) relative to the initial pressure $P_i$ is $\geq 0.5$ bar ($P_{ex} \geq (P_i + 0.5 \text{ bar})$). From pressure-time curve the explosion pressure, $P_{ex}$, and rate of explosion pressure rise, $(dP/dt)_{ex}$, can be determined for each dust concentration as for explosion violence determination tests. Optimum dust concentration, $C_{ex}$, at which the highest explosion pressure occurs at any given $O_2$ concentration, is determined. Maximum explosion pressures, $P_{max}$, and maximum rate of pressure rise, $(dP/dt)_{max}$, are determined by varying the dust concentrations at various oxygen levels. By increasing step by step the ratio of inert gas to air and varying the dust concentration, the oxygen concentration is reduced to a level at which explosions no longer occur at any dust concentration. Step changes in the oxygen concentration are made in multiples of 1% V/V at reduced oxygen levels. The highest oxygen concentration where no ignition occurs in three consecutive tests is reported as the LOC. The difference between the highest oxygen concentration, at which dust explosion no longer occur for any dust concentration and the lowest $O_2$ concentration that gives explosion should not exceed 1% V/V.

Experiments were carried out for both the flours for measuring explosion violence data, MEC and LOC as per procedure described above. Each experiment was repeated thrice. For calculating $P_{max}$ and $(dP/dt)_{max}$, the means from the maximum values of each series are taken. Data were collected as shown in Figure 4. 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 used to predict various parameters as explained. The results are presented in next section.

The MIT tests were conducted in the Godbert-Greenwald Furnace which consists of a vertical cylinder, the inside of which is electrically heated at a certain temperature, where the dispersion of dust-air cloud is produced and appearance of flame makes ignition evidence at fixed temperature; and MIE was measured by means of a high voltage capacitor discharge required to ignite the dust cloud at atmospheric pressure and room temperature in Hartmann Apparatus in accordance with standard procedure [22] for all the samples of wheat and rice flours.

**RESULTS & DISCUSSIONS**

For measuring explosion violence, the experimental pressure-time curves similar to Figure 4 were recorded for the dust concentrations for wheat and rice flour dusts during many series of experiments conducted for concentration ranges 50-1500 g/m$^3$ for particle sizes 147, 74 and 38 µm and moisture contents ~12 and 3%. Each experiment was repeated thrice. The experimental curves were analysed and values of $P_{ex}$, $(dP/dt)_{ex}$ and $(dP/dt)_{ex}V^{1/3}$ were estimated for each experiment. Correction for effect of vessel size for $P_{max} > 5.5$ bar is done using equation (2) and that of ignitor for $P_{max} < 5.5$ bar is done using equation (3). The detailed experimental results for explosion violence data, MEC and LOC are presented here for ~3% moisture content. Similar detailed data were obtained for other sizes.
Experiments were started with an initial dust concentration 250 g/m$^3$. The dust concentration was increased by 250 g/m$^3$ 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 for particle size 74 µm (~3 % moisture) are presented in Figure 5 for both theflours. The lower portion of the graph shows the maximum absolute explosion pressure, $P_{\text{ex}}$, plotted against dust concentration. The top portion shows the maximum rate of pressure rise, normalized by the cube root of chamber volume ($dP/dt \cdot V^{1/3}$) i.e. $K_{\text{St}}$. The maximum values of $K_{\text{St}}$ are 150 bar.m/s for wheat flour and 82 bar.m/s for rice flour. The maximum explosion pressures are 8.6 bar for wheat flour and 7.5 bar for rice flour. The maximum explosion data occurs at a dust concentration 750 g/m$^3$ for both the flours.

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 Figure 6 for wheat and rice flour dusts, which confirms the optimum dust concentrations for both the flours as 750 g/m$^3$ and maximum values of explosion data as indicated above.

For determining minimum explosible concentration experiments were conducted for low levels of dust concentrations 200, 150, 100, 90, 80, 70, 60 and 50 g/m$^3$. Explosions for 74 µm particle size (~3% moisture) could be observed upto a dust concentration 90 g/m$^3$ for both the flours. These dust concentrations are equal to the minimum explosible concentrations (MEC). The estimated $P_{\text{ex}}$ and $(dP/dt)_{\text{ex}} \cdot V^{1/3}$ for these experiments are presented in Figure 7. 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 MEC values 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 $P_{\text{ex}}$ and $(dP/dt)_{\text{ex}}$ 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 flour dust concentration. However there is minimal effect on explosibility data until the stoichiometric concentration is reached. The explosion severity peaks at a dust concentration ($C_{\text{ex}}$) of 750 g/m$^3$. The process of reduced devolatilization continues with further increase of dust concentration. At dust concentration above $C_{\text{ex}}$ 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.

It is clearly established from the literature that explosibility increases as the dust particle size and moisture content decreases. The explosion violence data for other sizes- 147 and 38 µm of flours were also investigated as the particle size is very important in understanding the explosion hazard and obtaining data for the hazardous industrial situations. The moisture content was ~12% and ~3% in all the three sizes of wheat flour and rice flour. All the series of experiments were conducted for these samples. The final resultant values of explosion data are given in Table 3.

The experimental results indicate that as particle size is reduced from 147 to 38 µm, the $K_{\text{St}}$ value increased from 90 to 158 bar.m/s for wheat flour and 52 to 96 bar.m/s for rice flour, for moisture content ~3%.
Thus for both the dusts the reduction in particle size changes the dust explosion severity which in turn changes the design of explosion safety measures. The MEC increases with increase in particle diameter. This behaviour may be explained by the fact that for wheat and rice flour 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.

Systematic experiments were conducted to determine LOC for all the samples of wheat and rice flours to study the effect of reduced oxygen on explosion violence data at oxygen levels 21, 18, 15, 12, 9, and 6% for dust concentrations- 80, 90, 100, 125, 250, 500, 750, 1000 g/m$^3$ using 2.5 kJ ignition energy. As explosions were recorded at 9% oxygen and there was no explosion at 6% oxygen, further experiments were conducted at 7% and 8% oxygen levels. Each experiment was repeated thrice. The experimental curves were analysed and values of $P_{ex}$ and $(dP/dt)_{ex}$ were estimated for each experiment. $P_{max}$ and $(dP/dt)_{max}$ and $K_{St}$ were determined at each oxygen concentration. The resultant LOC values for all the samples are given in Table 3.

The experimental results showing the variation of maximum explosion pressure with dust concentration ($P_{ex}$) for each oxygen level are presented in Figures 8 & 9 for wheat flour and rice flour for 74 µm (~3% moisture).

Figure 10 shows the influence of reduced oxygen levels on maximum explosion pressure ($P_{max}$) and dust deflagration constant, $K_{St}$. Explosible behaviour was observed for oxygen concentrations down to 9% for both the flours. The maximum explosion pressure varied between 2.4 and 8.6 bar for wheat flour and 2.4 and 7.5 for rice flour when oxygen concentration was increased from 9 to 21%. The LOC value is 8% for both the flours. Similar experiments were conducted for LOC determination for other samples and it has been observed that dust particle size has a comparatively small influence on the limiting oxygen concentration and LOC was found to vary from 8 to 9%. No effect of moisture could be observed on LOC values.
The experiments were conducted for determining MIT and MIE for particle sizes 147, 74 and 38 µm for moisture contents ~ 12 and 3 %. The resultant experimental values of these parameters are summarized in Table 3 along with MEC, explosion violence data and LOC values. The details of these experiments will be covered in a separate publication.

The data presented above are in reasonably good agreement with those of other researchers [4,12,17-21] for wheat and rice flours, and present a systematic investigation over a wider range of particle size and moisture content. Comparison of \( P_{\text{max}} \) and \( K_{\text{St}} \) values for wheat and rice flour for some literature data (Table 2) and those from present study (Table 3) is shown in Figure 11. In cases where the explosion data for more than one sample of wheat/rice flour are reported in published work, maximum value has been presented in Figure 11. Comparable results should in principle be obtained by all laboratories when using the standard 20 litre procedures. The variation of the \( K_{\text{St}} \) values obtained by the laboratories reflects the difficult nature of the flours 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. The \( K_{\text{St}} \) values for the various flour samples were generally higher than previously published research and confirmed that values substantially above 100 are possible for finer particle sizes. The \( P_{\text{max}} \) and \( K_{\text{St}} \) data from present study show systematic increase of explosion violence with decreasing particle size and moisture content for both the flours. A study conducted by NABIN,UK [31] is worth mentioning here wherein explosive properties for a range of wheat-related dusts (a white bread making flour, chorleywood bread making flour, biscuit flour, heat-treated cake flour, whole meal, gluten, dust collector stock, wheat feed, wheat dust, screen room filter dust) as received as well as sieved (wheat feed) to 8.8 bar (wheat and screenroom filter dust) were recorded in excess of 1000 mJ for samples with moisture, 79 for wheatfeed (as received), 105 for rice flour have varying degree of explosion severity which increases as the particle size and moisture content decreases. The temperature of the surface; should not exceed two-thirds of the MIT value.

The minimum explosible concentration ranged from 60 to 200 g/m³ which confirms that a high density cloud is required for there to be significant risk of dust explosion.

**CONCLUSIONS**

The information and experimental data presented above demonstrate that the potential for dust explosion is present in all flour mills and associated facilities and given the appropriate circumstances, explosion can and will occur. Wheat flour and rice flour dusts have been found to have much wider range of values of explosion characteristics depending upon their particle size and moisture content. The data presented may be used by industries handling similar flours for providing adequate explosion safety measures and verifying the efficacy of existing safety measures. The values of \( P_{\text{max}} \) and \( K_{\text{St}} \) are of most concern for designing explosion safety measures specifically to silo, milling and other equipment manufacturers. Grain handling industries should be vigilant to the explosion problem and consider what is required to prevent explosion and ensure that the supplier of equipment installed in their plant are using the correct formulae and explosion data to calculate the strength of equipment needed or designing other explosion safety measures. The industries where uncommon processes for example producing very dry flours- are used, it may be required to conduct more experiments to examine whether there is any additional hazard. Also milling industries may use some ingredients dusts which were not tested in the research; industries should seek information on explosibility of these ingredients from their suppliers. It is essential that material characteristics be examined and explosion data used accordingly.

Industries should assess explosion risk systematically and ensure that the proper management procedures are in place. Priorities should be – avoidance of dust clouds, elimination of ignition sources, containment, suppression and venting.
Greatest care should be given to those areas or processes with a higher measurable risk, i.e. drying, filter stocks, bin filling. Good housekeeping within a milling plant are essential for reduction of explosion risk. Elimination of ignition sources should include consideration of – mechanical friction, hot work (e.g. welding), grinding, electrical discharge, smoking, lighting and electrical equipment, spontaneous combustion, risk of fire. Training and provision of information and instruction to all staff are valuable components of an explosion prevention strategy, preventing ignorance from contributing to an accident.

Although technology for protecting personnel and property from dust explosions have developed significantly since investigation of the flour dust explosion that occurred in a bakery in Turin in 1785, severe losses still occur during handling of grain, food and feed products. Current standards and guidelines for explosion protection are reasonably well developed, but there is still a need for improved methodologies, particularly for design of relatively complex geometries: grain elevators, pneumatic conveying systems, large silo complexes, etc.

**NOMENCLATURE**

- IE - Ignition energy, J
- C_d - Dust concentration, g/m^3
- C_{o_d} - Optimum dust concentration, g/m^3
- K_d - Dust deflagration index, bar/m/s
- P - Pressure, bar
- P_{max} - Maximum explosion pressure for the dust concentration tested, bar
- P_{d temptation} - Pressure due to chemical ignitors (=1.6(IE/10000)), bar
- P_{max} - Maximum explosion pressure, bar
- P_{ex} - Corrected explosion pressure, bar
- t - Time, s
- V - Vessel volume, m^3

**REFERENCES**