AN EXPERIMENTAL INVESTIGATION INTO THE DUST EXPLOSION OF BULK SOLIDS

A

THESIS

Submitted in partial fulfillment of the requirement for the award of degree of

MASTER OF ENGINEERING

IN

THERMAL ENGINEERING

Submitted by

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Declaration

I hereby certify that the work which is being presented in on the topic "An experimental investigation into the dust explosion of bulk solids", in partial fulfillment of the requirements for the award of degree of Master of Engineering in Thermal engineering submitted in Mechanical Engineering Department of Thapar University, Patiala, is an authentic record of my work carried out under the supervision of Dr. S.S. Mallick and Dr. Sanghamitra Barman.

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ABSTRACT

This paper presents an experiment investigation on dust explosion. Dust is common in process industries that manufacture, store and handle particulate material. More than 70% of dusts processed in industries are combustible. Dust explosion regularly occurs in process industries, cause serious industry damages and live loss. Dust explosion was found in literature since 1785 and the records are available from the early 20th century. Lot of experiments were done to control explosions occurring in coal mines and other processing industries but still explosions are occurring in different countries due to different dusts, these accidents disclose that there are still some technical problems unsolved. Industrial technology in India is similar to developed countries but information relevant to dust explosion occurring in India is almost negligible because in most accidents that occurs in India the broad term explosion is used and recorded while the type of explosion goes unpublicized. It is impossible to eliminate dust explosion but it can be reduced by using different methods. Dust explosion can be prevented if technical safety parameters of dust are known. Characteristics of bulk solids depend upon environmental conditions. Indian dusts are different from dusts of other countries in terms of moisture content, ash content, minerals etc. It is observed that lot of work has been done in other countries on dust explosion characteristics but a limited work has been reported on Indian dusts explosion characteristics. So it has been decided to investigate the dust explosion characteristics of Indian dust. In this study characteristic of wheat husk, wood dust and coal dust such as P_{max}, T_{max}, minimum and maximum concentration required for explosion has been calculated. Characteristics for wheat husk, wood dust has been calculated for particle size less than 300 µm, coal dust characteristics are calculated for particle size less than 53µm and at105 µm, in 5000 cm^3 container. Further, empirical model for explosion pressure has been developed.

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NOTATIONS

P **:** Pressure

T **:** Temperature (K)

ρ_o **:** Particle density

ρ **:** Concentration of dust /m^3

μ **:** Viscosity of fluid

d_p **:** Diameter of dust particle

C_p **:** Specific heat of fluid

R_e **:** Reynolds number

W_{fo} **:** Particle settling velocity

g **:** Acceleration due to gravity

LEL **:** Lower explosive limit

MEL **:** Maximum explosive limit

MIT **:** Minimum ignition energy

max **:** Maximum

min **:** Minimum

CHAPTER 1: INTRODUCTION AND OBJECTIVES

1.1 Introduction

Dust explosions were found in literature since 1785 [1]. In Europe coal milling was an important industry and explosions due to coal dust were recognized earlier but in starting scientists did not accept this. It was found in 1803 that coal dust in passageways had burned and cause flame as well as violence of coal mine. In 1800s many more statements shows explosions because of coal dust even though there was no fire damp. A dust explosion crops up by rapid combustion of fine combustible particulars in air. Due to this there is liberation of gaseous products with huge pressure rise; this pressure rise will destruct plant, property and lives of people. Smaller will be the particle size, more fast and explosive burning will take place, till a stage is reached when particles are too much fine and they join to form nugget (smaller particle form bigger). The ignited combustible dust cloud would only cause a flash fire if dust cloud is unconfined, but if the ignited dust cloud is confined the gases released (heat generated) by combustion of cloud may result in rapid development of pressure and results to explosion. Explosion violence not only depends upon degree of subdivisions (finer particle size), it also depends upon energy released per unit confinement area. In some situations the destructive explosion also occurs even when cloud is not confined. Conditions required for a dust explosion to occur are presence of oxidant, combustible dust cloud, presence of oxygen, confinement area and an ignition source to trigger dust cloud. The oxygen required for the explosion is supplied by air.

The flame or spark that trigged a dust explosion can be produced by blowtorch, static electricity, electric spark, friction or any open flame. Dust composed of sugar, cotton, coal, flour, starch, grain, combustible metallic dust or other organic materials, which are highly explosive. Certain metallic dusts like magnesium, aluminum dust are also explosive. 70% of working dusts in industries are combustible [1]. Grain elevators, size reducer, packing dust, conveying—manual or mechanical cyclones, electrostatic precipitator, settling chambers, classifying operations mixing and blending operation storage, filter scrubbers, bag unloading stations, unloaders are mainly subject to dust explosions (where there is a chance of dust collection there will be a chance of dust explosion). Dust explosion is effected by particle size (finer the particle size more chances of explosion)**,** dust concentration (between LEL and MEL)**,** oxidant concentration (more percentage of oxidant or gases more will be possibility of explosion)**,** Ignition temperature**,** turbulence of dust cloud, admixed inert dust concentration**.**

Dust explosion is subdivided into two parts, primary dust explosion and secondary dust explosions. Primary dust explosion occur inside confined area such as silo, hopper etc. These are generally controlled by pressure relief ducts. Secondary dust explosions are initiated by primary explosion. When waves of primary dust explosion move, they will disturb the settling dust layer and form another dust cloud that will explode. It is not possible to eliminate the explosions, but there are certain methods to prevent the dust explosions. These are eliminated by ignition sources, using pressure relief vent holes, inerting the dust, static electrification of powder during pneumatic transport, magnetize surfactants etc. It is also possible to prevent dust explosion if characteristics of dust like minimum ignition energy required for explosion, minimum and maximum dust concentration required for explosion is known. Characteristics of bulk solids depend upon environmental conditions. Indian dusts are different from dusts of other countries in terms of moisture content, ash content, minerals etc. It is observed that lot of work has been done in other countries on dust explosion characteristics but a limited work has been reported on Indian dusts explosion characteristics. So it has been decided to investigate the dust explosion characteristics of Indian dust.

1.2 Objectives

While going through the literature it is found that dust explosions can be prevented if technical safety parameters for bulk solids are known. In different countries researchers have been trying to investigate the dust explosion characteristics of bulk solids, but a limited work have been reported on Indian dusts explosion characteristics. So it has been decided to investigate the dust explosion characteristics of wheat husk, wood dust and coal dust. These three dusts are easily found in agriculture area and power generating fields. Following are the parameters which are required to be investigated and set as objectives of the work:

- Develop a facility for conducting experiments of dust explosion.
- Measure pressure and temperature of explosions.
- Study of technical safety parameters (minimum and maximum dust concentration)
- To develop an empirical model based on existing data.

CHAPTER 2: LITERATURE REVIEW

2.1 Dust explosion

When a very fine dust gets suspended in air and is ignited by heating element or sparked, it will cause dust explosion. A dust explosion will cause a very rapid burning and due to this rapid burning there is release of gases with a huge pressure rise of explosive force that will cause of damage property, plant, and people lives. The formation of cloud would be due to cohesive forces between the dust particles. Initially one particle of dust will ignite and after that chain will start that will ignite the whole cloud. Dust cloud will be ignited by heating element such as spark, electric motor, heating operation etc. Sometimes dust clouds will also be ignited by electrostatic charge that is produced by friction between the particles.

Figure 2.1: Burning at the welded joint and dust explosion in pipe [2]

2.2 Mechanism of dust explosion

Surface area of dust is very large as compared to their mass. Burning will occur on the surface of dust where it reacts with oxygen. For 1.0 kg of a material of spherical shape with density and surface area of 1.0 g/cm^3, 0.3 m^2 respectively, if this material is crushed into spheres of 50 μm diameter then surface area is increased to 60 m^2. This large amount of increased surface area of dust allows the material to burn much faster. Finer will be the particle size; more rapid and explosive burning will occurs, till a limiting stage is reached when particles are too much fine in size. At this stage cohesive force of particles increase and they tend to form nugget (large diameter particle). If the dust cloud is ignited in unconfined area it will only burn but if the ignited dust cloud is confined the gases librated from burning will cause huge increase in pressure and cause loss of property and lives.

2.3 Conditions for dust explosion

For dust explosion to occur certain condition are required to fulfill; without fulfillment of these conditions there is no chance of dust explosion to occur.

These conditions are:

- The dust which will form cloud must be combustible.
- Finer the dust will be, more will be the chance of dust explosion.
- Dust per unit volume must be in explosive concentration (concentration must be between lower and upper explosive limit). Lower explosive limit means minimum concentration required for burning and upper explosive limit means maximum concentration required for burning.
- Supply of oxygen must be there (in absence of oxygen no explosion occurs).
- Without ignition source no explosion takes place [3].

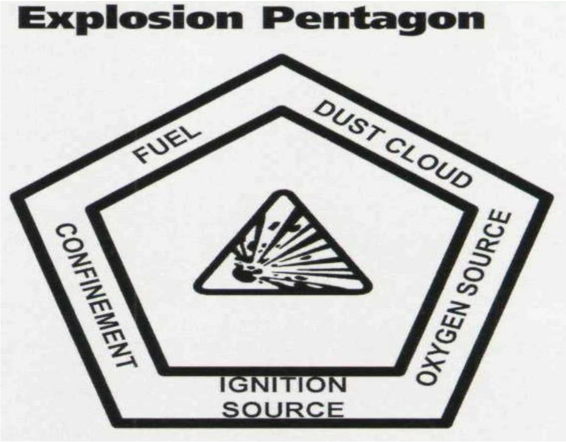


Figure 2.2: Explosion pentagon [1]

2.4 Dust clouds formation in environment

Dust cloud formation process

- Inter particles forces between dust particles (cohesion).
- Entrainment of particles when shock wave passing across deposit surface.
- Transport of dust particles in turbulent gas flow. [3]

2.5 Areas of dust explosions [1, 4]

Table 2.1 Areas of dust explosion

Size reduction	Conveying—manual or mechanical	Pneumatic separation
Cyclones	Filters	Tray drier
Electrostatic precipitator	Fluidized bed driers	Scrubbers
Driers	Unloaders	Pneumatic driers
Spray driers	Screening and classifying operations	Mixing, Blending
Storage	Bag unloading stations	Dust fired heaters

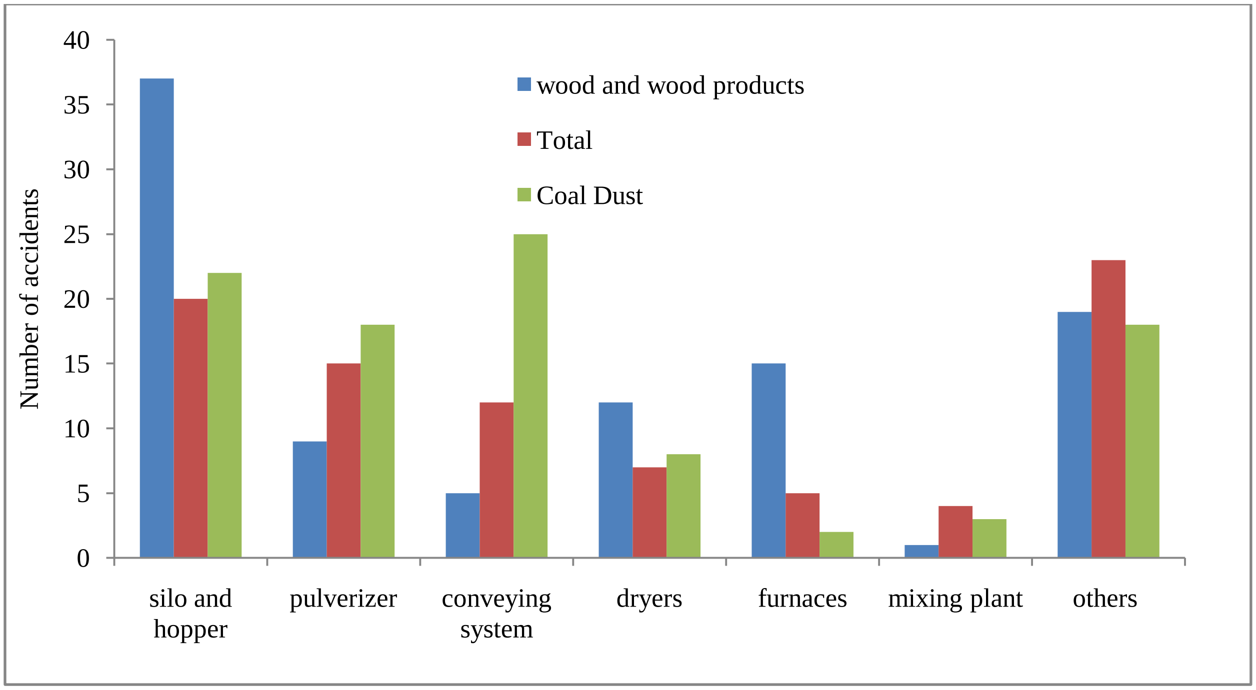


Figure 2.3: Frequency of explosions in different industries in Germany (%) [1]

Number of accidents occurred due to coal and wood dust are shown in figure 2.3. From study it has been found that more number of accidents occurred in silo and hopper. In this area wood and wood products are more hazardous than coal dust.

2.6 Factors which will influence the dust explosion [1, 5, 6, 7, 8]

- Particle size of dust particles
- Dust concentration (g/m^3)
- Oxidant concentration in dust cloud
- Ignition temperature of cloud
- Turbulence of cloud particle
- Maximum rate of pressure rise
- Presence of gases in dust

2.7 Types of dust explosions

There are two types of dust explosions

- Primary explosion
- Secondary explosion

2.7.1 Primary explosion

When combustible dust forms cloud and comes in contact with heating element then it will cause explosion. The dust explosion mainly occurs in tray drier, rotary driers, dust fired heaters, spray driers, settling chamber, size reduction, Pneumatic separation, mills, mixers, cyclone separators, filters, silos and pneumatic transport system. Dust explosion occurred in these vessels due to cloud formation is termed as primary dust explosion.

2.7.2 Secondary explosion

After primary explosion, when blast waves travel it will disturb the settling dust and again form cloud of that dust. Settling dust has very little thickness, but it is quite dangerous when it will form cloud. So explosion caused by this settling dust cloud is called secondary explosion [9, 10].

2.8 Flame propagation process in dust clouds [3]

- In dust clouds flame propagation may be laminar or turbulent.
- Heat transfer occurs by three ways; conduction, convection and radiation.
- Blast wave properties depend on the properties of burning combustible dust clouds.
- Blast wave effects structure and human lives.
- Ability of the blast wave to transfer dust layer into dust clouds.

2.9 Different causes which trigger dust explosion [1, 11]

Table 2.2 Causes which trigger dust explosion

Hot work material	Flames	Hot surfaces
Shock waves	Electrostatic charge	Electrical sparks
Friction sparks	Spark by impact	Self-heating
Static electricity		

2.10 Prevention from dust explosions [12]

There are certain methods to prevent dust explosions and their effect

- By eliminating ignition sources
- Use of pressure relief vent holes
- By inerting the dust
- By static electrification of powder during pneumatic transport
- By magnetize surfactants
- Flameless venting [13]

2.10.1 Elimination of ignition sources

To avoid dust explosion it is necessary to remove all sources that will ignite dust like naked flames, smoking, electricity spark, gas cutting, welding etc.

Other precautions:

- Earthing of all equipment to prevent from static electrical charges.
- Remove ferrous materials by magnetic separator, to prevent the intake of into dust producing grinding mills.

- Use non ferrous blades in fan to avoid explosion.
- Avoid smoking.
- Minimize the use of high speed belts and shafts.
- Try to eliminate all things that trigger explosion.

2.10.2 Relief of explosion pressure

If the ignited dust cloud is unconfined it will only cause flash fire, but if the ignited dust cloud is confined then the gases librated by combustion of dust cloud result in rapid development of pressure and results to explosion. To minimize the hazard there must be vent holes to release gases into environment. Provided relief vents must have to respond almost instaneously [14].

2.10.3 Inerting of dust

When dust is collected in an enclosure, inerting of dust is the best technique to avoid explosion. Inert gas will decrease the oxygen content in the plant atmosphere so that combustion will not occur. While choosing inert gas the reactivity of the dust, strength and duration of ignition source must be taken into consideration. CO_2 is effective than nitrogen as an inert gas for dust clouds of carbonaceous materials but at higher temperature nitrogen is more suitable [5, 15].

2.10.4 By magnetize surfactants

With the help of contact angle it’s very easy to find attraction of a solid surface towards water. The smaller will be the contact angle; the better will be the solution’s wettability of dust. The researchers found that magnetization can reduce the surface tension of water. So as the surface tension of water decrease, water will spread into large surface and more wettability of dust will take place [7].

2.10.5 Flameless venting

Figure2.4: Explosion before and after using flameless venting [13]

A flameless venting device is a used to keep gases safely out of confined area after explosion. It is made up of layers of metal mash, which does not permit fire to go out. This not only stops fire and dust particle after explosion, but also reduce the area of vent. Flameless venting is used in silos, bins, hoppers, dryers, dust collectors; cyclones and also in transport equipments such as belt conveyor, screw conveyor and bucket elevator [13].

Figure 2.5: Flameless vents type and their use [13]

2.11 Major dust explosions

2.11.1 Storage tank accidents [16]

Storage tanks of refineries, thermal and chemical plants contain huge volume of flammable and combustible hazardous chemicals. Small accident due to these chemicals leads to million dollar loss of property and life. During last 50 years, API, ASME, NFPA published many standards and guidelines for construction, selection of material and design of the storage tanks. Most of the companies follow these standards and guidelines in the design, construction and operation, but still storage accidents occur.

In last 40 years approximately 242 accidents occurred only in storage tanks. From fishbone diagram (diagram of accidents) the results conclude that about 179 accidents out of 242 were occurred in only petroleum refineries, in storages and oil terminals. Lightning cause 80 accidents and 72 are caused due human error including inattentiveness, maintenance and other explosions occurred due to equipment failure, leak, static electrification etc.

Table 2.3: Explosions occurred in storage tanks [16]

SNo.	**Date**	**Location/ Country**	**Loss (Millions $)**	**Description**
1	2/24/1986	Thessaloniki Greece	330	A flame of a cutting torch spark ignites the fuel spill from fuel tank.
2	9/1/1979	Deer park, Texas, USA	130	A 700000 DWT tanker off loading and in an 80000 barrel Ethanol at a refinery occurred during electric storms.

3	5/30/1978	Texas city Texas, USA	120	Due to unidentified failure liberate light Hydrocarbons which got spread to an ignition source. 11 tanks unit were destroyed.
4	8/20/1981	Kuwait	73	Due to fire 8 tanks got totally destroyed. The cause of fire is not known.
5	1.7/1983	Newark, New 52, Jersey USA 52	52	Due to overfilling of floating roof tank knock over thirteen hundred barrels gasoline into dike of tank. The vapor cloud was carried by the wind to the nearer incinerator and got ignited. This explosion destroyed 2 adjacent tanks as well as terminals.

2.11.2 Cause of accidents in storage tanks [16]

Table 2.4: Cause of accidents

Years	1960- 1969	1970-1979	1980-1989	1990-1999	2000-2003	Total accidents
Hot work/ Maintenance	` 1	5	9	12	5	32
Static electricity	2	1	2	2	5	12
Open flame	1	0	4	2	1	8
Natural disaster	1	2	1	1	2	7

2.11.3 Coal dust explosion in cement industry [17]

In United States from 10 June 1977 to 4 Feb. 1985, 26 explosions occurred in cement industries. All these 26 explosions occurred in coal fired systems. These explosions mainly cause damage of equipments, operating facilities and building. Small explosions from these 26 explosions caused personal injuries, second or third degree burns etc. The Ad Hoc committees for safety of the coal system of Portland Cement Association (PCA) had compiled thirteen explosions and fire that occurred in indirect fired system in cement plants. Nearly half of the accidents involved fire or/and explosions occurred in filter bag house due to indirect fired system and another half occurred in pulverizer coal mills and cyclone dust collectors.

2.11.4 Dust Explosions occurred in different countries

Table 2.5: Dust Explosions in different countries [1]

Year	Location	Material	Plant	Dead (d)/Injured (i)
2003	Kinton, NC	Polyethylene	Pharmaceutial	6d/38i
2003	Kentucky	Resin	Production line	7d
2000	Japan	Mg-AL alloy	-	1d/1i
2002	Mississippi	Rubber	Recycling	5d
1999	Michigan	Coal (secondary explosion)	Power house	6d/14i
1997	Blaye, France	Grain	Storage	11d
1994	Tokyo, Japan	Rubber waste	Shoe factory	5d/22i
1992	Moriya	Potassium Chloride and Aluminium	Mixing operation	3d/5i
1990	Japan	Benzoylperoxide	Storage	9d/17i

1987	China	Textile Dust	Dust Collection System	58d/177i
1981	Corpus Christi, TX	Grain Dust	Bucket Elevator	9d/30i
1981	Germany	Coal	Bucket Elevator	Loss of $6400000
1980	Ohama,NE,USA	Grain Dust	Head House	Loss of $ 33 Thousand
1980	St.Joseph,MO,USA	Grain Dust	Shipping Bin	1d/4i,loss $21lakh
1979	Lerida,spain	Grain Dust	Grain Silo	7d
1977	Galvesto,TX	Grain Dust	Grain Silo	15d
1977	Westwego,Louisiana	Grain Dust	Grain Silo	36d/10i
1973	Norways	Aluminum	Mixing Vessel	5d/2i
1972	Norways	Silicon	Milling section	5d/4i
1970	Kiel,FRG	Grain Dust	Grain Silo	6d/18i
1970	Germany	Grain Dust	Silo and Shipping Canal	6d/17i, loss $10 Million
1965	London,UK	Flour	Flour mill	4d/37i
1955	Wayneboro,GA	Grain Dust	Feed plant	3d/13i
1952	Sakatchewan	Grain Dust	Shipping bin	6d/14i
1952	Bound Brook,NJ	Phenolic resin Dust	Hammer mill	5d/21i
1930	Liverpool,UK	-	-	11d/32i
1926	USA	Sulphate Dust	-	3d/1i
1924	Peking, IL	Corn Starch	Starch Plant	42d
1919	Cedar ,Rapid ,IA	Corn Starch	Starch Plant	43d
1911	Manchester,UK	-	-	3d/5i
1911	Liverpool,UK	-	-	37d/100i

2.11.5 Dust explosions in China

Table 2.6: Dust explosions in china [18]

Year	Location	Material	Industry	Dead(d) /injured(i)
2011	Zhejiang	Aluminum	Metal	16i
2011	Sichuan	Aluminum	Metal	3d/15i
2011	Zhejiang	Aluminum	Metal	5d/1i
2011	Zhejiang	Aluminum	Metal	1d/10i
2010	Guangdong	Food Dust	Flour/feed	1d/4i
2010	Henan	Wheat flour	Flour/feed	14i
2010	Habei	Starch	Starch/candy	19d/49i
2010	Zhejiang	Aluminum	Metal	2d/6i
2009	Zhejiang	Wood bits	wood	8i
2008	Yunnan	Sulfur Dust	Chemical	7d/33i
2007	Guangdong	Starch	Starch/candy	29i
2007	Shanghai	Wood Bits	Wood	4d/5i
2002	Guangdong	Food Dust	Flour/feed	6d/12i
2002	Anhui	Malt Dust	Starch/candy	17i
1987	Heilongjiang	Flax Dust	Chemical	58d/177i
1986	Jilin	Flax dust	Chemical	5d/15i

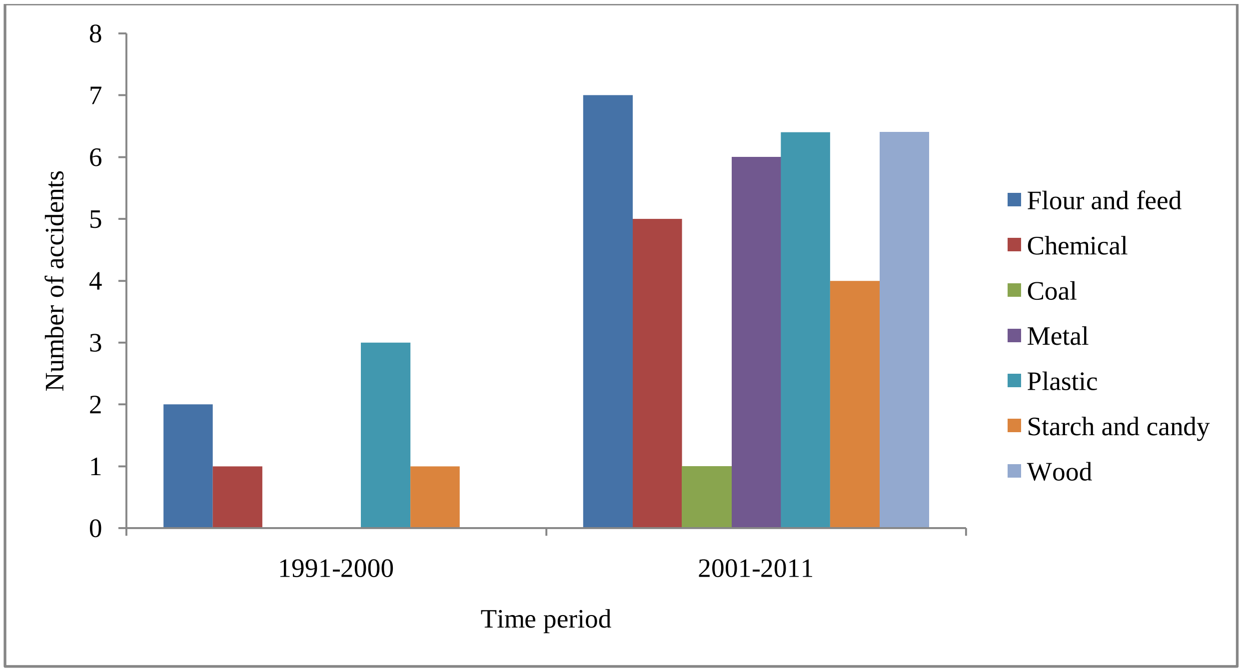


Figure2.6: Dust explosions in different time periods in china [18]

Analysis of dust explosion accidents occurred in china during period 1991-2011 is shown in figure 2.6. From this analysis it has been found that more dust explosions occurred during period of 2001-2011, because in these years industries increased with large number. It has been also studied that flour and feed dust is more problematic as compare to others.

2.12 Major dust explosion triggers in China [18]

Table 2.7: Ignition source cause number of accidents

Ignition source is required to ignite dust cloud. Without ignition source explosion will not occur. Certain ignition sources which trigger dust China are as follow:

Ignition source	**Number of accidents**
Static electricity	10
Welding and cutting	7
Friction spark	7

Electric spark	5
High temperature	4
Self heating and smoldering	3
Impart spark	2
Flame and direct heat	1
Unknown	33

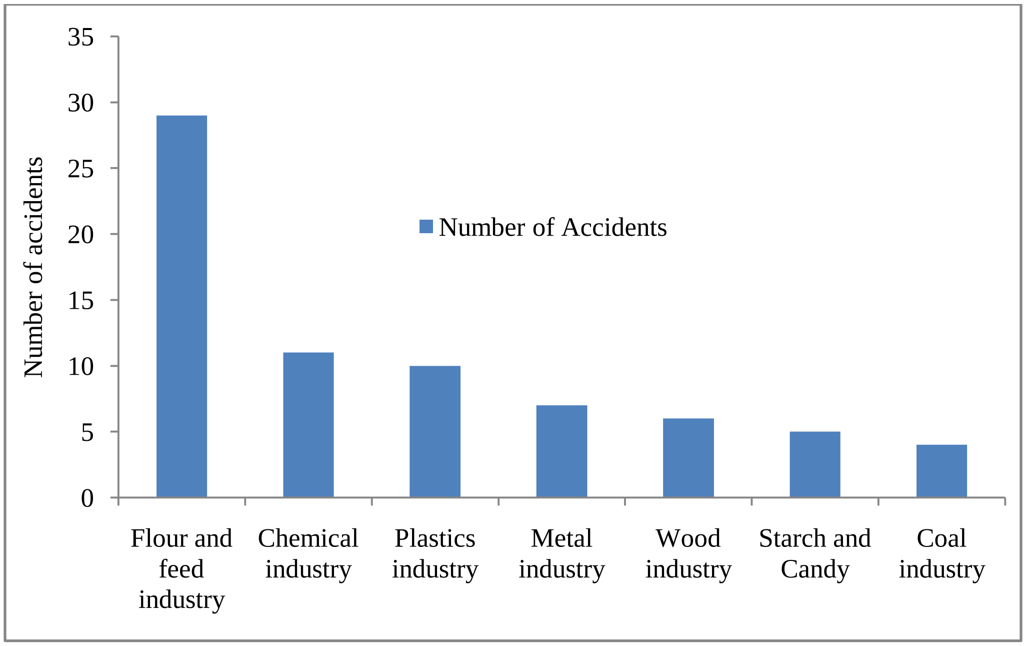


Figure 2.7: Explosions per industry in china [18]

Analysis of accidents occurred in different industries in China is shown in figure 2.7. From this study it has been analyzed that about 28 explosions occurred only in flour and feed industry. Explosions occurred in flour and food industries are more as compare to other industries. So from this, it can be easily analyzed that flour and feed dust is quite more dangerous than others.

2.13 Types of dusts

- **Explosible dust**

  Weakly Explosible

  Moderate Explosible

  Strongly Explosible

- **Non explosible dust**

2.13.1 Characteristics of dust according to K_{st}

Table 2.8: Characteristics of dust on Kst basis [19]

Explosion classes	Kst	Characteristics
St 0	**-**	**Non Explosible**
St1	**$0 < K_{st} \leq 200$**	**Weak to moderate**
St2	**$200 < K_{st} \leq 300$**	**Strong explosion**
St3	**$K_{st} > 300$**	**Extremely Explosible**

2.13.2 Combustible dust and non combustible dust [8]

Table 2.9: Combustible and non combustible dusts

Combustible dust	Non combustible dust
Aluminum/resin mix	Acrofibre insulation
Biscuit	Alumina
Bronzing powder	Amophos (food phosphate)
Butter milk powder	Asbestos
Button (Plastic)	Bronze/ Aluminum mix

Cuprous oxide	Cement /Wood flour mix
Carbon black	Cuprous oxide
Cardboard	Disprin
Cardboard / Sisal mix	Gluten
Chocolate	Insul fluff
Coal	Kelp powder
Coconut shells	Nylon flock
Coffee kernels	Polyvinyl acetate
Corn flour	Semolina
Cotton waste	Talcum powder
Fiber glass / plywood mix	Vitreous enamel overspray
Flour	Zinc oxide
Food (mixture of various foods)	Manganese ore
Grain	--
Hard board	--
Jute	--
Lactose	--
Leather	--
Milk powder	--
Paper	--
Plastic powder	--
Rubber	--
Rubber/ leather/plastic/wood mi	--
Soya bean flour	--
Sulphur (100%)	--
Wheat, wheat/ barely mix	--
Wheat flour/ gluten mix	--
Wood	--
Wood/ Formica mix/ wool	--

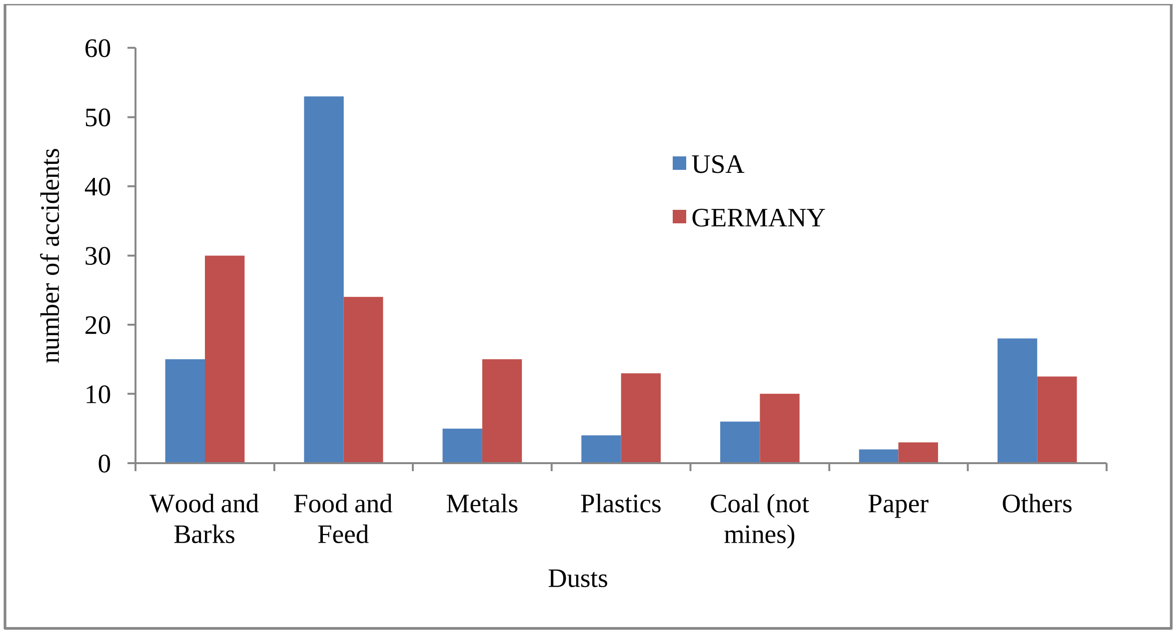


Fig2.8: Explosion frequency in USA and Germany due to different dusts [1]

Figure 2.8 shows, dust explosion accidents due to different dusts in USA and Germany. In this analysis it has been found that more than 50 explosions occurred only due to food and feed dust. Explosions occurred due to food and feed dust are more as compare to other dusts. This data clearly shows that food and feed dust is quite more dangerous than others.

2.14 Technical safety parameters according to foreigner dusts

Table 2.10: Technical safety parameters [20]

Material	**Lower explosive limit g/m^3**	**Minimum ignition energy (joules)**	**Minimum ignition temperature of cloud**	**Minimum ignition temperature of layer**	**Maximum explosive pressure psi**	**Maximum rate-of pressurize psi/ sec**
Corn	45	.04	400	250	95	6000
Corncobs	30	.04	400	190	110	5000
Grain mixed	55	.03	430	230	115	5500
Sov	35	.05	520	190	99	6500

Sugar	35	.03	350	220	91	5000
Wheat	55	.06	480	220	103	3600
Wheat starch	25	.02	380	210	105	8500
Flour	50	.05	380	360	95	3700
Coal	55	.06	610	-	83	2300

2.15 Investigation of magnesium and bituminous coal dust explosion characteristics [21]

Due to light weight and high mechanical strength magnesium is one of the best engineering materials. Magnesium powder is used in different process industries like metallurgy, aeronautics, firework, painting and chemical industry. Magnesium dust is highly combustible and explosive dust. There could be lot of hazards during production, storage, transportation and handling of magnesium dust. If in confined area magnesium dust cloud concentration is under LEL and MEL and cloud comes in contact with trigging element, explosion will takes place. Safety handling of magnesium powder requires technical safety parameters to avoid dust explosion.

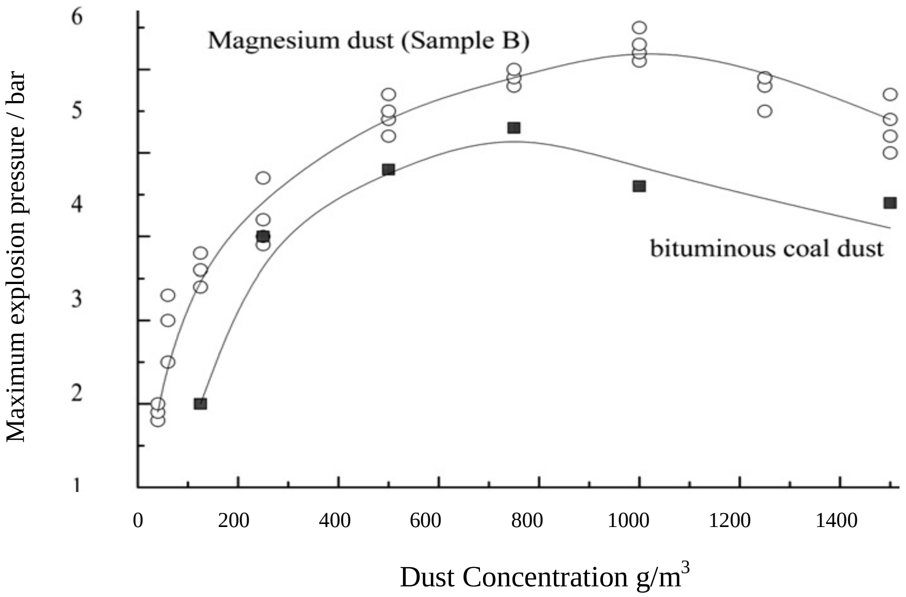


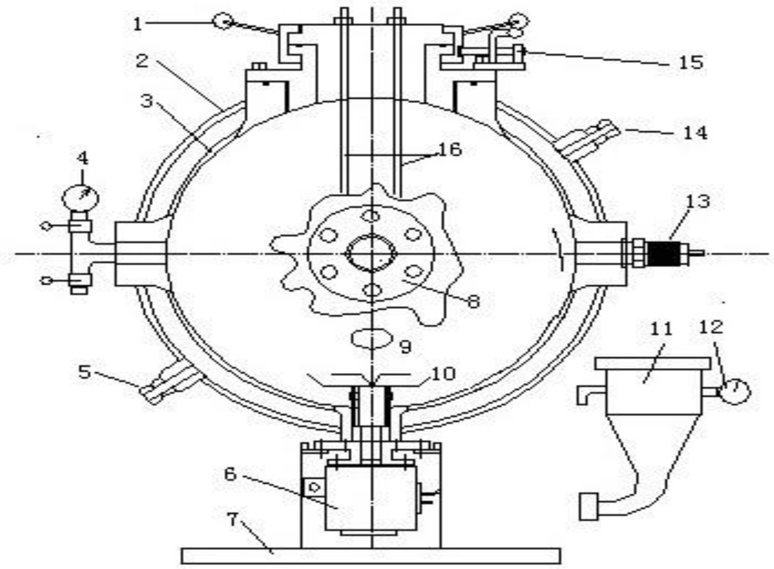
Figure 2.9: Variation in explosion pressure due to dust concentration [21]

Variation in explosion pressure with dust concentration is shown in figure 2.9. In this study two dusts; magnesium and bituminous coal dust with size 22.4 micrometer and 27.6 micrometer respectively is used. It has been found that magnesium dust is more hazardous as compare to coal. Increase in pressure due to magnesium dust explosion is more than 5 bar while pressure increased due to coal dust explosion is less than 5 bar.

2.16 Determination of the MIT (minimum ignition temp.) of coal dust cloud [22]

Coal dust particle size (250-500 µm), (150-250 µm), (75-150 µm), (48-75 µm), (25-48 µm) were tested respectively at the environment temperature (293± 5) K and the pressure of powder is 0.8 MPa. MIT was determined by changing dust concentration of coal.

Determination of technical safety parameters using 20L sphere vessel



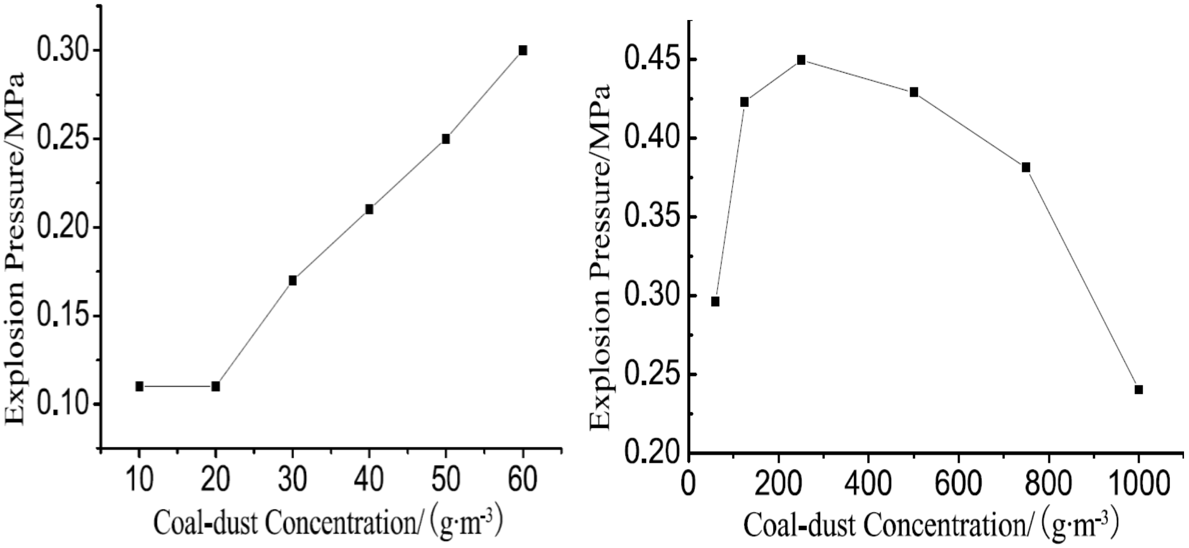
1- The operating handle; 2- the outer wall; 3- The inner wall; 4- Vacuum table; 5-cooling water inlet; 6- fast opening valve; 7- base; 8- observation window; 9- inlet; 10-dust dispersed valve; 11- gas chamber ;12- electric contact pressure gauge; 13- pressure sensor; 14- cooling water outer; 15- security lock

Figure 2.10: Schematic of 20L sphere vessel dust explosion experiment [22]

Coal dust was sprayed into the storage tank at pressure of 2MPa and temperature of (295± 5) K. Coal dust was scattered into the container by pressurized gas through dust dispersion system. To ignite the dust 10KJ energy is supplied at the center of the tank by chemical igniter. Maximum pressure and temperature was recorded with the help of pressure and temperature sensors. Lower explosive limit and maximum explosive limit was found at different dust concentrations.

Effects of dust concentration on coal dust explosion characteristics are as follows:

It has been analyzed from the first graph that explosion pressure is constant during initial dust concentration but after 20 g/m^3 explosion pressure rise with increase in dust concentration. In the second graph explosion pressure first increase up to approx 0.45 MPa then decrease and become minimum at concentration more than 1000 g/m^3.



Relationship between dust concentration and Explosion pressure [22]

Relationship between dust concentration and Explosion pressure [22]

Figure 2.11: Experimental results of dust explosion in 20L sphere

2.17 Coal dust explosion with limited oxygen concentration [23]

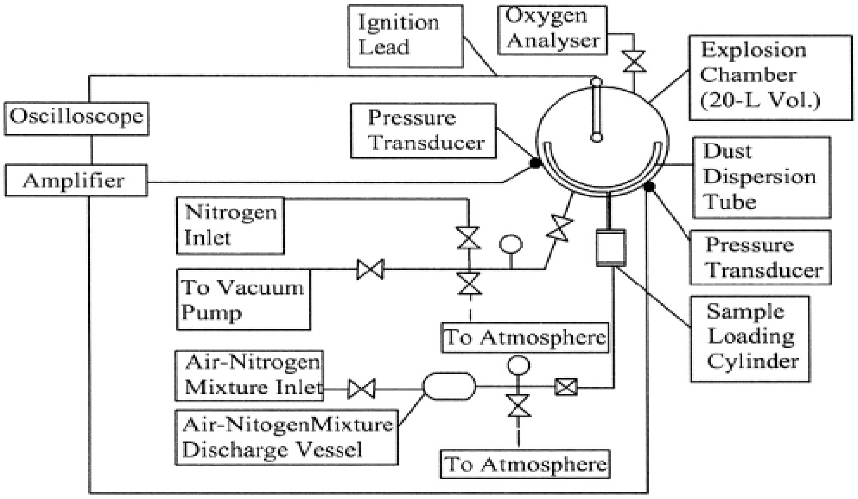


Figure 2.12: Experimental setup used by CSIR to find effect of oxygen concentration on explosion [23]

A research program on explosion characteristics of coal dust was done at CSIR- CBRI; Roorkee, for finding explosion safety parameters for coal dust. An experiment was done to find the effect of oxygen levels on explosion with different coal samples of varying volatile matter, moisture and concentration ; coal A with 27.28 % volatile matter, coal B with 19.69% volatile matter. This experiment was done in 20L sphere at ambient conditions. The 20L hollow sphere made up of steel used to determine limiting oxygen concentration of dusts. Maximum working pressure for the sphere was 30bar. Sphere was filled with mixture of air /nitrogen gas at desired oxygen concentration by using partial pressure method. To detect the oxygen concentration, an oxygen analyzer was designed for accurate measurement of oxygen in air nitrogen mixture. A LCD display provides oxygen percentage level by volume in the range 0-25% with a least count of 0.1% and accuracy of 2%. During experiment, pressure and time curve was recorded. The pressure recording started from partially evacuated pressure of 0.4bar. To spread dust, air valve was opened at 40ms and closed at 90ms. The igniter was started at 100ms when chamber was at

1 bar pressure. P_{ex} was the maximum explosion pressure (MEP). $(dp/dt)_{ex}$ was the rate at which pressure would rise with respect to time during explosion. P_{max} and $(dp/dt)_{ex}$ was reached maximum at a particular concentration but after that with increase in concentration again pressure drop will takes place.

$Kst = (dp/dt) \times V^{1/3}$ where

P – Pressure (bar)

t- Time in seconds

V – Volume of vessel (m^3)

K_{st} – explosibility dust constant (bar m/s)

To find the LOC various experiments were conducted at different rage of dust concentration according to standard procedure. First experiment was done at 21% oxygen, to determine the most severe dust explosion. Then more tests were carried out at different oxygen concentrations. In initial experiments the oxygen concentration is lowered by 3% and after that it is reduced 1%.

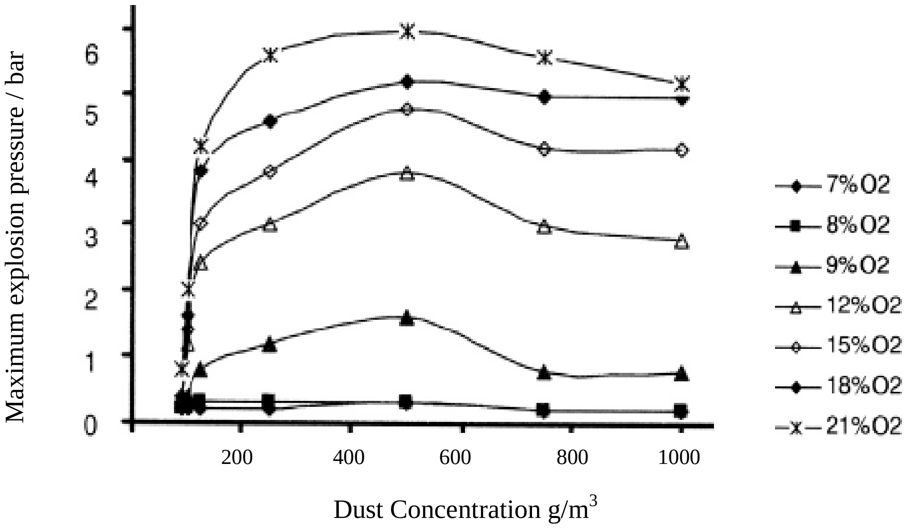


Figure 2.13: Maximum explosion pressure with variation in concentration of oxygen [23]

Analysis of explosion characteristics with variable dust concentration and varying oxygen level is done in figure 2.13. In this analysis it has been found that with decrease in oxygen percentage explosion pressure will also decrease. Explosion pressure decreases with oxygen percentage because if percentage of oxygen is less then mixture of dust and air become richer. This means dust concentration is more per unit volume of air and proper combustion will not occur.

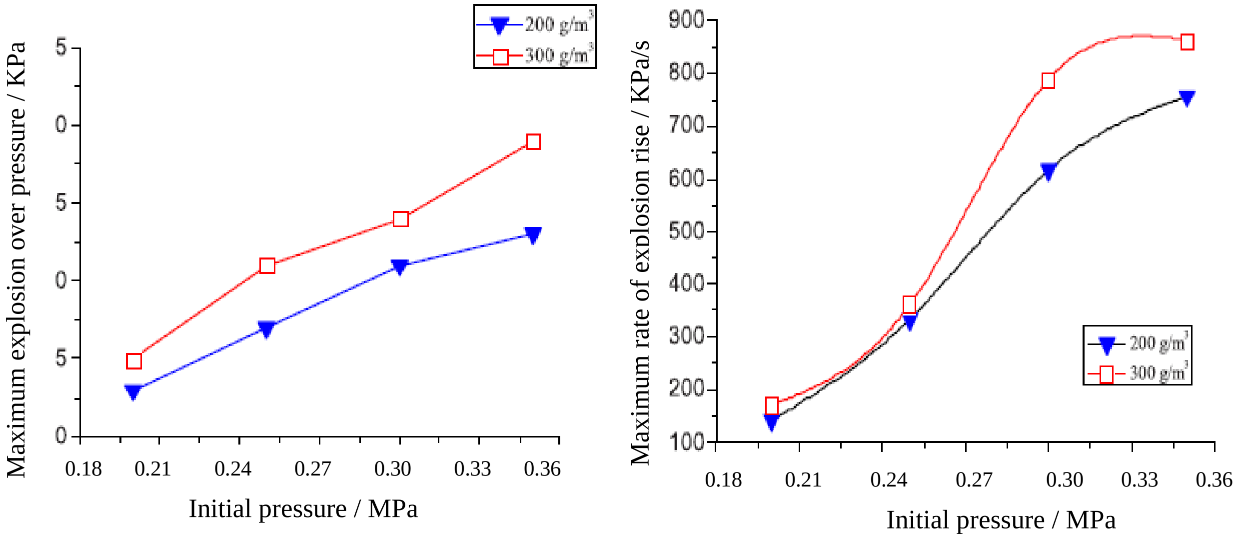
2.18 Influence of initial pressure on explosion of methane – coal dust mixture [24]

Experimental setup consisted of five parts – an explosion vessel, data acquisition system, an ignition system, dust and gas transportation system and a high speed camera. A rectangular box with dimensions 0.6×0.1×0.1 was used for an explosion vessel with gas kits and flange to avoid gas leakage. Vessel was consisted of three side glass and one side was made of metal. Two PCB pressure-transducers were installed on metal (stainless steel) plate. Signals produced by these transducers were stored, analyzed by data acquisition system.

By using weighing machine weight pulverized coal and put that coal into the grove of flange at the end of explosion tube. Methane and air mixture was pumped into the cylinder with a controlled flow of methane. As the valve of mixture cylinder was opened it will spread dust inside the explosion tube. After making the cloud inside the tube, press the spark button and the spark started between two electrodes ignite the cloud. Pressure transducer and temperature sensors were used to detect pressure, temperature respectively and results were displayed on computer screen.

Figure 2.14: Experimental setup

Relation between initial pressure, explosion overpressure and rate of explosion pressure is shown by following graphs:



Maximum explosion overpressure of methane- coal Maximum rate of overpressure rise of methane - coal

Figure 2.15: Relation between initial pressure and maximum explosion overpressure [24]

Figure 2.15 shows variation of over pressure and rate of over pressure with initial pressure. In this study two concentrations 200 g/m^3 and 300 g/m^3 of methane -coal mixture is used. During analysis it has been found that explosion overpressure depends directly on initial pressure. As initial pressure in the container increased; rapid increase in over pressure will be observed.

2.19 Effect of different diameter on explosion pressure [25]

Figure 2.16 shows how the variation in maximum explosion pressure took place due to variation in diameter of dust particles. Aluminium dust particles with 7 micrometer diameter had high value of explosion pressure and particles with 42 micrometer had least value of pressure.

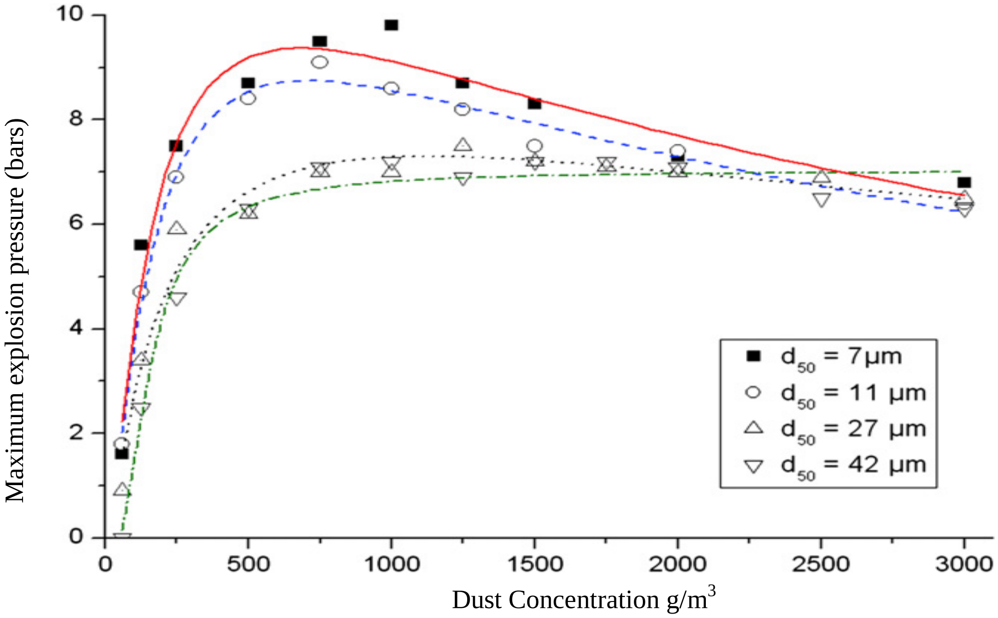


Figure 2.16: Effect of diameter of particle on explosion pressure [25]

From study of graph it has been found that as the size of dust particle will decrease explosion pressure will increase but it is possible only up to a limited value of diameter, after that value if diameter of dust decrease, particles will collapse and form bigger diameter particles. In this condition explosion pressure will decrease or may explosion will not take place.

2.20 Gaps in study

As evident from the literature, dust explosion is a big problem for the industries throughout the world. In developed countries like China, USA, Japan etc number of explosions has been reported in past years. India is a developing country, but information related to dust explosions in India is almost negligible. There are few explosions in notice, for example explosion occurred at Bhopal in 1984 and at Vishakhapatnam in 1996 (HPCL) (chemical industry), but after that no information was found. It is not possible to stop dust explosions but these explosions can be avoided. There are certain methods to avoid dust explosions. By knowing technical safety parameters of dust, explosions can be avoided. Characteristics of bulk solids depend upon environmental conditions. Indian dusts are different from dusts of other countries in terms of moisture content, ash content, minerals etc. It has been observed that lot of work is done in other countries on dust explosion characteristics but a limited work has been reported on Indian dusts explosion characteristics. So it has been decided to investigate the dust explosion characteristics of Indian dust.

CHAPTER 3: EXPERIMENTAL SET UP

3.1 An experimental investigation on characteristics of dusts

The study presents an investigation on the characteristics of dusts. In this experiment three dusts; wood dust, wheat husk and coal has been used. As already discussed that dust explosion causes loss of human lives and property, if it is under confined area. It is not possible to stop dust explosion, but it can be avoided by several methods. To avoid dust explosions one of the best method is to study technical safety parameters of dust. So the present work involves the study of technical safety parameters for different dusts. This chapter is divided into four parts: first part deals with experimental setup for outdoor testing of dust explosion and rest all parts deals with technical safety parameters for different dusts.

3.2 Schematic of experimental setup

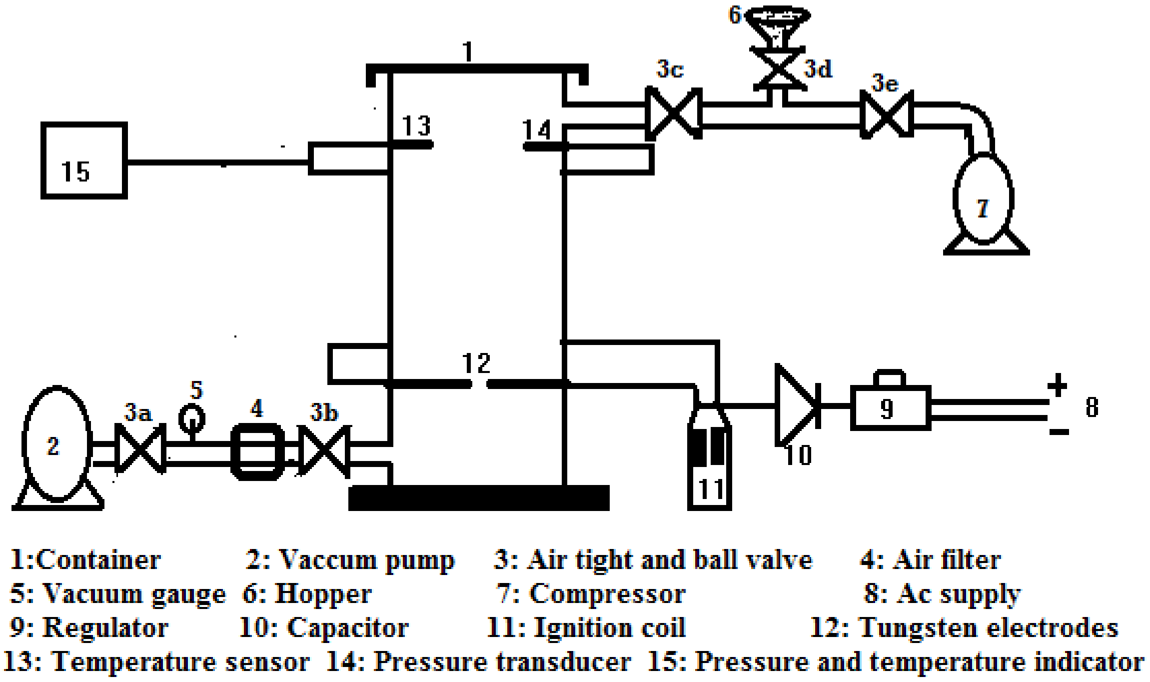


Figure 3.1: Schematic of experimental setup

3.3 Layout of experiment setup

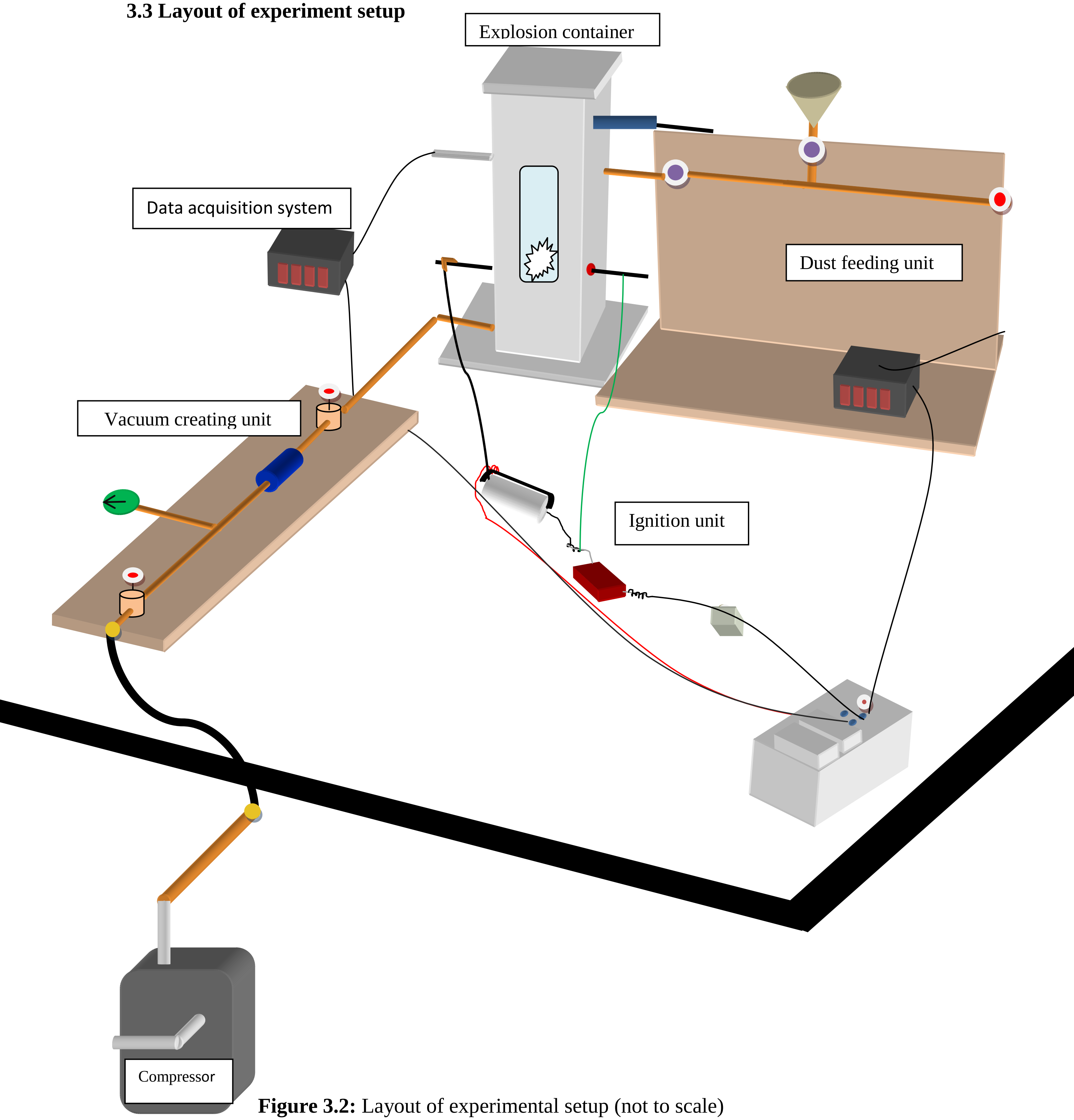


Figure 3.2: Layout of experimental setup (not to scale)

3.4 Experimental setup

Figure 3.3: Experimental setup

An Experimental Setup developed for dust explosion is shown in Figure 3.3. It consists of five units: container with dimensions (10×10×50) cm^3, vacuum creating unit, dust feeding unit, ignition unit, sensor and indicator unit. Three sides of container were made up of cast iron and one side was made of glass. Vacuum creating unit was consisting of air tight valves, air filter, vacuum gauge and vacuum pump. Vacuum pump was used to create vacuum inside container, air filter is used so that no dust particle will enter to vacuum pump. Vacuum pressure gauge shows how much vacuum was in container. Dust feeding unit consists of two ball valves, one air tight valve, a hopper and a compressor. Hopper was used to feed dust into container; compressor will perform two operations, supply of air and dust feeding. An ignition unit consists of AC power supply, Volume type fan regulator, capacitor, an ignition coil and tungsten electrodes. Tungsten electrodes were used to produce spark, volume type fan regulator was used to increase or decrease voltage. Capacitor was used to pass current required for ignition coil; an ignition coil was used to step up the voltage. Sensors and indicator unit consists of pressure transducer, temperature sensor and digital indicator. Pressure transducer and temperature sensor measured pressure and temperature respectively and digital indicators were used to display their readings.

3.5 Experiment procedure

Before performing experiment make sure that all the connections should be air tight. Now create vacuum inside container with the help of vacuum pump. While creating vacuum close valve 3d, 3e and open all other valves. Note pressure reading from gauge and close valve 3a. After 10 minutes check pressure; if it is stable then further experiment can be proceeded (**figure 3.1)**.

Following are the experiment procedure steps

- Close valve 3c, 3d, 3e and open valve 3a and 3b.
- With the help of vacuum pump suck air and create vacuum into container up to 0.6bars.
- Close valve 3b and switch of the vacuum pump.
- Weight dust on digital weighing machine and put it into hopper.
- Open valve 3c and 3d make sure that 3e must be close.
- After few seconds open valve 3e and start compressor.
- Cloud formation will be seen through sight glass.
- Switch off compressor after few seconds and switch on ignition coil for 4-5 seconds.
- When dust particles come into contact with spark they will ignite.
- There is increase pressure and temperature inside container due to release of gases.
- When gases did not found any way to leave into atmosphere they lift upper cover of container and make a sound of explosion.

- Pressure transducer and temperature sensor detect explosion temperature and pressure.
- Note readings from digital pressure and temperature display screen.

3.6 Precautions

- Air Leakage should not be there.
- Make all electrical connections carefully.
- Well insulate the Tungsten rods so there is no spark between container and rods.
- Before touching container switch off spark plug and discharge capacitor.
- Wear helmet during experiments.
- Keep yourself away from container as much as possible.

3.7 List of equipments used in experiment and their functions

Container
Acrylic sheet
Ignition coil
Capacitor
Volume type regulator
Tungsten Rods
Electric insulators
Pressure transducer
Temperature Sensor
Air tight and Ball valve
Compressor
Vacuum pump
Air Filter

1: Container

Figure 3.4: Explosion Container used in experiment

Figure 3.4 shows container with volume 5000 cm^3 is made up of three sides of cast iron and one side is of acrylic glass sheet of dimensions (26×10×4) cm^3**.** In this, explosions will take place and with the help sight glass inside view can be seen.

2: Acrylic sheet

Figure 3.5: Sight glass (Acrylic sheet)

Figure 3.5 shows light weight transparent acrylic sheet with molecular formula $(C_5O_2H_8)_n$. Its melting point is around about 463 K. 4mm thicker sheet is attached on one side of container so that one can see inside container.

3: Ignition coil

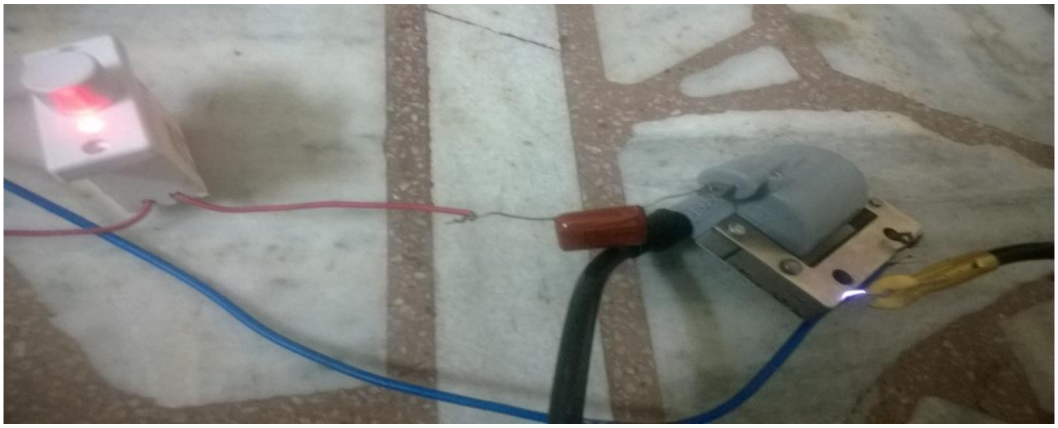


Figure 3.6: spark produced by ignition coil

An ignition coil used in automobiles to produce spark between the spark plug electrodes is shown in figure 3.6. It is an induction coil used to convert low voltage to high voltage. It consists of primary and secondary windings; secondary winding have hundred times more turns than that of primary. At least 22KV is required to produce spark between the gap of 4mm.

4: Capacitor

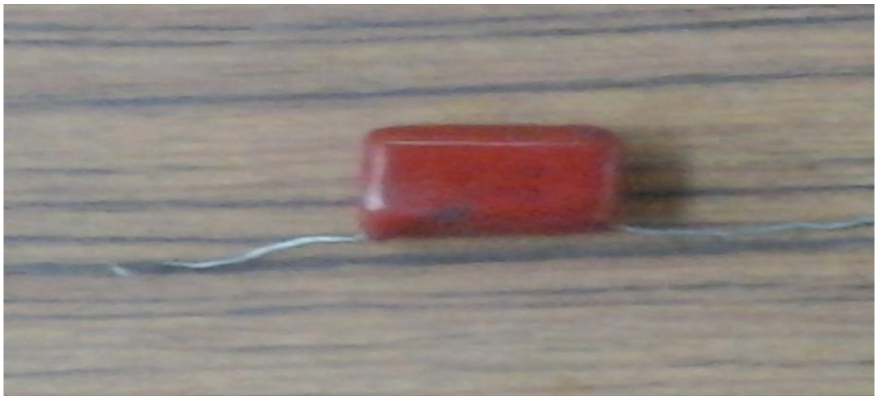


Figure 3.7: Capacitor of 1 microfarad

Figure 3.7 shows a two terminal component called capacitor used to store charge. It consists of two electrically conductive plates separated by insulator. In this experiment, capacitor of 1 microfarad is used to convert AC supply of 220 Volt into 12Volt.

5: Volume type regulator

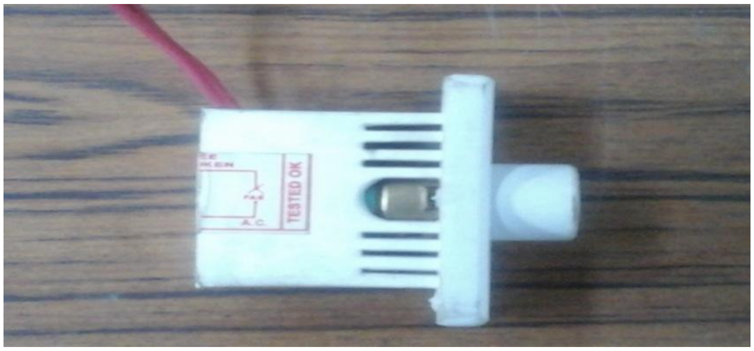


Figure 3.8: Volume type regulator

A regulator is used to increase resistance in circuit as shown in figure 3.8. In this experiment regulator is attached before capacitor to control the spark produced by ignition coil.

6: Tungsten rods

Figure 3.9: Tungsten rods used to produce spark

Figure 3.9 shows tungsten rods with 4mm diameter. These rods were placed at the bottom of the container with a gap of 4mm to produce spark between them. Tungsten rods mainly used in TIG welding because of their high melting point and good conductivity. Because of these properties tungsten rods are used in this experimental setup.

7: Electric insulator:

Figure 3.10: Insulators used for safety purpose

Figure 3.10 shows insulator used to separate tungsten rods from container, so that there was no spark between container and tungsten rods. In the absence of these insulators whole charge will go to container and lead to poor spark between rods. Also it prevents from shock.

8: Pressure transducer:

Figure 3.11: Pressure transducer

Figure 3.11 shows pressure transducer which generate electric signal as pressure foist on it. Pressure transducers are used in daily life to measure pressure of air, water etc. In this experiment pressure transducer of 0-10 bar is used to find pressure of gases after explosion.

9: Temperature sensor

Figure 3.12: Temperature sensor

Temperature sensor is used to measure temperature of flame after explosion; as shown in figure 3.12. There are different types of temperature sensors but in this experimental setup K type sensor with indicator model of PP35 has been used.

10: Air tight and Ball valve

Figure 3.13: Air tight and Ball valve

Figure 3.13 shows air tight valve used to control the flow of fluid by opening, closing or by partially obstructing the flow. Ball valve consists of spherical disc which controls flow of fluid through it. This spherical disc had a hole which permits fluid to stop and flow. Air tight valve is used only for air purpose because it doesn't permit dust to pass. Ball valve has been used for dust feeding purpose because it allows dust to pass through it.

11: Compressor and Vacuum pump

Figure 3.14: Compressor and Vacuum pump

Figure 3.14 shows compressor which is used to suck air at low pressure and deliver at high pressure. In this experimental setup reciprocating type compressor has been used to feed dust and air mixture into container. Same compressor can be used as vacuum pump by changing inlet and outlet ports.

12: Air filter

Figure 3.15: Air filter

Figure 3.15 shows air filter which obstruct impurities. It consists of large number of meshes which doesn't allow dust to pass. Air filter is used before vacuum pump so that during suction no dust particles go inside vacuum pump.

3.8 Type of dusts used for an experiment

1) Wheat husk
2) Wood dust
3) Pulverized Coal dust

3.9 Experimental results and discussion

In this experimental work three dusts, wheat husk, wood dust, coal dust have been used to study their explosion characteristics. The particle size of wheat husk and wood dust is less than 300 micrometer; dust size of coal is 105 micrometer and less than 53 micrometer. During dust explosion experiment various parameters like pressure, temperature has been recorded. Different concentrations are used to find minimum, maximum explosible dust concentrations required for explosion. Graphs have been made to find the relation between different parameters and to compare characteristics of different dusts

3.9.1: Dust Explosion using wheat husk

Sample of wheat husk contains different size dust particles. With the help of sieving machine different size dust samples are collected. In this experiment dust sample of size less than 300 micrometer is used. Samples of different concentrations have been prepared with the help of digital weighing machine. After this put dried dust with variable concentration into container by performing all steps of experiment procedure and give a spark of 5 seconds. Note Reading of maximum pressure and temperature after explosion for different concentrations of dust and also find maximum and minimum explosive limit for wheat husk of particle size less than 300 micro meters.

Explosion characteristics of wheat husk

Wheat husk of size less than 300 micrometer is used for the experiment of dust explosion. In this study relation between temperature and pressure with dust concentration has been studied. This experiment has been done to find explosion flame temperatures, flame pressure, minimum and maximum explosible limit by using different dust concentrations.

Relation between temperature and concentration for wheat husk

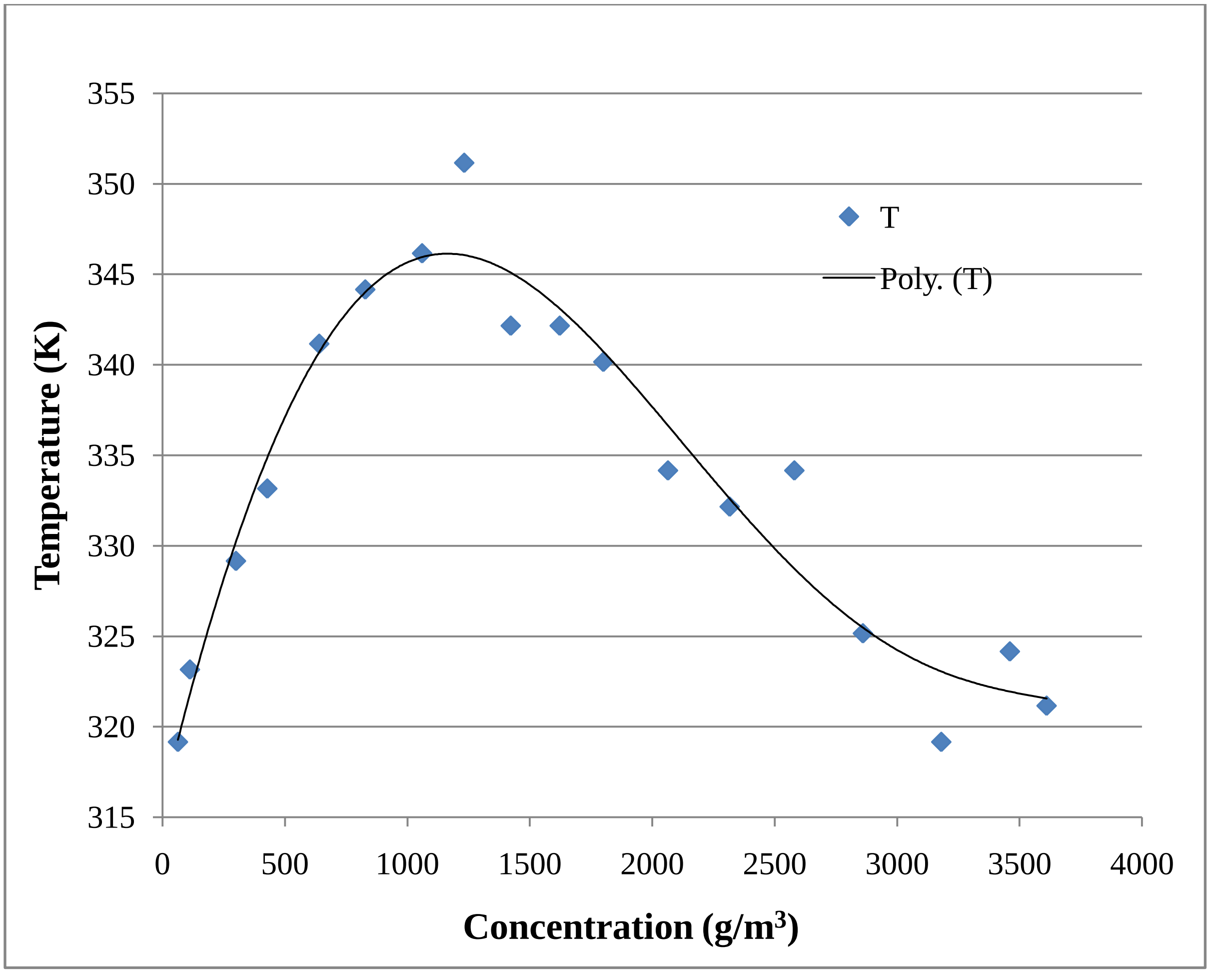


Figure 3.16: Variation of temperature with dust concentration for wheat husk

Figure 3.16 shows variation of temperature with dust concentration. It has been observed that when concentration of dust is less than 63 g/m^3 or more than 3610 g/m^3 there is no explosion inside container. This shows dust explosion will be avoided if concentration is less than 63 g/m^3 and more than 3610 g/m^3. On the other hand maximum temperature is 351.15 K at concentration level of 1232 g/m^3 which shows explosion at this concentration is much more dangerous than others. At concentration level of 1232 g/m^3, temperature of explosion flame is maximum because at this concentration air and dust mixture becomes stoichiometric. Which means oxygen required for burning is in proper proportion to dust. But at concentration levels of 63 g/m^3 and 3610 g/m^3, dust and air concentration is very lean and very rich respectively. Lean mixture means dust concentration per unit volume of air is very low; rich mixture means dust concentration per unit volume of air is very high. Because of lean and rich mixture of dust and air, burning does not occur.

Relation between pressure and concentration for wheat husk

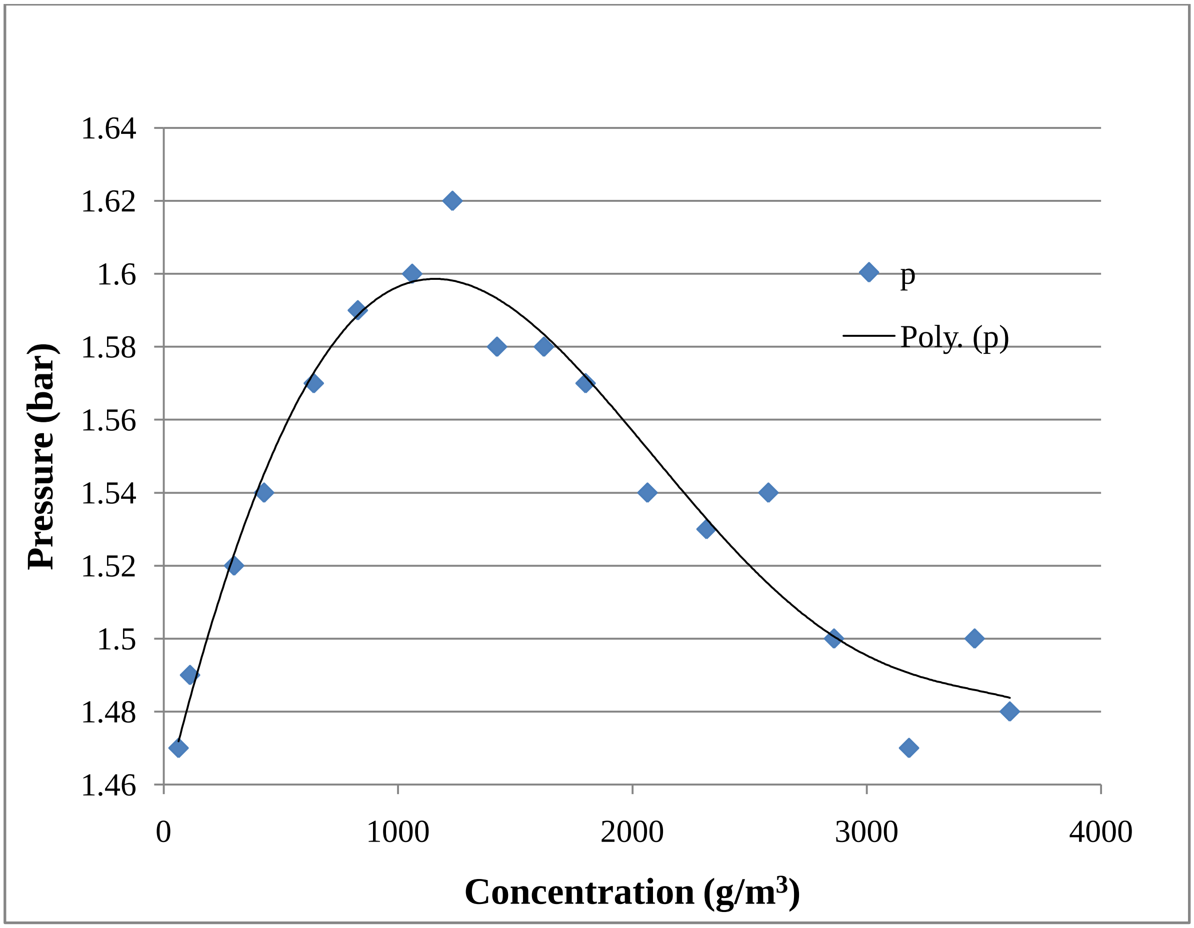


Figure 3.17: Variation of pressure with dust concentration for wheat husk

Figure 3.17 shows variation of pressure with dust concentration. It has been observed that when concentration of dust is less than 63 g/m^3 or more than 3610 g/m^3 there is no explosion inside container. This shows dust explosion will be avoided if concentration is less than 63 g/m^3 and more than 3610 g/m^3. On the other hand maximum pressure is 1.62 bar at concentration level of 1232 g/m^3 which shows explosion at this concentration is much more dangerous than others. At concentration level of 1232 g/m^3, pressure of explosion is maximum because at this concentration air and dust mixture become stoichiometric. Which means oxygen required for burning is in proper proportion to dust. But at concentration levels of 63 g/m^3 and 3610 g/m^3, dust and air concentration is very lean and very rich respectively. Lean mixture means dust concentration per unit volume of air is very low; rich mixture means dust concentration per unit volume of air is very high. Because of lean and rich mixture of dust and air, burning does not occur.

3.9.2 Dust Explosion using wood dust

Sample of wood dust contains different size dust particles. With the help of sieving machine different size dust samples are collected. In this experiment dust sample of size less than 300 micrometer is used. Samples of different concentrations have been prepared with the help of digital weighing machine. After this put dried dust with variable concentration into container by performing all steps of experiment procedure and give a spark of 5 seconds. Note Reading of maximum pressure and temperature after explosion for different concentrations of dust and also find maximum and minimum explosive limit for wood dust of particle size less than 300 micro meters.

Explosion characteristics of wood dust:

Wood dust of size less than 300 micrometer is used for the experiment of dust explosion. In this study relation between temperature and pressure with dust concentration has been studied. This experiment has been done to find explosion flame temperatures, flame pressure, minimum and maximum explosible limit by using different dust concentrations.

Relation between temperature and concentration for wood dust

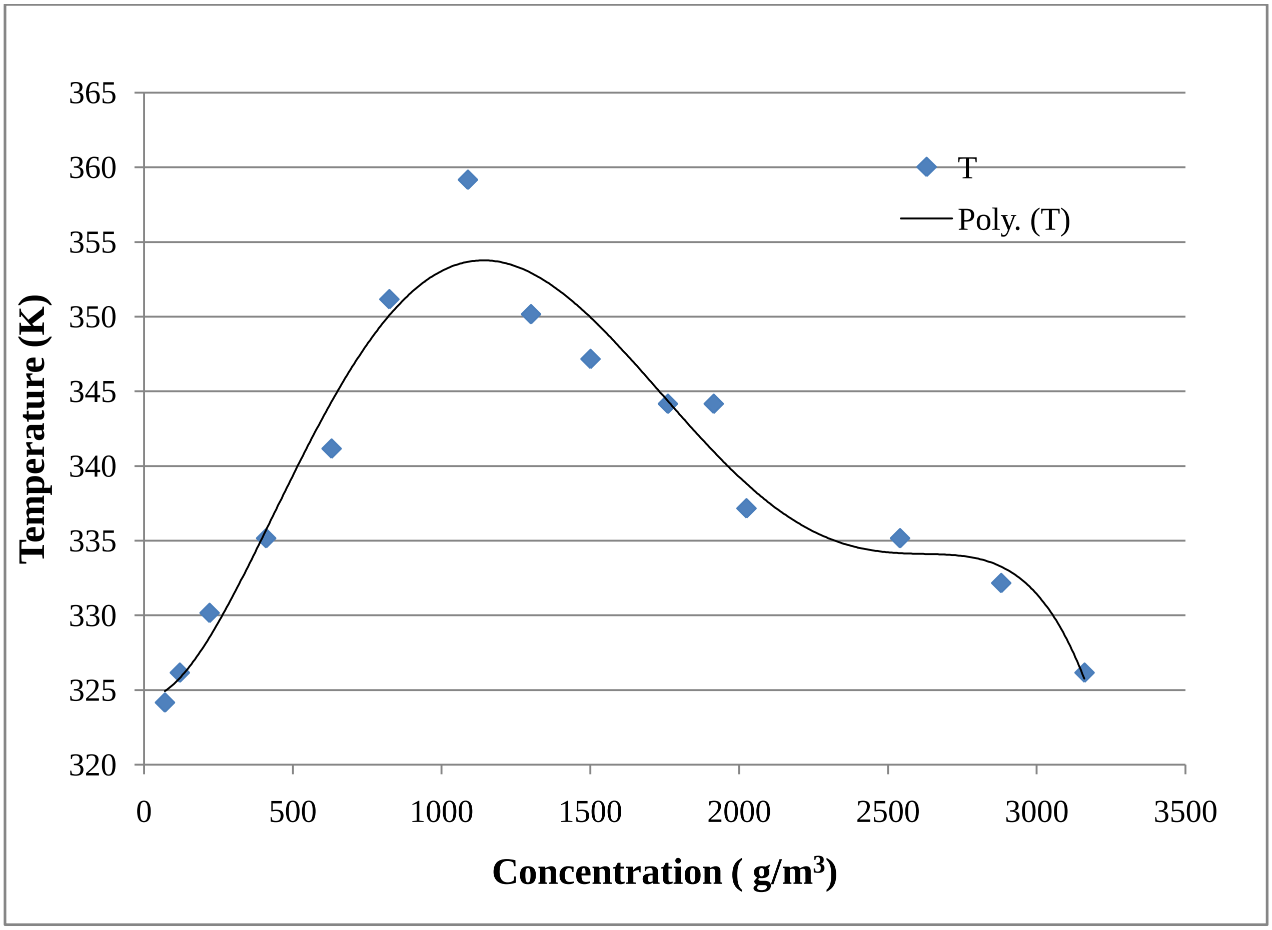


Figure 3.18: Variation of temperature with dust concentration for wood dust

Figure 3.18 shows variation of temperature with dust concentration. It has been observed that when concentration of dust is less than 70 g/m^3 or more than 3160 g/m^3 there is no explosion inside container. This shows dust explosion will be avoided if concentration is less than 70 g/m^3 or more than 3160 g/m^3. On the other hand maximum temperature is 359.15 K at concentration level of 1088 g/m^3 which shows explosion at this concentration is much more dangerous than others. At concentration level of 1088 g/m^3, temperature of explosion is maximum because at this concentration air and dust mixture become stoichiometric. Which means oxygen required for burning is in proper proportion to dust. But at concentration levels of 70 g/m^3 and 3160 g/m^3, dust and air concentration is very lean and very rich respectively. Because of lean and rich mixture of dust and air, burning does not occur.

Relation between pressure and concentration for wood dust

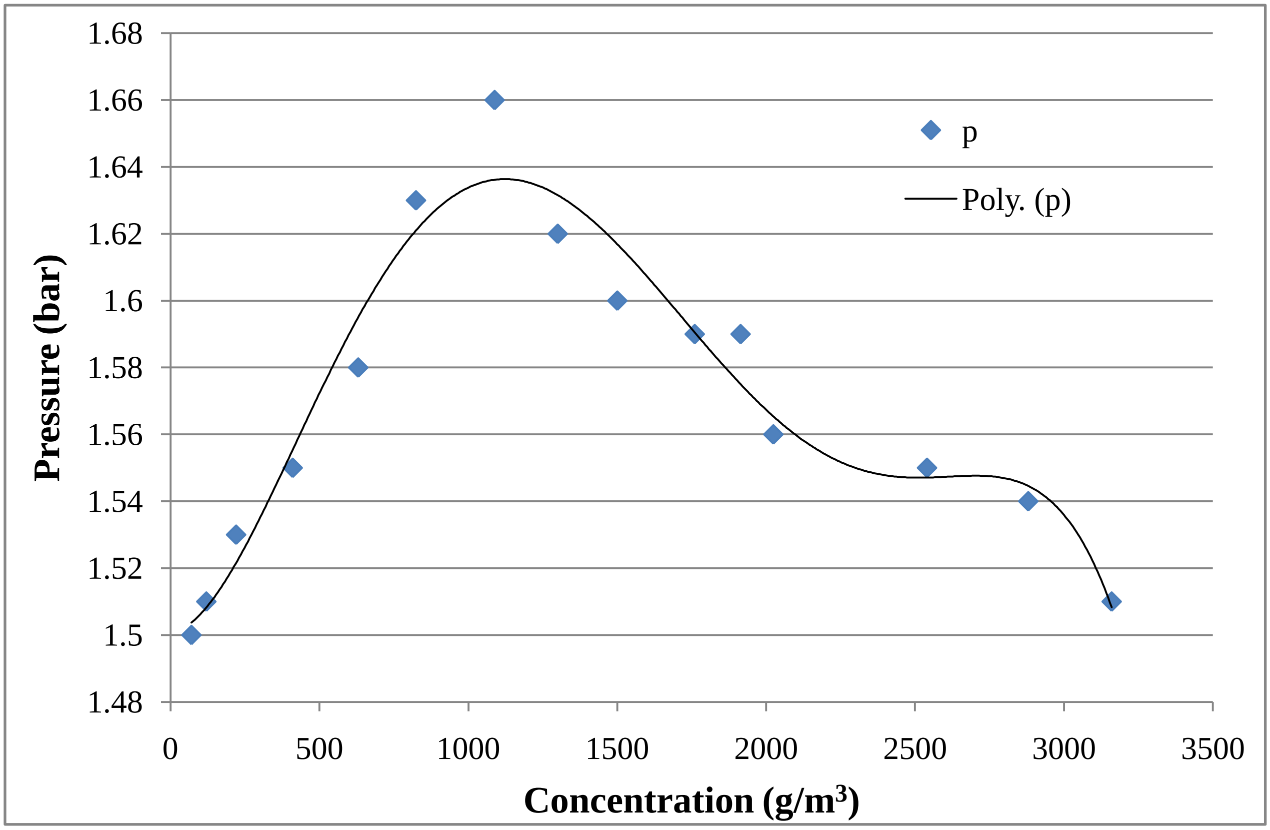


Figure 3.19: Variation of pressure with dust concentration for wood dust

Figure 3.19 shows variation of pressure with dust concentration. It has been observed that when concentration of dust is less than 70 g/m^3 or more than 3160 g/m^3 there is no explosion inside container. This shows dust explosion will be avoided if concentration level is less than 70 g/m^3 and more than 3160 g/m^3. On the other hand maximum pressure is 1.66 bar at concentration level of 1088 g/m^3 which shows explosion at this concentration is much more dangerous than others.

At concentration level of 1088 g/m^3, pressure of explosion is maximum because at this concentration air and dust mixture become stoichiometric. Which means oxygen required for burning is in proper proportion to dust. But at concentration levels of 70 g/m^3 and 3160 g/m^3, dust and air concentration is very lean and very rich respectively. Because of lean and rich mixture of dust and air, burning does not occur.

3.9.3 Dust Explosion using pulverized coal

Specifications of pulverized coal

ASH percentage on fire basis: 26.45

VM percentage on fire basis: 26.34

Gross C.V (Kcals / Kgms) on fire basis: 4319.21

Sample of coal dust contains different size dust particles. With the help of sieving machine different size dust samples are collected. In these experiments two dust samples of size less than 53 micro meters and 105 micro meters are used for experiment. Samples of different concentrations have been prepared with the help of digital weighing machine. After this put dried dust with variable concentration into container by performing all steps of experiment procedure and give a variable spark.

Characteristics of coal dust:

Coal of size 105 micrometer and less than 53 micrometer is used for an experiment of dust explosion. In this study relation between temperature and pressure with dust concentration has been studied. This experiment has been done to find explosion flame temperatures, flame pressure, minimum and maximum explosible limit by using different dust concentrations.

Dust explosion using 105 micrometer coal dust

Table 3.1: Explosion status with variable dust and spark timing

Dust concentration g/m^3	Spark timing	Result
70.4	5,8,10 seconds	No explosion
120	5,8,10 seconds	No explosion
180.43	5,8,10 seconds	No explosion
200.60	5,8,10 seconds	No explosion
250.50	5,8,10 seconds	No explosion
300.84	5,8,10 seconds	No explosion
369.5	5,8,10 seconds	No explosion
400.71	5,8,10 seconds	No explosion
558.8	5,8,10 seconds	No explosion
600.9	5,8,10 seconds	No explosion

Dust explosion using coal dust of size less than 53 micrometer

Table 3.2: Explosion status with variable dust and spark timing

Dust concentration g/m^3	Spark timing	Result
74.5	5,8,10 seconds	No explosion
138.52	5,8,10 seconds	No explosion
168.43	5,8,10 seconds	No explosion
220.60	5,8,10 seconds	No explosion
286.50	5,8,10 seconds	No explosion
332.84	5,8,10 seconds	No explosion
387.5	5,8,10 seconds	No explosion
428.71	5,8,10 seconds	No explosion
523.8	5,8,10 seconds	No explosion
597.9	5,8,10 seconds	No explosion

Variable dust concentration samples have been used to study characteristics of coal dust. A variable spark of 5, 8, and 10 seconds are given to coal dust, but there is no explosion occurred inside container. From above results it has been found that coal dust explosion does not occur without presence of oxidant. Coal dust explosion may occur if initial temperature is very high or if spark will be given for large time, but chances of this explosion may be very less because ignition temperature of coal dust is very high.

3.10 Comparison between characteristics of wheat husk and wood dust

While doing comparison study it is found that temperature rise in case of wood dust, at most of the concentrations is higher than wheat husk. It has been observed in case of wood dust maximum temperature is 359.15 K and for wheat husk maximum temperature is 351.15K. It clearly shows that after explosion flame temperature is more for wood dust as compare to wheat husk. It concludes that wood dust is more hazardous as compare to wheat husk.

Comparison of temperature characteristics of wheat husk and wood dust

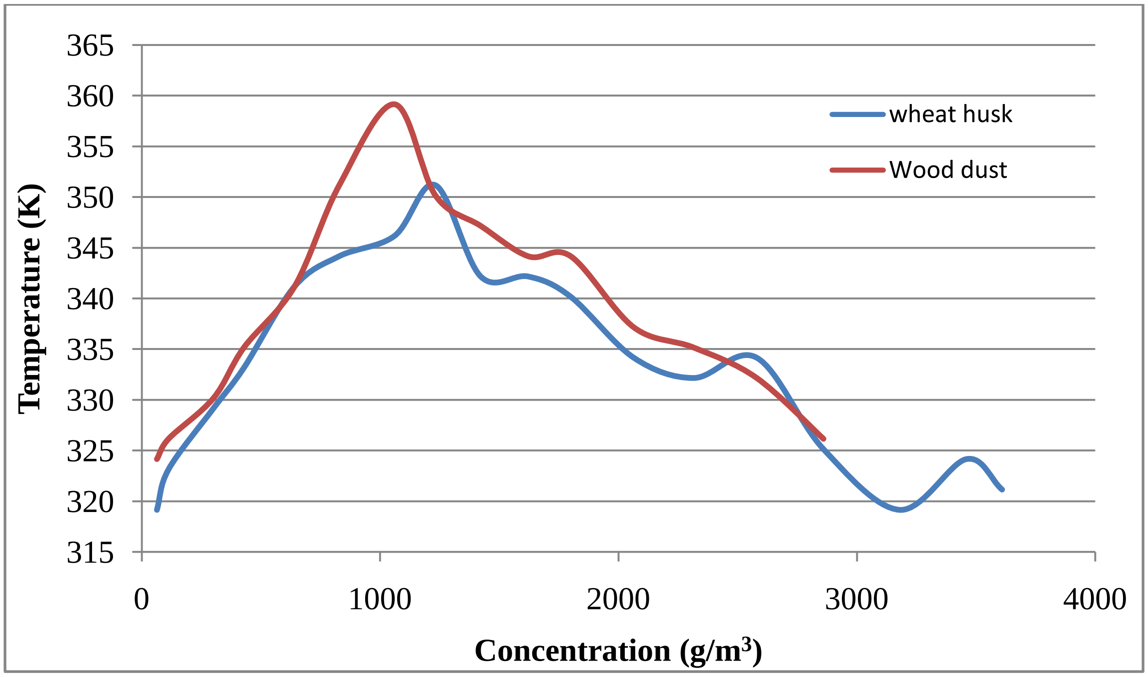


Figure 3.20: Comparison between explosion temperature of wheat husk and wood dust

Comparison of pressure characteristics of wheat husk and wood dust

While doing comparison study it is found that pressure rise in case of wood dust, at most of the concentrations is higher than wheat husk. It has been observed in case of wood dust maximum pressure is 1.66 bar and for wheat husk maximum pressure is 1.62 bar. It clearly shows that after explosion flame pressure is more for wood dust as compare to wheat husk. It concludes that wood dust is more destructive as compare to wheat husk.

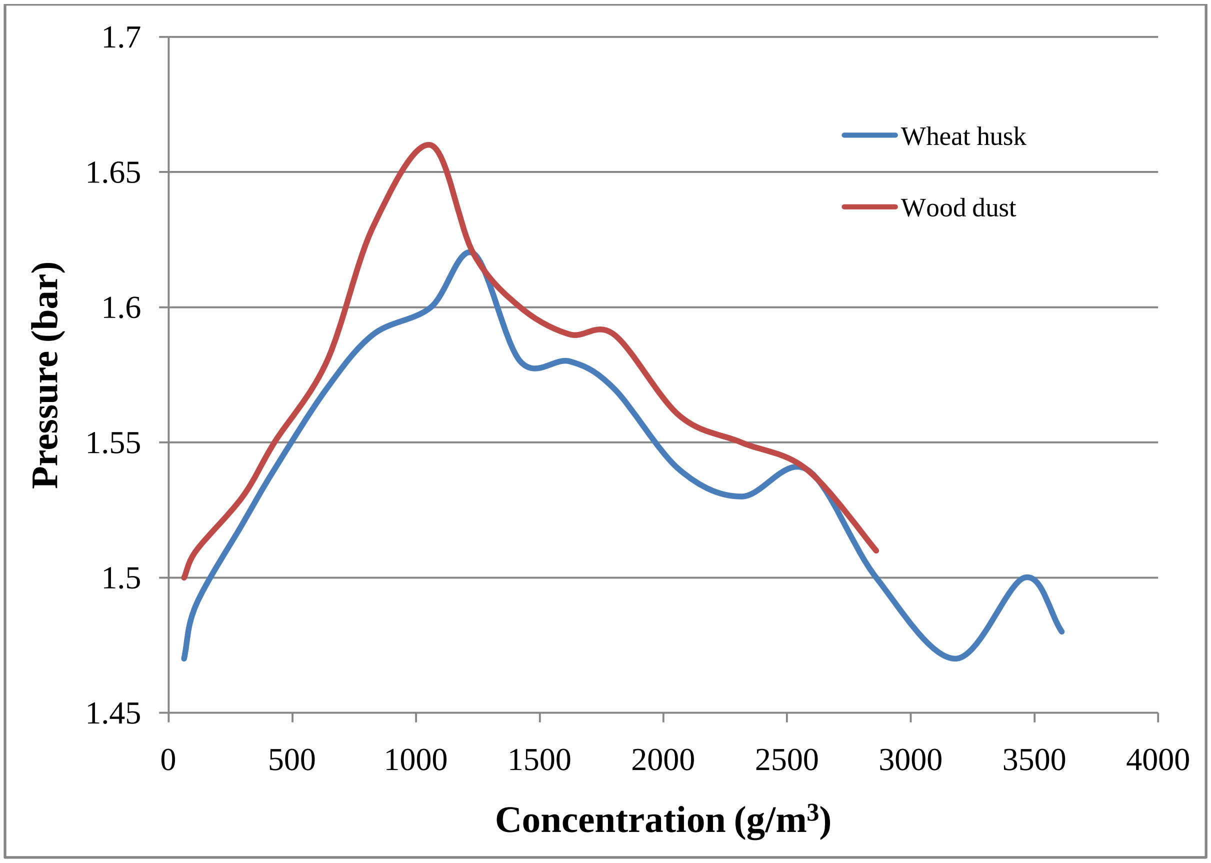


Figure 3.21: Comparison between explosion pressure of wheat husk and wood dust

CHAPTER 4: EMPIRICAL MODELING FOR EXPLOSION PRESSURE AND IT’S VALIDATION

4.1 Empirical modeling of explosion pressure

Empirical modeling is any kind of modeling, which is based on empirical observations instead of mathematically described relationship of the system modeled. Empirical evidence is the source of knowledge achieve by mean of observation or experimentation. Empirical evidence is that information which justifies a belief in truth and falsity of the claim. From literature it is found that it is difficult to make a model for explosion pressure. Lots of models are available but no model for explosion pressure has been found. So it has been decided to work in this area.

4.2 Empirical modeling

Parameters like concentration of dust, Initial temperature, viscosity of Fluid, diameter of particle and specific heat of fluid; directly or indirectly effects explosion pressure. So in this model of explosion pressure, take all these parameters as a function of pressure.

Explosion pressure $P = f(\rho, T_{i,}\ \mu, d_{p,} C_p)$

By using Buckingham Π theorem

$\Pi_1 = P\,(\rho)^a\,(T_i)^b\,(\mu)^c\,(d_p)^d$

$\Pi_1 = P \times \rho \times (d_p)^2 / (\mu)^2$

$\Pi_2 = C_p\,(\rho)^a\,(T_i)^b\,(\mu)^c\,(d_p)^d$

$\Pi_2 = C_p \times (\rho)^2 \times T_i \times (d_p)^2 / (\mu)^2$

It is found that lots of experiments have been done in the literature work. So lots of graphs are available for experimental work. Obtain experimental readings from these graphs and on the behalf of these readings empirical model can be predicted.

Π_1, Π_2 terms for 7 micrometer Aluminium particle (Figure 2.16) [25]

Table 4.1 Concentration, pressure, pi1 and pi2 values

ρ	P		π1	π2
88.778	1.244		1376.184	299.0681
103.304	1.886		2427.781	404.9427
110.367	2.528		3476.698	462.2084
124.868	3.211		4996.226	591.6456
139.12	4.294		7443.93	734.4098
153.571	5.057		9677.269	894.9067
182.698	6.221		14162.65	1266.563
234.412	7.064		20633.89	2085.062
345.852	7.866		33899.62	4538.788
450.005	8.388		47035.57	7684.118
628.659	9.11		71364.82	14996.49
852.189	9.672		102707.7	27556.95
1083.506	9.712		131126.6	44547.36
1180.82	9.231		135826.1	52908.66
1337.935	8.589		143195.1	67924.96
1464.9	8.428		153844.9	81428.29
1651.665	8.107		166852.5	103515
1793.68	7.746		173130.3	122081.3
1928.183	7.465		179361.3	141076.9

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-2.13409	0.332	-6.423	6.3E-06	-2.835	-1.433	-2.83	-1.433
X Variable 1	1.331951	0.073	18.246	1.3E-12	1.178	1.486	1.178	1.486

Π_1, Π_2 terms for 10 micrometer magnesium particle (Figure 4.1) [26]

Graph from where experimantal readings of pressures and concentrations are taken

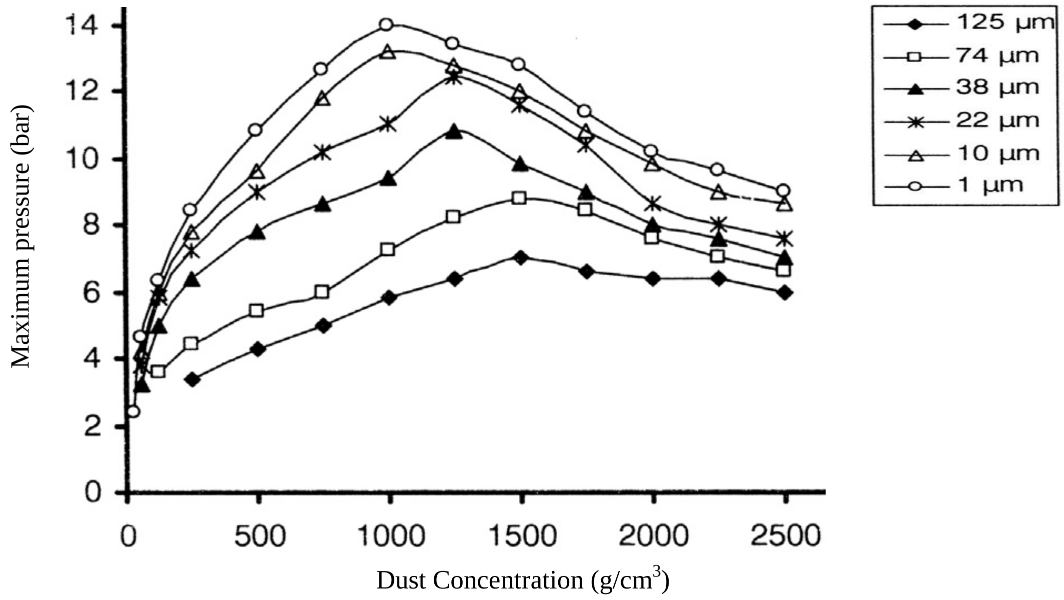


Figure 4.1: Shows relation between maximum pressure and dust concentration

Table 4.2 Concentration, pressure, pi1 and pi2 values

ρ	p		π1	π2
181.752	6.963		32183.27	2558.124
289.384	8.049		59233.99	6485.035
419.755	9.026		96348.68	13644.42
542.46	9.949		137246.6	22787.61
649.936	10.872		179694.4	32711.8
788.024	11.958		239636.3	48088.6
948.799	12.881		310798.1	69712.67
1139.201	12.932		374645.6	100499.5
1336.648	12.384		420952	138355.8
1549.167	11.672		459830.8	185848.8
1708.336	10.908		473885	226000.7
1875.171	10.197		486259.2	272298.4
2080.024	9.432		498915.2	335042.5
2307.823	8.774		514937.7	412447.1
2452.334	8.608		536829.6	465721.2

Value K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-4.64666	0.512	-9.075	5.48E-07	-5.753	-3.540	-5.753	-3.541
X Variable 1	1.761173	0.095	18.594	9.51E-11	1.557	1.966	1.557	1.966

Π_1, Π_2 terms for 11 micrometer Aluminium particle (Figure 2.16) [25]

Table 4.3 Concentration, pressure, pi1and pi2 values

ρ	p		π1	π2
74.239	1.947		4447.726	516.4317
94.947	2.965		8662.553	844.7168
115.558	4.071		14475.75	1251.263
147.271	5.00		22658.29	2032.278
211.374	6.239		40579.48	4186.506
319.257	7.345		72155.95	9550.574
492.69	8.363		126787.3	22745.53
797.466	8.982		220406.9	59589.94
1048.952	8.451		272774.4	103100.3
1300.39	7.965		318712.7	158451.3
1628.238	7.434		372460.6	248418.8
2097.566	7.212		465491	412268.3
2381.537	6.903		505865.6	531451.1
2632.782	6.593		534118.9	649113.1
2927.759	6.195		558105.9	803191.8

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-3.37684	0.405	-8.344	1.4E-06	-4.251	-2.502	-4.251	-2.502
X Variable 1	1.566882	0.08	19.637	4.8E-11	1.395	1.74	1.395	1.74

Π_1, Π_2 terms for 22 micrometer magnesium particle (Figure 4.1) [26]

Table 4.4 Concentration, pressure, pi1and pi 2 values

ρ	p		π1	π2
166.132	6.553		133996.5	10344.64
219.898	7.044		190651.6	18123.88

334.836	7.809		321830.7	42021.63
442.108	8.519		463571.7	73259.74
595.272	9.447		692164.5	132812.7
717.616	9.993		882648.8	193015.8
900.977	10.648		1180815	304253.8
1076.931	11.522		1527270	434694.7
1207.098	12.286		1825379	546127
1381.96	12.013		2043369	715813
1556.356	11.249		2154879	907876
1677.661	10.703		2210089	1054914
1813.986	9.938		2218875	1233322
1919.906	9.228		2180658	1381556
2056.179	8.409		2128165	1584639
2208.096	8.027		2181580	1827446
2360.169	7.809		2268498	2087829

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-4.9667	0.479	-10.368	3.1E-08	-5.988	-3.946	-5.988	-3.946
X Variable 1	1.738272	0.079	21.943	8.2E-13	1.569	1.907	1.57	1.907

Π_1, Π_2 terms for 38 micrometer Magnesium particle (Figure 4.1) [26]

Table 4.5 Concentration, pressure, pi 1and pi 2 values

ρ	p		π1	π2
93.16	4.258		145665.6	9704.863
146.765	5.185		279442.9	24086.6
215.508	6.003		475065.5	51934.65
299.362	6.657		731807.7	100212.9
428.838	7.419		1168316	205644.4
543.02	7.963		1587868	329732.8
695.125	8.397		2143428	540326.5
832.04	8.831		2698211	774138.9
1037.464	9.592		3654298	1203584
1197.423	10.572		4648646	1603340
1356.889	10.515		5239325	2058823
1470.553	9.966		5381748	2418198
1637.303	9.253		5563312	2997703
1804.131	8.704		5766452	3639708

1933.037	8.265		5866847	4178407
2145.434	7.715		6078170	5147078
2373.072	7.274		6338784	6297270

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-4.57802	0.331	-13.849	5.9E-10	-5.283	-3.873	-5.283	-3.873
X Variable 1	1.638628	0.052	31.51	4.0E-15	1.528	1.749	1.528	1.749

Π_1, Π_2 terms for 57.5micrometer coal particle (Figure 4.2) [27]

Graph from where experimantal readings of pressures and concentrations are taken

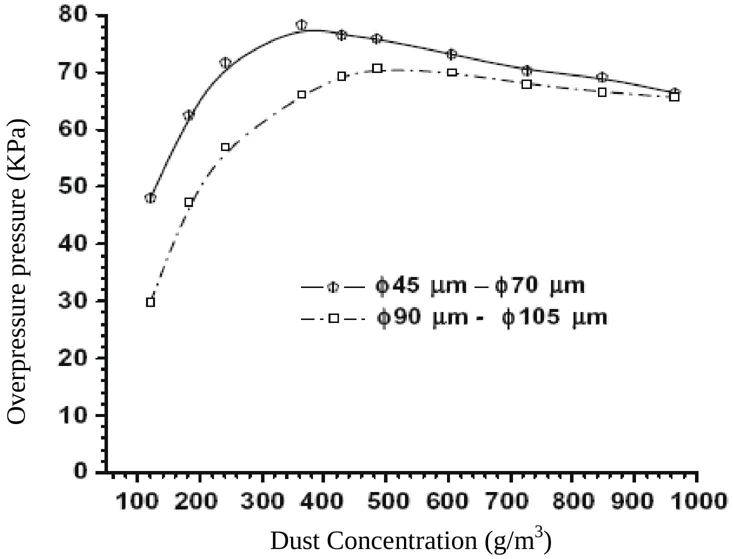


Figure 4.2: Relation between over pressure and dust concentration

Table 4.6 Concentration, pressure, pi 1 and pi 2 values

ρ	p		π1	π2
88.092	50.706		37556.58	19868.81
109.658	55.16		50857.48	30787.87
131.212	59.892		66074.31	44080.45
189.861	69.074		110265.7	92293.36
239.398	72.963		146863.4	146737.1
304.485	76.29		195309.7	237372.7

372.786	76.828		240807.2	355810
469.123	75.129		296336.1	563472.1
521.95	74.278		325971.3	697520.1
593.453	72.307		360792	901719.8
655.608	71.175		392339.5	1100493
727.09	69.761		426472.6	1353553
773.695	69.19		450094.2	1532634
832.722	68.617		480421	1775411
882.443	67.766		502792.5	1993757
935.292	66.358		521832.1	2239718

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-4.08534	0.274	-14.92	5.5E-10	-4.673	-3.498	-4.673	-3.498
X Variable 1	1.808858	0.051	35.383	4.3E-15	1.699	1.919	1.699	1.919

Π_1, Π_2 terms for 74 micrometer magnesium particle (Figure 4.1) [26]

Table 4.7 Concentration, pressure, pi 1and pi 2 values

ρ	p		π1	π2
161.299	3.804		854457	110329.1
214.669	4.237		1266618	195473
374.496	4.939		2575753	594731.7
564.676	5.585		4391779	1352152
701.485	5.798		5663887	2086717
861.338	6.554		7861367	3146110
1059.241	7.472		11021727	4757910
1173.37	7.903		12913530	5838438
1348.309	8.441		15848981	7709134
1568.687	8.705		19016171	10435164
1697.669	8.428		19924873	12221731
1834.195	8.042		20541284	14266509
1947.962	7.712		20920185	16091171
2114.841	7.27		21410664	18966279
2334.909	6.881		22373788	23118871

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-4.1068	0.276	-14.89	1.5E-09	-4.702	-3.511	-4.702	-3.510
X Variable 1	1.539668	0.04	38.779	7.9E-15	1.454	1.625	1.453	1.625

Π_1, Π_2 terms for 27.6 micrometer coal particle (Figure 2.9) [21]

Table 4.8 Concentration, pressure, pi 1 and pi 2 values

P	ρ		π1	π2
1.533	143.963		42752.92	12225
1.866	162.539		58723.12	15584.6
2.401	195.046		90719.76	22441.6
2.964	236.842		135990.8	33090.15
3.474	297.314		200086.5	52109.8
3.934	376.161		286669	83469.71
4.522	557.276		488172.8	183198.6
4.65	608.359		548006.3	218453.1
4.803	733.746		682701.7	317594.4
4.726	845.201		773795.8	421406.6
4.675	882.353		799091.8	459267.9
4.573	938.08		831024.3	519112.1
4.445	1003.096		863747.8	593562.4
4.266	1114.551		921071.8	732792.9
3.909	1309.598		991690.9	1011713
3.704	1434.985		1029653	1214720

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-2.59467	0.395	-6.569	1.3E-05	-3.442	-1.748	-3.442	-1.748
X Variable 1	1.403966	0.071	19.866	1.2E-11	1.252	1.555	1.252	1.555

Π_1, Π_2 terms for 7.5 micrometer magnesium particle (Figure 4.3) [21]

Graph from where experimantal readings of pressures and concentrations are taken

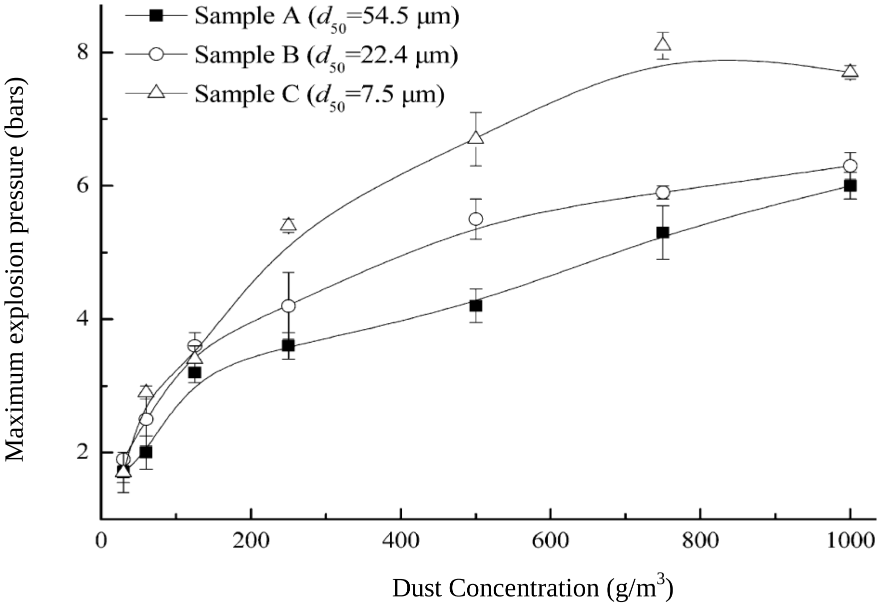


Figure 4.3: Relation between dust concentration and explosion pressure

Table 4.9 Concentration, pressure, pi 1and pi 2 values

ρ	p		π1	π2
69.767	2.117		2112.749	212.0244
81.395	2.335		2718.703	288.59
156.977	3.393		7618.983	1073.391
212.209	4.233		12849.59	1961.613
264.535	4.856		18375.49	3048.26
311.047	5.323		23684.25	4214.42
375.00	5.79		31058.96	6125.596
430.233	6.163		37929.14	8062.936
479.651	6.444		44213.81	10021.59
537.791	6.817		52442.56	12598.33
587.209	7.128		59873.89	15020.04
642.442	7.44		68372.89	17978.51
691.86	7.626		75473.09	20850.78
752.907	7.844		84480.41	24692.69
857.558	7.938		97375.95	32034.12
898.256	7.875		101187.7	35146.82
970.93	7.751		107652.2	41064.04

Value K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-2.08367	0.078	-26.538	5.1E-14	-2.251	-1.916	-2.251	-1.916
X Variable 1	1.314377	0.017	75.592	8.8E-21	1.277	1.351	1.277	1.351

Π_1, Π_2 terms for 22.4 micrometer magnesium particle (Figure 2.9) [21]

Table 4.10 Concentration, pressure, pi 1and pi 2 values

ρ	p		π1	π2
50.223	1.43		9164.0889	980.0869
70.312	1.948		17477.08556	1920.959
80.357	2.195		22506.54585	2509.035
107.143	2.639		36078.94261	4460.535
150.669	3.256		62597.77697	8820.782
194.196	3.577		88635.93466	14653.45
227.678	3.873		112517.2666	20141.95
287.946	4.22		155050.8349	32216.73
331.472	4.442		187878.0359	42692.64
445.311	4.962		281949.1512	77052.4
552.454	5.284		372485.6443	118590.9
786.828	5.805		582817.5739	240557.5
960.935	6.03		739370.1828	358795.8
1047.988	6.056		809827.9927	426748.4
1121.649	6.008		859879.323	488847.3
1202.006	5.886		902770.7963	561400.2
1302.452	5.69		945637.3161	659147.7
1376.113	5.494		964702.4046	735813.1
1419.639	5.397		977644.4701	783096.2
1453.121	5.299		982531.1023	820470.3

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-2.98958	0.17	-17.611	8.6E-13	-3.346	-2.633	-3.346	-2.633
X Variable 1	1.462279	0.032	46.329	3.5E-20	1.396	1.529	1.396	1.529

Π_1, Π_2 terms for 36.5 micrometer coal particle (Figure 2.11) [22]

Table 4.11 Concentration, pressure, pi 1, pi 2

ρ	P		π1	π2
0.073385	211000		52460.21	5556.017
0.087944	264000		78659.37	7979.238
0.102347	330000		114427.2	10806.85
0.121956	383000		158249.5	15344.59
0.182123	422000		260386	34219.89
0.292999	442000		438761.7	88568.9
0.394161	428000		571554.6	160286.3
0.546033	396000		732578.9	307600.3
0.647427	361000		791841.6	432444.7
0.774356	301000		789673.3	618629.1
0.840733	237000		675066.8	729231.1
0.891855	182000		549925.1	820611.3
0.953181	117000		377834.4	937345.6

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-5.35433	1.403	-3.815	0.00287	-8.443	-2.265	-8.443	-2.265
X Variable1	1.88574	0.255	7.408	1.4E-05	1.325	2.446	1.325	2.445

Π_1, Π_2 terms for 36.5 micrometer coal particle (Figure2.11) [22]

Table 4.12 Concentration, pressure, pi 1, pi 2

ρ	P		π1	π2
7.189	46000		1120.383	53.31949
12.581	46000		1960.71	163.2974
19.77	74000		4956.541	403.2388
23.963	104000		8443.351	592.4223
28.756	136000		13249.75	853.1118
32.051	150000		16288.2	1059.82
36.244	173000		21243.33	1355.256
41.636	198000		27930.23	1788.492
46.429	221000		34763.37	2223.963
51.221	249000		43210.34	2706.731
54.516	271000		50053.4	3066.175
57.512	289000		56311.44	3412.447

Value of K and n after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-1.13616	0.147	-7.713	1.6E-05	-1.464	-0.808	-1.464	-0.808
X Variable 1	0.987815	0.035	28.00	7.8E-11	0.909	1.066	0.909	1.066

Values of K, n of different graphs in table

Table 4.13: Different values of K and n from graphs

K	n
0.007344	1.331951
2.26E-05	1.761173
0.00042	1.566882
1.08E-05	1.738272
2.64E-05	1.638628
8.22E-05	1.808858
7.82E-05	1.539668
0.002543	1.403966
0.008248	1.314377
0.001024	1.462279
4.42E-06	1.88574
0.073087	0.987815

Use values of K and n, find value of K_1, m_1, m_2 and K_2 , x_1 , x_2 using equation

$K = K_1 (\rho_p / \rho_f)^{m1} (W_{f0} / (g \times d_p)^{½})^{m2}$ $n = K_2 (\rho_p / \rho_f)^{x1} (W_{f0} / (g \times d_p)^{½})^{x2}$

Where

ρ_p is particle density

ρ_f is fluid density

W_{fo} is particle velocity

g is acceleration due to gravity

d_p is particle diameter

For 7 micro meter aluminum dust K and n equation are

$K = 0.007344 = K_1 (2650/ 1.165)^{m1} \times (0.0039/ (9.8 \times 7\times10\text{^}{-6})^{1/2})^{m2}$

$n = 1.331951 = K_2 (2650/ 1.165)^{x1} \times (0.0039/ (9.8 \times 7\times10\text{^}{-6})^{1/2})^{x2}$

In the same way make equations of K and n for different dusts

After that apply regression and find value of K_1, K_2, m_1, m_2, x_1, x_2

Value of K_1, m_1, m_2 are

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-3.4891	17.049	-0.204	0.8424	-42.056	35.078	-42.056	35.078
X Variable 1	0.06288	5.321	0.011	0.991	-11.975	12.100	-11.975	12.10
X Variable 2	-0.92883	1.125	-0.825	0.430	-3.474	1.617	-3.474	1.617

Value of K_2, x_1, x_2 are

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.045072	1.038	0.043	0.966	-2.30	2.392	-2.302	2.392
X Variable 1	0.040075	0.323	0.124	0.904	-0.692	0.773	-0.693	0.772
X Variable 2	0.03479	0.068	0.508	0.624	-0.120	0.190	-0.120	0.19

Values of K_1, m_1, m_2 and K_2, x_1, x_2 are given below

Table 4.14: Values of K_1, m_1, m_2 and K_2, x_1, x_2

K_1	m_1	m_2	K_2	x_1	x_2
0.000324264	.06288	-0.92883	1.109358716	0.040075	0.03479

By using these values of K_1, m_1, m_2, K_2, x_1, x_2 find values of K, n for every graph and calculate pressure by using equation.

$$\Pi_1 = K (\Pi_2)^n \qquad (4.1)$$

$$\Pi_1 = P \times \rho \times (d_p)^2 / (\mu)^2$$

$$\Pi_2 = C_p \times (\rho)^2 \times T_i \times (d_p)^2 / (\mu)^2$$

Put Π_1, Π_2 in equation (4.1) and solve for p

$$P \times \rho \times (d_p)^2 / (\mu)^2 = K (C_p \times (\rho)^2 \times T_i \times (d_p)^2 / (\mu)^2)^n$$

$$P = K \{(\mu)^2 / \rho \times (d_p)^2\} (C_p \times (\rho)^2 \times T_i \times (d_p)^2 / (\mu)^2)^n$$

4.3 Validation of Model

Validation has been done by comparing experimental data with calculated data from model. Validation of model is required to check accuracy of empirical model.

4.3.1 Validation of model for 10 micrometer Al-2 Aluminium Particles (Figure 4.4) [28]

Values of K, n are: $K= 0.000324264\ \{2650/1.165\}^{0.06288} \times \{0.0079/\ (9.8\times10\times10^{-6})^{1/2}\}^{-0.92883}$

After solving we will get $K = 6.501198\times10^{-4}$

$n= 1.109358716\ \{2650/1.165\}^{.040075} \times \{0.0079/\ (9.8\times10\times10^{-6})^{1/2}\}^{0.03479}$

After solving we will get n= 1.500346

Graph from where experimantal readings of pressures and concentrations are taken

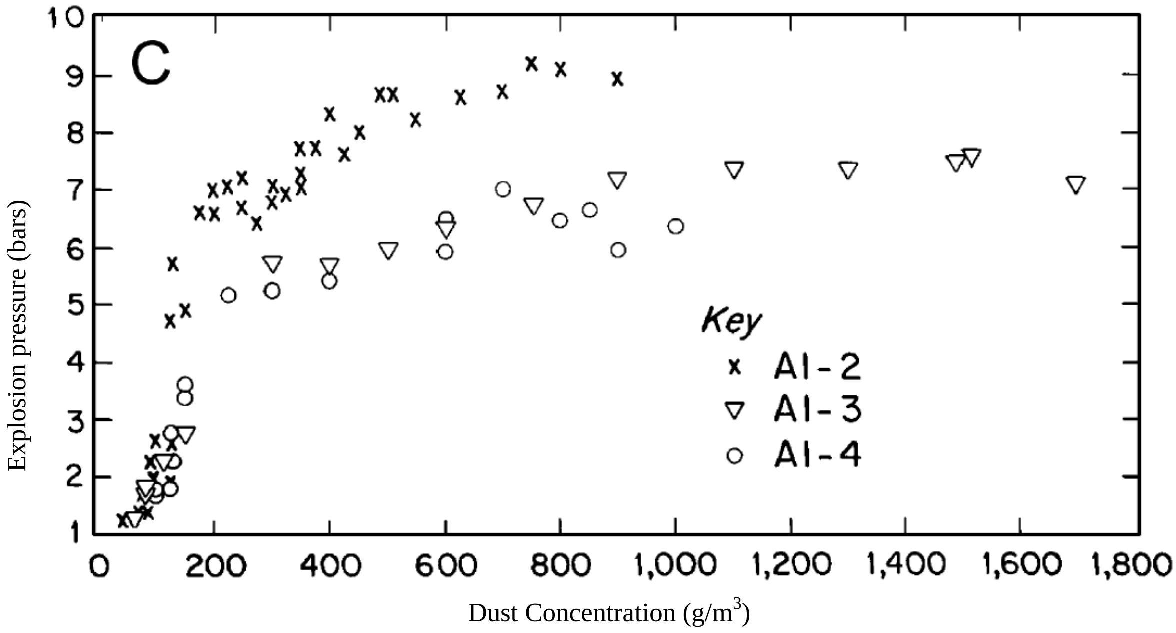


Figure 4.4: Relation between dust concentration and explosion pressure

Table 4.15: Pressure from experimental data and from model with variable concentration

ρ	P(from Graph)Bar		ρ	P(from model) N/m^2
51.347	0.269		51.347	145.5116
100.213	1.347		100.213	554.5123963
108.438	1.826		108.438	649.31078
133.332	4.072		133.332	981.789

255.369	6.287		255.369	3603.110347
309.439	6.647		309.439	5291.145135
382.512	7.425		382.512	8086.342654
458.163	7.754		458.163	11602.60323
552.671	7.964		552.671	16885.12639
633.744	8.383		633.744	22204.39604
755.36	9.042		755.36	31547.89853
806.594	8.892		806.594	35974.25454
906.395	8.713		906.395	45430.08558

4.3.2 Percentage error in model

Validation percentage Error = (Actual value – Theoretical value) / Actual value

= (26900 – 145.5116)/26900 = 0.9945 = 99.45%

= (628700 – 3603.110347)/628700 = 0.9942 = 99.42%

= (796400 – 16885.12634)/ 796400 = 0.9787 = 97.87%

= (871300 – 45430.08558)/ 871300 = 0.9478 = 94.78%

Average percentage error in Validation = 97.88%

4.4 Modification of empirical Model

97.88 percent error in model shows that there is lot of difference between the experimental results and theoretical empirical model results. This shows that there are certain more parameters that can effect explosion Pressure. So try another model by considering one more parameter called turbulence (Reynolds number).

Explosion pressure $P = f(\rho, T_i, \mu, d_p, C_p, Re)$

$\Pi_1 = P \times \rho \times (d_p)^2 / (\mu)^2$

$\Pi_2 = C_p \times (\rho)^2 \times T_i \times (d_p)^2 / (\mu)^2$

$\Pi_3 = Re$

$\Pi_1 = K (\Pi_2)^{n1} (\Pi_3)^{n2}$

Take different graphs of pressure and concentration for a given diameter dust. Find Π_1, Π_2, Π_3 terms and apply regression to find values of K, n_1 and n_2.

Π_1, Π_2, Π_3 terms for 10 micrometer Magnesium dust particle (Figure 4.1) [26]

Table 4.16: Concentration, pressure, pi 1, pi 2 and pi 3 values

ρ	P	π1	π2	π3
181.752	6.963	32183.26972	2558.124	0.000458
289.384	8.049	59233.99364	6485.035	0.00073
419.755	9.026	96348.68215	13644.42	0.001058
542.46	9.949	137246.6403	22787.61	0.001368
649.936	10.87	179694.4271	32711.8	0.001639
788.024	11.96	239636.2778	48088.6	0.001987
948.799	12.88	310798.1107	69712.67	0.002392
1139.201	12.93	374645.589	100499.5	0.002872
1336.648	12.38	420951.9909	138355.8	0.00337
1549.167	11.67	459830.832	185848.8	0.003906
1708.336	10.91	473885.0346	226000.7	0.004307
1875.171	10.2	486259.2416	272298.4	0.004728
2080.024	9.432	498915.1705	335042.5	0.005245
2307.823	8.774	514937.7119	412447.1	0.005819
2452.334	8.608	536829.594	465721.2	0.006183

Values after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	10.08503317	0.001	14028.28	1.16E-44	10.083	10.087	10.083	10.086
X Variable 1	7.04029E-05	8.69E-05	0.810	0.433433	-0.0001	0.0002	-0.001	0.0003
X Variable 2	1.999904265	9.68E-05	20652.04	1.12E-46	1.2	2.00012	1.2	2.0001

Π_1, Π_2, Π_3 terms for 11 micrometer Aluminium dust particle (Figure 2.16) [25]

Table 4.17: Concentration, pressure, pi 1, pi 2 and pi 3 values

ρ	P	π1	π2	π3
74.239	1.947	4447.726	516.4317	0.000391
94.947	2.965	8662.553	844.7168	0.0005
115.558	4.071	14475.75	1251.263	0.000609
147.271	5.000	22658.29	2032.278	0.000776
211.374	6.239	40579.48	4186.506	0.001114
319.257	7.345	72155.95	9550.574	0.001682

492.69	8.363	126787.3	22745.53	0.002596
797.466	8.982	220406.9	59589.94	0.004202
1048.952	8.451	272774.4	103100.3	0.005528
1300.39	7.965	318712.7	158451.3	0.006853
1628.238	7.434	372460.6	248418.8	0.00858
2097.566	7.212	465491	412268.3	0.011054
2381.537	6.903	505865.6	531451.1	0.01255
2632.782	6.593	534118.9	649113.1	0.013874
2927.759	6.195	558105.9	803191.8	0.015429

Values after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	9.527075	0.001	8528.196	4.55E-42	9.525	9.53	9.525	9.53
X Variable 1	0.00012	0.0001	0.87616	0.398143	-0.0001	0.0004	-0.0002	0.0004
X Variable 2	1.999815	0.0002	11624.61	1.11E-43	1.2	2.0002	1.2	2.0002

Π_1, Π_2, Π_3 terms for 22 micrometer Magnesium dust particle (Figure 4.1) [26]

Table 4.18: Concentration, pressure, pi 1, pi 2 and pi 3 values

ρ	p	π1	π2	π3
219.898	7.044	190651.6	18123.88	0.005367
334.836	7.809	321830.7	42021.63	0.008172
442.108	8.519	463571.7	73259.74	0.010791
595.272	9.447	692164.5	132812.7	0.014529
717.616	9.993	882648.8	193015.8	0.017515
900.977	10.648	1180815	304253.8	0.021991
1076.931	11.522	1527270	434694.7	0.026285
1207.098	12.286	1825379	546127	0.029462
1381.96	12.013	2043369	715813	0.03373
1556.356	11.249	2154879	907876	0.037987
1677.661	10.703	2210089	1054914	0.040947
1813.986	9.938	2218875	1233322	0.044275
1919.906	9.228	2180658	1381556	0.04686
2056.179	8.409	2128165	1584639	0.050186
2208.096	8.027	2181580	1827446	0.053894
2360.169	7.809	2268498	2087829	0.057606

Values after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	8.798763	2.69E-07	32719523	7.67E-92	8.8	8.799	8.799	8.799
X Variable 1	8.09E-09	3.44E-08	0.235	0.817719	-6.6E-08	8.24E-08	-6.6E-08	8.24E-08
X Variable 2	2	3.79E-08	52718208	1.56E-94	2	2	2	2

Π_1, Π_2, Π_3 terms for 36.5 micrometer Coal dust particle (Figure 2.11) [22]

Table 4.19: Concentration, pressure, pi 1, pi 2, pi 3 values

ρ	p	π1	π2	π3
12.581	46000	1960.71	163.2974	0.001088
19.77	74000	4956.541	403.2388	0.00171
23.963	104000	8443.351	592.4223	0.002073
28.756	136000	13249.75	853.1118	0.002487
32.051	150000	16288.2	1059.82	0.002773
36.244	173000	21243.33	1355.256	0.003135
41.636	198000	27930.23	1788.492	0.003602
46.429	221000	34763.37	2223.963	0.004017
51.221	249000	43210.34	2706.731	0.004431
54.516	271000	50053.4	3066.175	0.004716
57.512	289000	56311.44	3412.447	0.004975

Values after Regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	8.116929	0.01	713.089	1.68E-20	8.091	8.143	8.091	8.143
X Variable 1	0.002262	0.001	1.958	0.085861	-0.0004	0.005	-0.0004	0.005
X Variable 2	1.994904	0.003	779.943	8.18E-21	1.989	2.001	1.989	2.001

Π_1, Π_2, Π_3 terms for 57.5 micrometer Coal dust particle (Figure 4.2) [27]

Table 4.20: Concentration, pressure, pi 1, pi 2 and pi 3 values

ρ	p	π1	π2	π3
88.092	50.706	37556.58	19868.81	0.033207
109.658	55.16	50857.48	30787.87	0.041336
131.212	59.892	66074.31	44080.45	0.049461
189.861	69.074	110265.7	92293.36	0.071569
239.398	72.963	146863.4	146737.1	0.090242

304.485	76.29	195309.7	237372.7	0.114777
372.786	76.828	240807.2	355810	0.140523
469.123	75.129	296336.1	563472.1	0.176838
521.95	74.278	325971.3	697520.1	0.196751
593.453	72.307	360792	901719.8	0.223705
655.608	71.175	392339.5	1100493	0.247134
727.09	69.761	426472.6	1353553	0.27408
773.695	69.19	450094.2	1532634	0.291648
832.722	68.617	480421	1775411	0.313917
882.443	67.766	502792.5	1993757	0.332641
935.292	66.358	521832.1	2239718	0.352562

Values after Regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	7.255324	0.001	13351.28	8.82E-48	7.254	7.256	7.254	7.256
X Variable 1	6.17E-05	8.68E-05	0.710915	0.489696	-0.0001	0.0002	-0.0001	0.0002
X Variable 2	1.999923	9.54E-05	20954.14	2.52E-50	1.998	2.0001	1.9997	2.0001

Π_1, Π_2, Π_3 terms for 97.5 micrometer Coal dust particle (Figure 4.2) [27]

Table 4.21: Concentration, pressure, pi 1, pi 2 and pi 3 values

ρ	p	π1	π2	π3
94.935	34.417	78988.37	66347.6	0.14936
113.374	39.412	108020.4	94623.59	0.16723
128.719	44.13	137322.1	121971.3	0.189865
178.063	53.005	228167.8	233410.2	0.262649
227.547	58.269	320532.8	381166.5	0.33564
314.243	64.911	493114.4	726948.6	0.46352
435.166	69.878	735121.7	1394063	0.641886
525.22	69.853	886943.4	2030797	0.77472
618.415	69.271	1035608	2815351	0.912185
758.252	67.01	1228335	4232526	1.11845
848.345	66.152	1356686	5298068	1.2513
926.006	65.575	1467966	6312481	1.36589

Values after Regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	5.450809	0.399	13.647	2.56E-07	4.547	6.354	4.547	6.354
X Variable 1	0.178413	0.066	2.705	0.024182	0.029	0.328	0.029	0.328
X Variable 2	1.792685	0.085	21.104	5.65E-09	1.601	1.985	1.601	1.985

Π_1, Π_2, Π_3 terms for 27.6 micrometer Coal dust particle (Figure 2.9) [21]

Table 4.22: pressure, Concentration, pi 1, pi 2 and pi 3 values

P	ρ	π1	π2	π3
1.866	162.539	58723.1245	15584.6	0.048144
2.401	195.046	90719.75653	22441.6	0.048144
2.964	236.842	135990.818	33090.15	0.048144
3.474	297.314	200086.5246	52109.8	0.048144
3.934	376.161	286669.0318	83469.71	0.048144
4.522	557.276	488172.7854	183198.6	0.048144
4.65	608.359	548006.3074	218453.1	0.048144
4.803	733.746	682701.7257	317594.4	0.048144
4.726	845.201	773795.8325	421406.6	0.048144
4.675	882.353	799091.7533	459267.9	0.048144
4.573	938.08	831024.3419	519112.1	0.048144
4.445	1003.096	863747.7534	593562.4	0.048144
4.266	1114.551	921071.7532	732792.9	0.048144
3.909	1309.598	991690.9283	1011713	0.048144
3.704	1434.985	1029653.278	1214720	0.052754

Regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	5.55613	3.748	1.483	0.164	-2.609	13.722	-2.609	13.721
X Variable 1	1.440105	0.07	20.834	8.65E-11	1.289	1.591	1.289	1.591
X Variable 2	6.363198	2.76	2.306	0.04	0.35	12.377	0.35	12.377

Π_1, Π_2, Π_3 terms for 22.4 micrometer Magnesium dust particle (Figure2.9) [21]

Table 4.23: Concentration, pressure, pi 1, pi 2 and pi 3 values

ρ	p	π1	π2	π3
50.223	1.43	9164.089	980.08693	0.001362
70.312	1.948	17477.09	1920.9594	0.001906
80.357	2.195	22506.55	2509.035048	0.002179

107.143	2.639	36078.94	4460.534506	0.002905
150.669	3.256	62597.78	8820.782433	0.004085
194.196	3.577	88635.93	14653.44906	0.005265
227.678	3.873	112517.3	20141.94631	0.006172
287.946	4.22	155050.8	32216.72562	0.007806
331.472	4.442	187878	42692.63849	0.008986
445.311	4.962	281949.2	77052.39544	0.012073
552.454	5.284	372485.6	118590.9487	0.014977
786.828	5.805	582817.6	240557.5052	0.021331
960.935	6.03	739370.2	358795.7766	0.026051
1047.988	6.056	809828	426748.4163	0.028411
1121.649	6.008	859879.3	488847.3278	0.030408
1202.006	5.886	902770.8	561400.2085	0.032587
1302.452	5.69	945637.3	659147.7174	0.03531
1376.113	5.494	964702.4	735813.0631	0.037307
1419.639	5.397	977644.5	783096.2457	0.038487
1453.121	5.299	982531.1	820470.2848	0.039395

Values after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	8.720547	0.001	9821.654	7.45E-59	8.719	8.722	8.719	8.722
X Variable 1	0.000338	0.0001	3.040068	0.007395	0.0001	0.0006	0.0001	0.0006
X Variable 2	1.999576	0.0002	13213.64	4.81E-61	1.999	2.0	1.999	1.999

Π_1, Π_2, Π_3 terms for 22.4 micrometer Magnesium dust particle (Figure 4.3) [21]

Table 4.24: Concentration, pressure, pi 1, pi 2 and pi 3 values

ρ	P	π1	π2	π3
75.362	1.922	18482.33	2206.806	0.002043
92.754	2.264	26795.37	3342.909	0.002515
150.725	3.039	58447.59	8827.341	0.004086
202.899	3.349	86705.3	15996.28	0.005501
266.667	3.752	127668.2	27631.08	0.007229
318.841	4.031	163997.6	39500.96	0.008644
365.217	4.31	200853.2	51827.62	0.009901
417.391	4.589	244405.9	67693.26	0.011314
486.957	4.899	304402.8	92138.37	0.013202
565.217	5.178	373446	124133.7	0.015323
646.377	5.395	444967.2	162342.1	0.017524
689.855	5.457	480355.1	184916.2	0.018702

771.014	5.612	552116.3	230985	0.020903
843.478	5.767	620689.4	276443.8	0.022867
898.551	5.86	671878.8	313721.8	0.02436
971.014	5.984	741425.8	326746.7	0.026325

Values after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	6.827653	1.302	5.244	0.0002	4.015	9.640	4.015	9.640
X Variable 1	0.22949	0.157	1.437	0.174	-0.116	0.574	-0.116	0.574
X Variable 2	1.661293	0.228	7.281	6.17E-06	1.168	2.154	1.168	2.154

Π_1, Π_2, Π_3 terms for 54.5 micrometer Magnesium dust particle (Figure 4.2) [21]

Table 4.25: Concentration, pressure, pi 1, pi 2 and pi 3 values

ρ	p	π1	π2	π3
75.581	1.457	83180.16	13139.58	0.031159
104.651	1.922	151930.3	25190.86	0.043143
142.442	2.419	260268.4	46669.42	0.058722
191.86	2.698	390997.5	84669.14	0.079095
238.372	2.853	513694.1	130697.3	0.09827
308.14	3.101	721767.7	218399.9	0.127032
386.628	3.318	968985.5	343829.3	0.159389
470.93	3.628	1290539	510116	0.194143
555.233	3.969	1664577	709098.9	0.228897
613.372	4.217	1953778	865374.6	0.252865
691.86	4.558	2381991	1101014	0.285222
779.07	4.93	2901155	1396077	0.321175
848.837	5.178	3319968	1657314	0.349937
918.605	5.457	3786434	1940948	0.378699
973.837	5.612	4128112	2181367	0.401468

Values after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%
Intercept	-3.56571	4.36E-08	-8.2E+07	7.56E-90	-3.56571	-3.57	-3.57
X Variable 1	6.42E-08	2.26E-08	2.849442	0.014638	1.51E-08	1.1E-07	1.5E-08
X Variable 2	0.5	1.66E-08	30030817	1.25E-84	0.5	0.5	0.5

By applying regression different values of K, n_1, n_2 has been found for different graphs. Now by using different values of K, n_1, n_2; find values of K_1, m_1, m_2 and K_2, x_1, x_2 and K_3, y_1, y_2 from equation:

$K= K_1 (\rho_p / \rho_f)^{m1} (W_{f0}/ (g \times d_p)^{½})^{m2}$ $n_1 = K_2 (\rho_p / \rho_f)^{x1} (W_{f0}/ (g \times d_p)^{½})^{x2}$

$n_2= K_3 (\rho_p / \rho_f)^{y1} (W_{f0}/ (g \times d_p)^{½})^{y2}$

Where

ρ_p is particle density

ρ_f is fluid density

W_{fo} is particle settling velocity

g is acceleration due to gravity

d_p is particle diameter

Now

Put values of variables from different graphs in equation (4.2) and apply regression

$$K= K_1 (\rho_p / \rho_f)^{m1} (W_{f0}/ (g \times d_p)^{½})^{m2} \quad (4.2)$$

Values of K_1, m_1, m_2 after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	41.86012	48.597	0.861	0.418	-73.053	156.773	-73.053	156.773
X Variable 1	-10.2636	15.199	-0.675	0.521	-46.203	25.676	-46.204	25.676
X Variable 2	-8.67852	3.355	-2.587	0.036	-16.611	-0.746	-16.611	-0.746

Solve for K_2, x_1, x_2

Put values of variables from different graphs in equation (4.3) and apply regression

$$n_1 = K_2 (\rho_p / \rho_f)^{x1} (W_{f0}/ (g \times d_p)^{½})^{x2} \quad (4.3)$$

Values of K_2, x_1, x_2 after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-12.4594	52.315	-0.238	0.819	-136.165	111.246	-136.17	111.246
X Variable 1	3.140826	16.362	0.192	0.853	-35.549	41.831	-35.55	41.831
X Variable 2	-1.47945	3.611	-0.41	0.694	-10.019	7.06	-10.019	7.06

Solve for K_3, y_1, y_2

Put values of variables from different graphs in equation (4.4) and apply regression

$$n_2 = K_3 (\rho_p / \rho_f)^{y1} (W_{f0} / (g \times d_p)^{½})^{y2} \quad (4.4)$$

Values of K_3, y_1, y_2 after regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	6.397304	3.518	1.818	0.112	-1.922	14.717	-1.922	14.717
X Variable 1	-1.88388	1.1	-1.712	0.131	-4.486	0.7182	-4.486	0.718
X Variable 2	-0.52089	0.243	-2.145	0.069	-1.095	0.053	-1.095	0.053

Now by using K_1, m_1, m_2 and K_2, x_1, x_2 and K_3, y_1, y_2 find values of Values of K, n_1, n_2 for different graphs and after that find values of pressure from below equations.

$$\Pi_1 = K (\Pi_2)^{n1} (\Pi_3)^{n2}$$

$$P \times \rho \times (d_p)^2 / (\mu)^2 = K (C_p \times (\rho)^2 \times T_i \times (d_p)^2 / (\mu)^2)^{n1} \times (\rho \times d \times W_{f0} / \mu)^{n2}$$

Where W_{f0} is particle settling velocity and ρ is density of dust particles.

$$P = K \{(\mu)^2 / \rho \times (d_p)^2\} (C_p \times (\rho)^2 \times T_i \times (d_p)^2 / (\mu)^2)^{n1} \times (\rho \times d \times W_{f0} / \mu)^{n2}$$

4.5 Validation of Model

Validation has been done by comparing experimental data with calculated data from model. Validation of model is required to check accuracy of empirical model.

4.5.1 Validation for 10 micrometer aluminum Al-2 dust (Figure 4.4) [28]

Figure 4.5 shows comparison between experimental and calculated explosion pressure to check accuracy of empirical model.

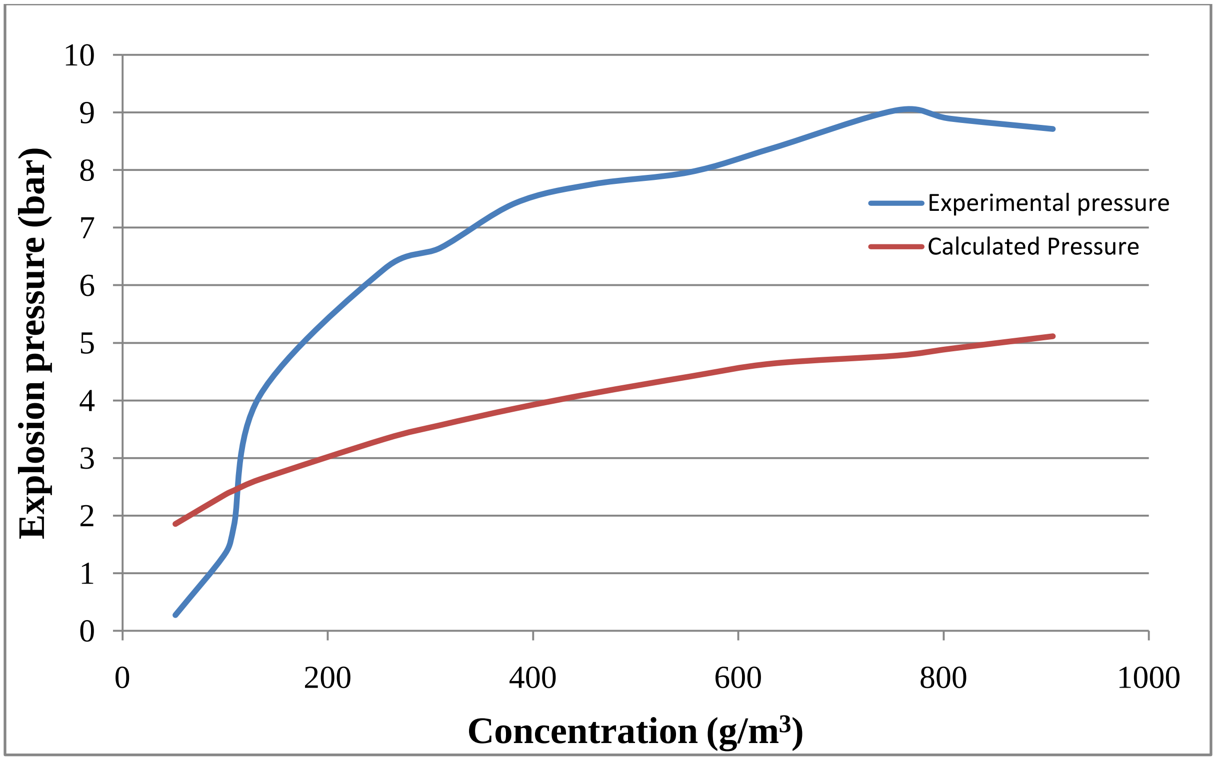


Figure 4.5: Shows comparison between experimental and calculated explosion pressure

4.5.2 Percentage error in model

Average percentage Error in validation = (Actual value – Theoretical value) / Actual value

= 43.2832%

This shows percentage error is reduced by 54.5968% after adding turbulence (Re) in variables.

CHAPTER 5: CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

The present research work entitled “An experimental investigation into the explosion of bulk solids” was aimed to use three combustible dusts. It has been decided to use two dusts, wheat husk and wood dust with particle size less than 300 micrometer. Two coal dust samples were used one is of 105 micrometer and other is less than 53 micrometer. After experimental work it has been observed that wood dust is more hazardous than wheat husk.

An empirical model was made to find explosion pressure. Initially it has been decided to take five variables that effect the explosion pressure and made a model by using these variables. After validation of this model it has been observed that there are some more parameters that can effect explosion pressure. After that one more variable was added called turbulence and by using six variables again a model was developed. After validation of second model it has been found that this model gives more accurate results than first model.

5.2 Future Scope

Experimental work scope

The present research work was aimed to three dusts of a particular particle diameter. But there are large number of combustible (metallic and nonmetallic) dusts.

1) Technical safety parameters can be investigated for coal dust by using oxidant.
2) System can be used for these three dusts with different diameters of particle.
3) System can be tried for different combustible dusts (metallic and nonmetallic).
4) System can be investigated to find rate of change of pressure.

Theoretical work scope

This present empirical model was aimed to find explosion pressure. During validation it was found that with five variables percentage error was more than six variables model. So by adding more variable, those can effect explosion pressure, error would be further reduced.

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APPENDIX A

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.975406
R Square	0.951417
Adjusted R Square	0.948559
Standard Error	0.221534
Observations	19

ANOVA

	df	SS	MS	F	Significance F
Regression	1	16.3385	16.3385	332.914	1.33E-12
Residual	17	0.83431	0.049077		
Total	18	17.1728			

Figure A1: Regression calculations of 7 micrometer Aluminium particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.981713
R Square	0.96376
Adjusted R Square	0.960973
Standard Error	0.136076
Observations	15

ANOVA

	df	SS	MS	F	Significance F
Regression	1	6.4016	6.4016	345.721	9.51E-11
Residual	13	0.2407	0.0185		
Total	14	6.6423			

Figure A2: Regression calculations of 10 micrometer magnesium particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.983558
R Square	0.967386
Adjusted R Square	0.964877
Standard Error	0.213624
Observations	15

ANOVA

	df	SS	MS	F	Significance F
Regression	1	17.597	17.597	385.6	4.79E-11
Residual	13	0.593	0.046		
Total	14	18.190			

Figure A3: Regression calculations of 11 micrometer Aluminium particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.984778
R Square	0.969787
Adjusted R Square	0.967773
Standard Error	0.129188
Observations	17

ANOVA

	df	SS	MS	F	Significance F
Regression	1	8.036	8.036	481.478	8.20E-13
Residual	15	0.25	0.017		
Total	16	8.286			

Figure A4: Regression calculations of 22 micrometer magnesium particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.992531
R Square	0.985117
Adjusted R Square	0.984125
Standard Error	0.108336
Observations	17

ANOVA

	df	SS	MS	F	Significance F
Regression	1	11.653	11.653	992.868	4.02E-15
Residual	15	0.176	0.012		
Total	16	11.829			

Figure A5: Regression calculations of 38 micrometer Magnesium particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.994455
R Square	0.988941
Adjusted R Square	0.988151
Standard Error	0.074276
Observations	16

ANOVA

	df	SS	MS	F	Significance F
Regression	1	6.907	6.906	1251.93	4.26E-15
Residual	14	0.077	0.006		
Total	15	6.984			

Figure A6: Regression calculations of 57.5micrometer coal particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.995706
R Square	0.991429
Adjusted R Square	0.99077
Standard Error	0.069655
Observations	15

ANOVA

	df	SS	MS	F	Significance F
Regression	1	7.296	7.296	1503.83	7.99E-15
Residual	13	0.063	0.005		
Total	14	7.359			

Figure A7: Regression calculations of 74 micrometer magnesium particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.982723
R Square	0.965745
Adjusted R Square	0.963298
Standard Error	0.128147
Observations	16

ANOVA

	df	SS	MS	F	Significance F
Regression	1	6.482	6.482	394.694	1.18E-11
Residual	14	0.229	0.016		
Total	15	6.711			

Figure A8: Regression calculations of 27.6 micrometer coal particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99869
R Square	0.997382
Adjusted R Square	0.997207
Standard Error	0.036828
Observations	17

ANOVA

	df	SS	MS	F	Significance F
Regression	1	7.750	7.750	5714.21	8.75E-21
Residual	15	0.020	0.001		
Total	16	7.770			

Figure A9: Regression calculations of 7.5 micrometer magnesium particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.995833
R Square	0.991683
Adjusted R Square	0.991221
Standard Error	0.092022
Observations	20

ANOVA

	df	SS	MS	F	Significance F
Regression	1	18.176	18.176	2146.37	3.54E-20
Residual	18	0.152	0.008		
Total	19	18.328			

Figure A10: Regression calculations of 22.4 micrometer magnesium particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.912709
R Square	0.833037
Adjusted R Square	0.817858
Standard Error	0.357695
Observations	13

ANOVA

	df	SS	MS	F	Significance F
Regression	1	7.022	7.022	54.883	1.35E-05
Residual	11	1.407	0.128		
Total	12	8.429			

Figure A11: Regression calculations of 36.5 micrometer coal particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.993683
R Square	0.987406
Adjusted R Square	0.986146
Standard Error	0.064838
Observations	12

ANOVA

	df	SS	MS	F	Significance F
Regression	1	3.3	3.296	784.01	7.84E-11
Residual	10	0.042	0.004		
Total	11	3.338			

Figure A12: Regression calculations of 36.5 micrometer coal particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.304576
R Square	0.092767
Adjusted R Square	-0.10884
Standard Error	1.395986
Observations	12

ANOVA

	df	SS	MS	F	Significance F
Regression	2	1.793	0.897	0.460	0.645
Residual	9	17.538	1.949		
Total	11	19.332			

Figure A13: Regression calculations values of k_1, $m_{1,}$ n_1

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.173832
R Square	0.030218
Adjusted R Square	-0.18529
Standard Error	0.084962
Observations	12

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.002	0.001	0.140	0.871
Residual	9	0.065	0.007		
Total	11	0.067			

Figure A14: Regression calculations values of Value of K_2, x_1, x_2

APPENDIX B

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.999999999
R Square	0.999999999
Adjusted R Square	0.999999999
Standard Error	2.37569E-05
Observations	15

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	6.642	3.321	5.88E+09	1.12E-54
Residual	12	6.77E-09	5.64E-10		
Total	14	6.642344			

Figure B1: Regression calculations of 10 micrometer Magnesium dust particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	1
Standard Error	6.63E-05
Observations	15

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	18.190	9.095	2.07E+09	5.9E-52
Residual	12	5.27E-08	4.39E-09		
Total	14	18.190			

Figure B2: Regression calculations of 11 micrometer Aluminium dust particle

Summary Output

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	1
Standard Error	9.35E-09
Observations	16

ANOVA

	df	SS	MS	F	Significance F
Regression	2	5.871374	2.935687	3.36E+16	7.30E-103
Residual	13	1.14E-15	8.74E-17		
Total	15	5.871374			

Figure B3: Regression calculations of 22 micrometer Magnesium dust particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	1
Standard Error	6.49E-05
Observations	11

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	1.693099	0.846549	2.01E+08	1.57E-31
Residual	8	3.37E-08	4.21E-09		
Total	10	1.693099			

Figure B4: Regression calculations of 36.5 micrometer Coal dust particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	1
Standard Error	1.33E-05
Observations	16

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	6.984	3.492074	1.99E+10	2.23E-62
Residual	13	2.29E-09	1.76E-10		
Total	15	6.984			

Figure B5: Regression calculations of 57.5 micrometer Coal dust particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.999888
R Square	0.999776
Adjusted R Square	0.999726
Standard Error	0.011816
Observations	12

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	5.608	2.804	20083.09	3.77E-17
Residual	9	0.0013	0.0001		
Total	11	5.61			

Figure B6: Regression calculations of 97.5 micrometer coal dust particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.988133
R Square	0.976406
Adjusted R Square	0.972474
Standard Error	0.102342
Observations	15

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	5.201	2.601	248.305	1.72E-10
Residual	12	0.126	0.010		
Total	14	5.327			

Figure B7: Regression calculations of 27.6 micrometer Coal dust particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	1
Standard Error	2.95E-05
Observations	20

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	18.328	9.164014	1.05E+10	5.26E-78
Residual	17	1.48E-08	8.73E-10		
Total	19	18.328			

Figure B8: Regression calculations of 22.4 micrometer Magnesium dust particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.999874
R Square	0.999749
Adjusted R Square	0.99971
Standard Error	0.011784
Observations	16

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	7.189	3.595	25888.18	3.96E-24
Residual	13	0.002	0.00014		
Total	15	7.191			

Figure B9: Regression calculations of 22.4 micrometer Magnesium dust particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	1
Standard Error	1.96E-09
Observations	15

ANOVA

	df	SS	MS	F	Significance F
Regression	2	1.803861	0.901931	2.35E+17	2.7E-100
Residual	12	4.6E-17	3.83E-18		
Total	14	1.803861			

Figure B10: Regression calculations of 54.5 micrometer Magnesium dust particle

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.712927
R Square	0.508264
Adjusted R Square	0.367769
Standard Error	3.119688
Observations	10

ANOVA

	df	SS	MS	F	Significance F
Regression	2	70.41717	35.20859	3.617647	0.08338
Residual	7	68.12719	9.732456		
Total	9	138.5444			

Figure B11: Regression calculations for Values of K_1, m_1, m_2

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.227597
R Square	0.051801
Adjusted R Square	-0.21911
Standard Error	3.358388
Observations	10

ANOVA

	Df	SS	MS	F	Significance F
Regression	2	4.313	2.157	0.191	0.83
Residual	7	78.951	11.279		
Total	9	83.265			

Figure B12: Regression calculations for Values of Values of K_2, x_1, x_2

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.650202
R Square	0.422763
Adjusted R Square	0.257838
Standard Error	0.225865
Observations	10

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.261	0.131	2.563	0.146
Residual	7	0.357	0.051		
Total	9	0.619			

Figure B13: Regression calculations for Values of Values of Values of K_3, y_1, y_2