LEAN FLAMMABILITY LIMITS OF DUST-AIR MIXTURES

Thesis by

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ABSTRACT

The lean flammability limits of dust-air mixtures have been investigated under both constant volume and constant pressure conditions. The dust fuels used were cornstarch dust and two different coal dust samples. A 180 litre cylindrical vessel was used for experiments under constant volume, while a 53 litre vertical tube, of high length to diameter ratio (L/D), was used for experiments under both constant volume and constant pressure. Both upward and downward propagation limits were investigated in the closed vertical tube, whereas only upward limits were investigated in the open tube. A different dust dispersion method was used for each vessel. The criterion for self sustained flame propagation in the 180 litre vessel was the evidence of an explosion overpressure in excess of 20.7 kPa. A dust-air mixture in the vertical tube was taken to be flammable if the flame propagated at least three quarters of the length of the tube. The measured lean limits in the 180 litre cylinder were, $75 - 80 g/m^3$ for cornstarch dust and $40 g/m^3$ for both of the coal dust samples. $200 g/m^3$ was the minimum concentration of cornstarch in which a sustained flame propagation was detected in the closed vertical tube, for both the upward and downward propagation directions, whereas, $400 g/m^3$ was the lean limit for cornstarch obtained under constant pressure conditions. No sustained flame propagation was observed for either of the coal samples, under any tested conditions in the vertical tube. Settling of coal dust particles, appears to hinder flame propagation in the vertical tube by decreasing the burning rate and limiting the amount of coal dust that has time to burn. It becomes evident that different apparatus and experimental conditions coupled with arbitrarily set limit criteria, yield very subjective flammability limits. The lean flammability limit of a dust-air mixture does not appear to be a fundamental property of the mixture, hence, prudence must be exercised in assessing explosion hazards based on any given value for lean flammability limit.

RESUME

Les limites de flammabilité imférieures de mélanges poussières-air ont été étudiées dans les deux conditions suivantes: volume constant et pression constante. Les particules combustibles utilisées sont l'amidon de mais et deux différentes sortes de poussières de charbon. Une enceinte cylindrique de 180 L a été utilisée pour les expériences à volume constant, alors qu'un tube vertical de 53 L de grand rapport L/D a été utilisé pour des expériences, aussi bien à volume constant qu'à pression constante. Le tube vertical, lorsqu'il était fermé, a permis d'étudier les limites lors de propagation à la fois montante et descendante. Dans le cas où il était ouvert, seules les limites de propagation montante ont été étudiées Pour chacune des chambres une méthode différente de mise en suspension des poussières a été utilisée. Dans le cas de l'enceinte de 180 L, le critère d'auto- propagation de la flamme correspond à une limite arbitraire de surpression du mélange de 20.7 kPa, alors que pour le tube vertical l'inflammation d'une suspension est qualifiée de réelle si la flamme se propage jusqu'aux trois quarts de la longueur du tube. Les mesures donnent comme limites inférieures pour le cylindre de 180 L $75 - 80$ g/m^3 pour l'amidon de mais et 40 g/m^3 pour les deux échantillons de poussières de charbon. La concentration minimale d'amidon, pour laquelle la propagation de la flamme a été observée dans le tube vertical fermé, est 200 g/m^3 dans le cas de la propagation montante et descendante. Par contre, il faut un minimum de 400 g/m^3 pour les expériences à pression constante pour le même appareil.

Aucunes conditions experimentales dans le tube vertical n'a permis l'observation de la propagation d'une flamme auto- entretenue. La chute des particules de charbon semble retardes la propagation de la flamme en diminuent le tause de combustion et en limitant la quantité de poussières de charbon qui peut brûler.

Il est donc évident que l'utilisation d'appareils différents dans des conditions expérimentales données associées à des crétères de limitation subjectifs mènent à des limites de flammabilité arbitraires.

La limite de flammabilité inferieure d'un mélange poussière-air ne semble pas être une propriété fondamentale du mélange; une grand prudence est donc de rigueur quant à l'utilisation et à l'application de toute valeur de limite de flammabilité qui puisse être donnée.

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C_D	- actual dust concentration in the vessel as in Figs. 31 and 32
D	- diameter of test vessel
dp/dt	- representative rate of pressure rise in the vertical tube
$(dp/dt)_{max}$	- peak rate of pressure rise
K_{st}	- parameter, (dp/dt)max V/3, named Kst factor
L	- length of test vessel
P_o	- atmospheric pressure
S	- surface area of test vessel
t	- time
t_D	- ignition delay time
u	- flame speed
W_g	- actual mass of dust dispersed as in Figs. 31 and 32
V	- volume of test vessel
x	- axial position in the test tube
Δp_{max}	- peak explosion overpressure
ϵ_{eff}	- effective energy produced by igniter

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1 INTRODUCTION

The minimum suspended dust concentration in air which can sustain flame propagation is referred to as the lean flammability limit. So many dusts, harmlessly handled daily by millions of people or present in peoples' daily routines, have the potential of exploding if they become airborne for some duration of time. The lower the flammability limit of a substance, the more hazardous it is. An accurate knowledge of the lean flammability limits of dust-air mixtures is of great practical importance in assessing the fire and explosion hazards posed by dusts in mining, agricultural, chemical, pharmaceutical, storage, transportation and other industrial environments. Systematic research in dust explosions dates back to the late 19th century. The main dust researched was coal dust arising for the need to prevent coal mine explosions. A main hazard in handling coal is its ability to form self-sustaining explosions. Typically, the source of an explosion in a coal mine is a pocket of flammable methane-air mixture being ignited by a spark, hot surface or some other ignition source. The pressure waves and resulting flow generated by such local explosions, entrain dust from the floor and other surfaces and create a coal dust-air atmosphere. If the concentration of dust is high enough, the flame can propagate through the coal dust-air mixture, continuously generating a flammable mixture in front of it and accelerating down the mine passageway. The result can be extensive damage to the mine, equipment, and inevitably death or injury to miners at the site of flame passage.

Many other industries are characterized by the unavoidable intense production of dusts. Aside from coal mines, some primary sites for dust explosions have been in the food and textile industries. The United States Department of Agriculture reported 31 accidents under its jurisdiction, in 1977, resulting in 65 deaths and 876 injuries. During the years 1970-1978 in Poland, there were more than 20 explosions in the food and textile industries [1], while more than 400 dust explosions occurred in the Federal Republic of Germany and its neighbouring countries, during the years 1960-1972 [2]. Over the past fifty years, a lot of data on dust-air explosions in closed bombs of various shapes and sizes, has been and continues to be accumulated. There has been a practical need to identify parameters from dust-air combustion experiments, which can be used for the explosibility classification of different dusts. Five such parameters are used in combination in the U.S. to determine the sensitivity of a sample dust to ignition and the severity of its explosion [3]. Some West European countries choose the standard explosion pressure rise value to classify dust explosibility, while others, including Poland, use the lean flammability limit as the main parameter for explosive hazard classification [4].

Confinements and barriers in the combustion region cause acceleration of the flame front due to increased turbulence [5,6] which causes better entrainment of dust particles and consequently increased pressure rise and explosion effect. On the other hand, vent holes allow for relief of pressure build up, thus decreasing the effects of the explosion. Since most potential sites of dust explosions are neither totally confined (constant volume) nor totally unconfined (constant pressure), it would be essential for industry to have an accurate knowledge of the lean flammability limit(s) of a dust-air mixture, under both constant volume and constant pressure conditions. Unfortunately, results from flammability limit investigations conducted over the years, indicate that the lean flammability limit of a dust-air mixture does not appear to be a fundamental property of the dust-air medium. Rather, it appears to depend strongly on the test conditions and chosen flammability limit criterion, used for its determination.

2 GENERAL CONSIDERATIONS AND PRESENT OBJECTIVES

2.1 Determination of Flammability Limits

Flammability limits are usually referred to as the boundaries for the range of fuel-oxidizer compositions which are capable of sustaining flame propagation. The minimum and maximum fuel concentrations in the oxidizer environment, which can sustain flame propagation, are respectively known as the lean and rich flammability limits. Fuel- oxidizer composition outside these limits, will not be combustible. There exists no universal theory for predicting flammability limits.

Attempts have been made to link the minimum explosive concentration of fuel to its heat of combustion or higher heating value [7]. However, very limited success can be claimed, other than at best, an approximation to the limits by such theoretical means. It is necessary to have a good knowledge of the fuel compositions in air which can explode, so that any potential hazards can be accurately assessed. Hence, the limits have to be determined experimentally. For gaseous fuels, the traditional apparatus used is an open cylindrical tube mounted vertically, about 1.5 m long and at least .1 m in diameter, with ignition electrodes at the bottom. Monitored streams of gaseous fuel are flowed through the cylindrical tube until a desired concentration is achieved, at which time the flow is stopped and a spark is provided for ignition. The visual observation in a dark room (or with a photo multiplier), of flame propagation at least three-quarters of the length of the tube, establishes the upward propagation limit. By placing the ignition electrodes at the top and following a similar procedure, the downward propagation limit can be determined. Similarly, the horizontal limit can be determined by placing the cylindrical tube horizontally. As a result of the effects of buoyancy at near limit compositions, the determined propagation limits will generally be direction-dependent, with the flammability range for upward propagation being somewhat wider than that for the downward direction. There is fairly good agreement of reported results for flammability limits for gases. Data for the flammability limits determined in various laboratories around the world, has been accumulated by the U.S. Bureau of Mines and published by Coward and Jones in Bulletin 503 [8] and later updated by Zabetakis in Bulletin 627 [9].

Flammability limits for dust fuels have been determined in a different way than that for gaseous fuels. Rich flammability limits for dust fuels are not observed in practice. No standard apparatus or procedure exist for the determination of dust limits. The majority of experimentation on the field has been conducted in closed bombs of spherical geometry or cylindrical vessels with L/D near unity. The amount of dust necessary to achieve a desired concentration is placed in a bowl or dispersion bed. A jet of pressurized air discharges into the dust receptacle, entraining and dispersing the dust in the combustion chamber. Ignition by a spark or the more powerful pyrotechnic igniter, follows a pre-set time delay after the onset of the dust dispersion process. Diagnostics have mainly consisted of the pressure-time history inside the closed vessel as detected by a pressure transducer. In some instances, in addition to pressure measurements, any resulting flame propagation was detected by optical means or by probes specifically designed for the purpose.

A major part of the explosibility classification of dusts was undertaken by Hartmann et al [3,10-14] at the U.S. Bureau of Mines. The emphasis was the classification of dusts on such explosibility parameters as: minimum ignition energy, minimum surface ignition temperature, lean flammability limit, maximum oxygen concentration to prevent ignition, maximum overpressure and peak rate of pressure rise. Using the earliest standard apparatus, the 1.23 litre Hartmann bomb, extensive data on lean flammability limits has been accumulated [15-17].

About the late 1970's, the scientific community replaced the 1.23 litre Hartmann bomb, first with a 7.8 litre modified Hartmann bomb at the U.S. Bureau of Mines [18-21] and currently uses the 20 litre [22-24] and 1 m^3 vessels as the minimum acceptable standards volumes for dust combustion research. There are several important considerations which led to the abandonment of the Hartmann bomb as a tool for scientific research in dust combustion. Most notably, the results from experiments performed in the Hartmann apparatus did not correlate well with those produced from other larger vessels, and further, scaling to actual industrial applications from such results was not possible. The non- uniform dust distribution in the vessel, the necessity of a weak ignition source due to the small vessel volume [24], the cold wall quenching effects [26], the dust flame thickness compared to the integral vessel dimensions and a soft and very specific flammability limit criterion, are some of the major limitations of the Hartmann standard apparatus and procedures. As a result, any results for lean flammability limits of dust obtained in the Hartmann bomb are apparatus dependent and have little fundamental significance. McGill University uses a 23 litre vertical tube and a 180 litre Hartmann type cylindrical apparatus for lean flammability tests. Almost all of the past lean limit tests have been performed in closed bombs, otherwise referred to as constant volume conditions. Only recently have constant pressure lean limit determinations been attempted. Veyssiere, Proust et al. [27,28] used a fluidized bed in an open vertical glass tube to create a quasi-quiescent dust-air suspension, while Jarosinski et al. [29] used turbulent dust dispersion in an open-ended vertical tube for constant pressure simulations.

A quick survey of the literature on the subject of lean flammability limits of dust-air mixtures, obtained in different investigations and under the different conditions of constant volume and constant pressure, will reveal significant discrepancies for the same type of dust. Hertzberg [19] has reported lean flammability limits for coal dusts ranging from $5 - 500\ g/m^3$, while reports for the lean limit of cornstarch dusts determined by different researchers or under different test conditions, vary from $40 - 400\ g/m^3$. The major reasons for large reported variations in lean limit results obtained under constant volume, can be attributed to differences in dust particles themselves (size, volatile content, moisture), initial and boundary conditions, experimental procedure, ignition source characteristics, and to a great extent, the criteria used to establish the flammability limit.

Criteria for ascertaining flammability limits have been arbitrarily selected by different research teams, working in different laboratories, on a variety of test chambers and following dissimilar experimental procedures. The requirement of a gas flame to have been observed to travel a given distance (3/4 of length of tube) before the mixture could be deemed flammable, may not be adequate and other criteria have been sought. In experiments under constant volume, the pressure inside the test vessel increases with any combustion, so that a criterion based on pressure rise is possible. A certain minimum measure of the degree of burning, as indicated by the peak explosion overpressure, Δp_{max}, or the peak rate of change of some parameter, like pressure, temperature or burning velocity, have all been suggested as acceptable limit criteria. The breaking of a pressure pre-calibrated diaphragm by the exploding mixture, has been used as a criterion in the Hartmann bomb and other investigations [17]. Hertzberg has used the normalized peak explosion overpressure, $(\Delta p_{max}/P_o)$ as the propagation criterion for the limit [19], or in combination with the vessel size normalized peak rate of pressure rise, K_{st} [24]. Bartknecht found that the dust explosion hazard in vessels with L/D near unity can be approximated by the "cubic law" [30],

$$K_{st} = (dp/dt)_{max} V^{1/3}$$

It provides a measure of the maximum burning rate and is used to classify the explosion severity of different dust in Europe.

Thus, it becomes evident that variations in reported flammability limits obtained experimentally, may be a direct result of the different arbitrary criteria used to determine these limits. At near limit concentrations, there exists a large departure of the combustion phenomena of the fuel from its normal features. It has been suggested that apart from simply stating that a given fuel-air mixture can sustain flame propagation, it may be necessary to provide additional specifications on the "quality" of flame propagation that is required, before one can establish if the mixture is flammable or not.

2.2 Effects of Buoyancy

Buoyancy can severely limit the fraction of total fuel that can burn in a given vessel near the limits of flammability. Since the burning velocity for near limit mixtures is very low, an expanding flame kernel will rise much the same as a gas bubble in a liquid. Buoyancy will distort the shape of the rising fireball, maintaining a roughly spherical curvature for the top half while causing the bottom parts to flatten out or even dimple in towards the flame, as a result of the low burning velocity. Flame propagation in the downward direction is limited by the much higher buoyant rise velocity compared to the burning velocity. Since the flame cannot burn downwards, only the fraction of fuel within the conical volume traced out by the rising and expanding fireball, will be able to burn. Consequently, the original point of ignition finds itself in the cold unburned mixture. When the flame reaches the top of the combustion vessel, it will remain there, burning horizontally and getting cooled by the surrounding walls. As a result of buoyancy, only a small fraction of the total fuel is consumed by the flame, resulting in a much lower pressure rise in the chamber compared to that which would be expected for all the fuel burning. If the criterion for determining flammability limits is solely based on a minimum pressure rise in the vessel, it becomes evident that buoyancy will have a marked effect on the actual values of flammability limits. Such limitations on the fuel burning are most pronounced in vessels with central ignition and when flame propagation is limited to the upward and horizontal directions only. In high L/D vertical tubes with ignition at the bottom end, buoyancy will aid flame propagation and the total fraction of fuel consumed will tend to be significantly higher than that in a low L/D vessel, of the same volume, with central ignition. Downward propagation of near limit mixtures should generally not be aided by buoyancy effects.

Buoyancy induced motions cause severe distortions to the flame. Resulting changes in the flame curvature affect the cellular instability mechanisms. In general, the fuel and oxygen will have different molecular weights and consequently, their diffusivities will be different. This creates a preferential diffusion situation, where there is a local enrichment of fuel or oxygen at the curved flame front. A good example of this selective diffusion mechanism, is manifested in the upward propagating lean hydrogen-air flame, where buoyancy causes the distorted fireball to completely break-up into small flamelets. Due to hydrogen's very high mass diffusivity compared to oxygen, any convex curvature of the flame, will allow the hydrogen molecules to diffuse preferentially and consequently enrich the flame locally. While there is no continuous flame front in lean upward hydrogen-air mixtures, propagation of the burning is allowed to continue because of the distortions to flame curvature caused by buoyancy induced motions.

Near limit flames are slow and have thick reaction zones. As a result of buoyancy and the unburned flow gradients, it is possible for different portions of the flame surface to be convected along with different flow velocities causing the flame to stretch. A flame may be quenched in such a situation due to excessive convective cooling of the stretched flame surface. Once again, one can see the very important role played by buoyancy effects in determining if flame propagation can be sustained, thus affecting the flammability limits.

2.3 Ignition Effects and Requirements

Before one can determine if a given fuel-oxidizer mixture can sustain flame propagation, there must be an initial combustion wave present. An adequate ignition kernel will maintain the initial combustion wave and spread the flame to the unburned mixture.

For any combustible mixture at a finite temperature, there is always a finite rate of reaction. When the temperature of the combustible mixture is kept much below its adiabatic flame temperature, the heat losses from the volume of mixture exceed the heat produced by the reaction and keep the combustible volume stable. However, when the temperature of the combustible mixture is raised to nearly that of the adiabatic flame temperature, the rate of heat production in the volume occupied by the mixture, exceeds the rate at which heat is lost. The result is an unstable mixture, characterized by an accelerating reaction rate, producing peak temperatures near, or at, the adiabatic flame temperature. When this condition occurs, a sufficient flame kernel can exist and spread the flame through diffusion of mass, energy and momentum, to the neighbouring unreacted mixture. Thus, the ignition problem reduces to finding the smallest volume of hot combustible mixture at the adiabatic flame temperature that can cause reaction to spread. This smallest volume is referred to as the minimum flame kernel. Near the limits of flammability, the size of the minimum flame kernel increases drastically, as a bigger volume of combustible mixture is necessary to produce sufficient energy from reaction and maintain the adiabatic flame temperature. An explosive mixture which is kept stable at a given temperature, will require an external energy source to bring about the onset of chemical reactions. This external energy has often been provided by an electric spark produced by a discharging capacitor or exploding wire, or by a chemical igniter. The energy addition by an electric spark is typically of the order of microseconds while for a chemical igniter it is of the order of milliseconds. Ignition energy has been found to play a critical role in the determination of flammability limits. Near limit mixtures require very strong ignition sources to initiate the combustion process.

The flammability range can be significantly enlarged by the provision of higher ignition energies [19,24,31,32]. Inadequate ignition energy may severely underestimate the potential hazard posed by some fuel-air mixtures since the flammability range for that fuel will appear to be narrower than it really is. Theoretically speaking, it is always possible to provide a high enough ignition energy and of appropriate duration so that the necessary minimum flame kernel for flame propagation can exist. However, too large an ignition volume compared to the test vessel's dimensions, can overdrive the system by changing the initial conditions of the unreacted mixture. It is unknown over what distances the flame can be said to be truly self propagating and independent of the ignition conditions. Further, strong ignition sources can generate large ignition kernels resulting in the creation of high overpressures caused by localized burning, or from only marginal flame propagation. Such effects resulting from strong ignition sources may lead to the misleading conclusion that a self-sustained propagation is possible, whereas it would not be the case were it not for the ignition source being excessive compared to the vessel's dimensions.

There comes a point where it serves no practical purpose to determine flammability limits by continuously increasing the ignition energy provided to the combustible mixture, and using larger and larger test volumes to avoid overdriving effects. In the determination of flammability limits, one must decide on an appropriate apparatus volume and geometry and then determine the ignition source characteristics necessary. The ignition source must be of sufficient duration and energy so as to enable a sufficient quantity of fuel to be ignited an maintained at a high enough temperature to initiate any potential reaction. The ignition energy and duration are most critical in the determination of flammability limits for dust fuel-air mixtures. A high ignition energy is necessary to cause sufficient devolatilization of particles so that combustion can predominantly be sustained in the facilitating gaseous phase. The duration of the igniter is of paramount importance for successfully igniting a dust-air mixture. In a relatively short duration spark, a large portion of the energy is used for shock wave production, where the motion of the air behind the shock disperses the dust particles away from the hot spark center. This shock dispersion of particles lowers the possibility of ignition of the dust- air mixture. On the other hand, long lasting igniters enhance the probability that some dust particles will traverse the ignition region, during the highly transient dust dispersion process, and spread ignition centers to other regions of the bomb.

2.4 Effects of Turbulence

One of the most fundamental differences between the combustion experimentation of gases and dusts, is the need to have turbulence in the vessel at the time of ignition for dust fuels. Turbulence is necessary to disperse and suspend the dust in the bomb. Almost always, an air blast originating from a pressurized dispersion chamber is directed into the dust placement container, entraining and dispersing the dust throughout the combustion vessel. While the concentration of a gas-air mixture remains time-invariant, once premixed, there exist highly transient dust concentration gradients throughout the vessel, as a result of the transient nature of the decaying dispersion-induced turbulence. Since turbulence controls the initial dispersion process, it determines the distribution of dust and the uniformity of the dust cloud in the vessel. As time elapses after the onset of dust dispersion, the turbulence decays in its effectiveness to entrain and suspend dust particles within its eddies. Following a time delay after the onset of the dust dispersion process, the ignition source is activated. Ignition will usually occur with a large amount of turbulence still present in the vessel, so that most of the dust will still be in suspension. It thus, becomes necessary to briefly look into some of the potential effects of turbulence, in the determination of flammability limits.

At concentrations near the limits of flammability, turbulence can be a very important parameter in deciding whether or not a sustained flame propagation can exist. Turbulence influences flame propagation by increasing the transport rates of heat and mass and causing a dramatic change in the burning velocity. Turbulent flows are characterized by eddies which move randomly in all directions. By rapid mixing with the cold mixtures ahead of the flame front, it is possible for turbulence to quench the flame. On the other hand, turbulence may promote flame propagation by increasing the burning rate and allowing less time for heat losses to the walls of the combustion vessel. As turbulent eddies are overtaken by the flame front and begin to burn, they maintain their initial random motion and may assist in flame propagation, by spreading multiple ignition points to the unreacted mixture ahead of the average flow. Finally, turbulence may counteract some of the limitations to burning imposed by buoyancy, by randomly distributing ignition sources through the combustion volume.

2.5 Factors Influencing Dust Combustion

There are many unique features which distinguish the combustion of dust fuels in air from that of premixed homogeneous gaseous fuels in air. Parameters which can affect the initiation and propagation of dust-air flames are many and some of the major ones are summarized by Wolanski [7] in Fig. 1. The large variation in reported lean flammability limit for the same dust in air, is largely due to the numerous parameters which affect dust combustion but are difficult to control between laboratories.

One of the first problems encountered in the combustion of a dust is getting the dust to be suspended uniformly in air. The uniformity of the suspension depends on the specific dispersion technique applied, the initial and boundary conditions present in the combustion vessel, and the properties (size, shape, humidity, specific gravity) of individual dust particles. While a premixed homogeneous gas mixture will maintain its composition, agglomeration and segregation of particles due to sedimentation effects, as well as non-isotropic dispersion-induced turbulent phenomena, make a perfectly homogeneous dust-air suspension very difficult, if not impossible, to obtain. The non-uniform transient dust distribution after dispersion, coupled with the timing of ignition after the onset of the dispersion process, are primary sources for reported discrepancies in flammability limit results, since they differ widely for different combustion vessels.

There are many types of combustible dusts. Many are volatile- content organic dusts, such as coal dust and cornstarch, while others are inorganic and contain volatile matter, such as iron and aluminum dusts. Appendix A describes a typical accepted model for the combustion process of volatile content carbonaceous dusts. The complexities associated with evolution of volatiles, heterogeneous surface reactions, heat transfer phenomena, and relatively long particle burn-up times, makes the burning of dust-air mixtures unique. Individual dust particle properties will inevitably affect the combustion behaviour of the dust. The size, shape and density of individual particles, their volatile content, the moisture present in the dust mixture, all can readily affect the flammability limits of dusts.

The effects of dust particle size and wetness to the flammability behaviour, cannot be overemphasized. Explosibility of a combustible dust increases substantially as the particle size is decreased. If a cubic solid fuel is reduced to smaller particles one-eighth of the original length, a 700% increase in surface area results [33]. Such a larger surface area greatly facilitates the burning of the original amount of cubic solid fuel particles. The burning rate has been found to depend on the surface area to volume ratio, S/V, of the dust particle. Greater S/V of smaller particles implies that they may remain in suspension for a relatively long time, heat up faster, and release volatiles at a faster rate, compared to larger particles of the same dust. Any moisture contained in a dust sample may cause individual particles to agglomerate and form much larger particles, which settle at a faster rate and may often be harder to burn. It is often necessary to dry the dust prior to experimenting with it. However, there is no standard dust drying procedure followed by all laboratories. The explosibility parameters have been shown to be affected by the dust particle size and moisture content in the sample. The peak explosion overpressure and peak rate of pressure rise from the constant volume combustion of a dust-air mixture, can increase with increasing S/V [30]. The minimum ignition energy for a dry dust has been found to be a few times less than that which is necessary to ignite a wet dust of the same sample [7]. Furthermore, the lean flammability limit, quenching distance (related to flame thickness), and ignition temperature all have been shown to increase with increasing particle size and wetness in the dust sample [7,19,24,29,34]. For very fine particles, rapid devolatilization can take place and allow for homogeneous combustion reactions in the gaseous phase. On the other hand, rapid and complete devolatilization for larger particles, is not always possible in the finite time it takes the flame front to traverse a given region at the limit burning velocity. In such a situation, the dust-air mixture is under devolatilization rate control and a higher dust loading of large particles is necessary, so as to enable the minimum amount of combustible volatiles necessary for flame propagation to be present. Consequently, the lean flammability limit will usually rise with increasing particle size. Furthermore, measured lean limits for dusts have been shown to be inversely related to the combustible volatile contents trapped within the particles [19].

The existence of volatiles in dusts and the subsequent gaseous-phase reactions of the released volatiles from the particles as they are heated up, has led to attempts of enhancing the understanding of the dust flame propagation mechanism by drawing analogies with relatively well understood gas flame phenomena. Limited similarities have been established between two phase, dust-air, and single phase gaseous combustion. Unlike experiments with gaseous fuels, experiments with many dust fuels have a substantially lower repeatability. Nevertheless, experimental results show that repeatability can be enhanced for very fine dust-air mixtures, whereby the lean limit dust flame propagation mechanism is controlled by the gaseous phase reaction rate [24].

2.6 Outline of Present Objectives

After examining the large number of factors which can affect the determination of lean flammability limits of dust-air mixtures, it becomes apparent that the experimentally determined lean flammability limit alone, is not expected to be defined as a fundamental property of any particular dust-air mixture. Nevertheless, much can be learned by comparing lean limit results obtained under different experimental conditions and with different flame propagation criteria, if one can successfully explain the physical phenomena involved in the different combustion scenaria. The objectives of the present investigation can be outlined as follows:

1) To inquire about any changes in the flammability behaviour of different dusts that may result from different test conditions, by comparing the Δp_{max}, K_{st} and flammability limit results, obtained from the closed 53 litre vertical tube of high L/D, to the corresponding ones obtained from the 180 litre Hartmann type cylindrical vessel.

2) To determine the most appropriate ignition delay time after the onset of dust dispersion, for every test dust in each vessel, so that a proper flammability limit investigation may be conducted.

3) To develop appropriate criteria for each vessel, so that it is possible to establish if a given fuel-air mixture can sustain flame propagation.

4) To determine the constant volume lean flammability limit of each test dust, in the 180 litre cylindrical vessel and in the 53 litre closed vertical tube.

5) To examine the effects of direction of flame propagation on the flammability limits, by investigating both upward and downward propagating dust-air flames in the closed vertical tube.

6) To inquire if there are any changes in the lean flammability limit of a dust, if it is determined under constant volume or under constant pressure conditions, by either keeping the vertical tube closed or opening the bottom end of the tube to the atmosphere at ignition.

7) To compare all lean flammability data from the present investigation, with relevant benchmark data and attempt to explain any discrepancies.

8) Finally, to decide if the determined lean flammability limits have any fundamental significance.

3 EXPERIMENTAL DETAILS

3.1 General Description

The present study was performed in two separate cylindrical apparatus of different volume and geometry. Lean flammability behaviour of dust- air mixtures was investigated under both constant volume and constant pressure conditions. A 180 litre test vessel with L/D ratio of 2 was used for the determination of lean flammability limits under constant volume conditions, while a 52 litre vertical tube with L/D ratio near 10 was used to examine the flammability behaviour of lean dust-air mixtures for both constant volume and constant pressure experimental conditions. While there were notable similarities in the experimental procedure and initial conditions of the tests in both the vessels, the boundary conditions in the two vessels were very different.

3.2 180 Litre Cylindrical Vessel and Instrumentation

The principal apparatus used for flammability limit determinations at constant volume has a volume of 180 litres and is cylindrical in shape with rounded dome-shaped ends. The cylinder itself consists of a straight portion (48.2 *cm* inner diameter, with a mean equivalent cylindrical length of approximately 22 *cm* each. The entire confinement is made of thick steel. An overall view of the apparatus is illustrated in the photograph in Fig. 2 and schematically in Fig. 3.

The mass of dust necessary to obtain any desired nominal composition of fuel-air mixture in the 180 litre vessel, must be determined and weighed out. This amount of dust is placed in a hemispherical stainless-steel receptable, located at the bottom of the bomb. The bomb is then bolted tight and evacuated to .7 kPa (56 $torr$) below atmospheric. Dispersion of the dust as well as the production of turbulence results from a strong jet of air being discharged into the dust receptable. The jet of air originates in a 1 litre vessel, pressurized to 1.5 MPa (200 $psig$), and is released by the activation of a solenoid valve. With the addition of the air used for dust dispersion into the test vessel, one ensures that ignition will occur at atmospheric pressure. Ignition is achieved centrally via a pyrotechnic electric match connected directly to a 110 V AC line. The igniter itself, consists of a thin glow wire wrapped with 1.2 g of grounded black gun powder. The effective energy [35] (or $\frac{5}{2}V\Delta p_{max}$) produced by one such igniter in this vessel, was found to be slightly over 3.6 kJ. Diagnostics are composed solely of pressure time history measurements in the explosion vessel via a PCB 113A24 piezoelectric transducer ($\sim$ 5 mV/psi sensitivity), coupled to a Tektronix oscilloscope. A permanent record of the resulting combustion pressure trace is achieved by taking a Polaroid photograph of the oscilloscope trace. A typical record of the pressure-time history, as obtained by a Polaroid camera, is found in Fig. 4. The vertical axis represents pressure while the horizontal one indicates time evolution. The pressure trace was produced from the combustion of 70 g/m^3 Lingan 10-E coal dust at an ignition delay time of 500 ms. From this trace the peak explosion overpressure, Δp_{max} and the peak rate of pressure rise, $(dp/dt)_{max}$, are readily deducible. The vertical spike on the top beam indicates the time of ignition of the dust-air mixture. A solid state delay generator is used to vary the time between the onset of dust dispersion and activation of the ignition source. Ignition delay time-dependent lean flammability limits of different dusts were determined in this apparatus.

3.3 53 Litre Vertical Tube

3.3.1 Overall description

A vertical steel combustion tube, made up of two smaller identical tubes bolted together was employed to investigate lean dust-air flammability behaviour under "constant volume" and constant pressure conditions. With an L/D near 10, this vertical tube allows for distinct flame propagation. The total length of the tube is 1.86 m and has an inner diameter of .19 m, making up a test volume of 52.7 litres.

The apparatus is shown in a photograph in Fig. 5 and schematically in Fig. 6.

The ends of the tube are initially closed by blind flanges. For experimentation under constant pressure conditions, the bottom flange is freely floating. Depending on the intended direction of flame propagation, the ignition source rests on either the bottom or top flange. Each of the two segments of the tube contains its own dust dispersion system and is essentially identical in construction as the other. The dispersion system was developed by Pu et al. [6] in another study in the same tube and was found to produce a relatively uniform dust distribution.

3.3.2 Dust dispersion

The method of dust dispersion is essentially a linear version of the circular perforated tube used by Bartknecht in his standard 20 litre sphere or the 1 m^3 vessel [30]. The linear dispersion tube in the present apparatus is 14 mm in diameter and 910 mm long. It runs from top to bottom along one side of the inner wall of each of the joined two sections making up the tube. Small holes were drilled along the entire length of each dispersion tube, ranging in diameter from 1 mm to 2 mm. The diameter of the holes near the middle of the dispersion tube are larger than at the extremities of the tube because it was found [6] that a more uniform dust distribution after dispersion, can be obtained in this manner. The dispersion tube itself has an inner diameter of 14 mm. Each dispersion tube is connected in series with a small dust placement chamber (10 cm^3), and through a solenoid valve to a pressurized air reservoir (230 cm^3). The air reservoir volume was pressurized to 1.13 MPa (150 $psig$) prior to dispersion. This level of pressurization in the air reservoir has been found to be effective in entraining almost all the available dust when it flows through the dust placement chamber. As well, the pressure of 1.13 MPa is well within the operating range of the solenoid valves used for the dispersion process. When the solenoid valves are activated, the high pressure air is released and flows through the dust placement chambers, entraining the dust and dispersing it in the test vessel, through the linear array of holes in the dispersion tubes. The entire dust entrainment and dispersion process occurs under 100 ms. A circular rod with .95 cm diameter is placed 4 mm away from the dispersion holes and runs parallel to the dispersion tube along its entire length, in order to suppress the directed momentum of the dispersion jets. The rod serves as an obstacle to the dust-air jet, breaking it up, and minimizing the amount of dust impacting the opposite wall of the vessel, which would cause it to get stuck there or drop to the bottom. In addition, a deflected jet can entrain and disperse dust more effectively, which in turn enhances a more uniform dust concentration. Finally, to further improve the dispersion process, the dust placement chamber is placed at the top of each tube so that the dust-air mixture can flow downward along the dispersion tube and one of the two test sections with its dispersion system is shown in Fig. 7, when ignition occurs at the bottom.

3.3.3 Ignition of the dust-air mixture

For all the flammability tests performed, ignition took place at atmospheric pressure. The vessel was initially evacuated to 8.7 kPa (140 $torr$) below atmospheric pressure such that with the introduction of the air used for dispersion, the pressure inside the vessel would rise to atmospheric. Ignition follows the onset of dispersion after a preset time delay of 60 ms. The igniter is identical to the pyrotechnic electric matches used for experimentation in the 180 litre vessel; it consists of a glow wire wrapped with 1.2g grounded black gun powder. The effective energy [35] ($\frac{5}{2}V\Delta p_{max}$) produced by the igniter in the 53 litre vessel has been shown to vary from 4.2 kJ to 4.9 kJ. Positioning of the igniter depends on the direction of the intended flame propagation. When an upward propagating flame is to be investigated, the igniter rests on the bottom flange and points up, whereas for a downward propagating flame, the igniter rests on the top flange and points down.

Under constant pressure conditions, acoustic vibrations can be heard after ignition of the dust-air mixture. A damping section was built so as to damp out the vibrations produced by the burning mixture, which can markedly distort the flame "front". The damping section was located at the very top of the test vessel and was suspended by a steel rod (4 *cm* long) fastened in a leak-proof manner to the top flange. It consisted of pink fiberglass insulation separated via a porous metallic circular plate (2 *mm* thick) from the remainder of the combustion volume of the vessel. The circular plate was .19 *m* in diameter and had circular holes of 2 *mm* diameter uniformly distributed on the entire plate surface spaced 3 *mm* between hole centers. The hole diameter of 2 *mm* was deemed to be less than the quenching distance of the fuels used, so that an upward propagating dust-air flame would not transmit past the circular plate and burn the fiberglass.

3.3.4 Experiments in the closed tube

For "constant volume" experiments, the reactants and products of combustion are physically confined inside the bomb. After loading the mass of dust necessary to achieve a desired concentration, the dust placement chambers are tightly shut. Both the top and bottom flanges are bolted closed and remain so during the course of the experiment. The dispersed dust particles are restricted to the following paths: dropping to the bottom flange as a result of gravity, getting stuck on the walls or obstacles of the combustion space, being blown around in the vessel as a result of turbulent dispersion eddies or induced flow fields from combustion, or, entering the combustion region and burning. Any burning will raise the pressure in the test vessel above atmospheric. Since the vessel is closed (constant volume), the overpressure produced by the igniter and any combustion of the mixture can be detected by a pressure transducer. For all trials under constant volume conditions, the pressure-time history during combustion was transmitted via a PCB 113A24 piezoelectric transducer to an oscilloscope for recording. A similar pressure trace is obtained as in the 180 litre cylinder in (see Fig. 4). The peak explosion overpressure, Δp_{max}, and the representative rate of pressure rise, (dp/dt), were readily deduced. However, pressure measurements of the combustion process alone are not the best indicators of flammability behaviour in view of the high L/D of the vessel. If the combustible mixture can sustain flame propagation, the flame "front" must travel along the axial length of the tube. Clearly, the most appropriate diagnostic in this case would be something which can detect flame passage at different locations along the axis of the test vessel. The flame arrival is detected by four ionization probes biased at a 700 V DC potential and their signals are recorded on an oscilloscope. Both upward and downward propagating dust-air flames, under constant volume, were investigated. The direction of flame propagation was decided solely from which flange the igniter was mounted on. For upward propagation, the igniter is mounted on the bottom flange and the opposite is true for downward. The positions of the ionization probes for both upward and downward directions of flame propagation are identified in Table 1. After any constant volume trial, the dispersion system was purged of any residue and the bomb was opened up and swept clean.

3.3.5 Experiments with the bottom end of the tube open

Performance of flammability tests under conditions of constant pressure was made possible by releasing the bottom flange at ignition. Once the flange is released, the pressure in the vessel remains constant at the atmospheric value. Initially, the procedure is the same as that for constant volume tests. The top and bottom flanges are bolted to the corresponding ends of the vertical tube and the dust receptable chambers are shut. However, after evacuating the bomb to 18.7 kPa below atmospheric, the nut on each of the two bolts holding the bottom flange, is loosened to the extremity of each bolt. The partial vacuum inside the bomb is more than enough to hold the flange up at its initial position. Once dispersion occurs, the pressure within the vessel builds up and the flange is released. The falling flange holds the igniter and rides on the two bolts as it drops down a distance of 5 cm below its initial position. An illustration of the bottom flange resting on the nuts of the two bolts after an experiment, can be found in Fig. 8a. A simple circuit was designed and constructed which sent a signal to the oscilloscope, as soon as the flange began to drop and open the circuit by breaking a wire joined across two leads (see Fig. 8b). The performance of this circuit construction was somewhat limited due to leads taking time to bend before the connecting wire connected across them can break-off and trigger the oscilloscope. Nevertheless, one was able to deduce that the flange had dropped before 120 *ms* following the onset of the dispersion process. Ignition occurred at the most, a few tens of milliseconds before the flange began to drop. The falling flange was able to immediately relieve any pressure build up at the time of ignition, allowing any flame propagation to occur at atmospheric pressure. Once the bottom of the test tube is open, combustion products as well as settling and entrained particles near the opening can exit the tube, while any potential flame can propagate upward freely. For constant pressure tests, the combustion pressure-time history is of no use in assessing flammability behaviour. The ionization probes used for the constant volume experiments were the sole diagnostic for detecting any sustained flame propagation up the open tube. Since dust and combustion products vent to the atmosphere under experiments of this nature, a filtered containment was built which totally enclosed the open section of the tube. After each trial, the dispersion system was purged of any residue and the vessel with its filtered containment region, were swept clean of any dust and combustion products.

The addition of the damping section decreased the axial length of the available combustion space by 4 *cm* and thus reduced the effective combustion volume of the vessel from 52.7 litres down to 51.6 litres. To determine the effectiveness of the damping section, it was removed for several trials. The pressure time histories of vibrations produced by combustion and recorded on the oscilloscope, with and without damping section were compared. There was no noticeable difference in the decay behaviour of the produced vibrations between the two cases. Considering the fact that the pressure trace produced by vibrations diminishes totally in about

200 ms, and constant pressure upward flame propagation takes roughly five times that amount of time to reach only half way up the tube, vibration effects were discarded and the damping section removed. Fig. 9 shows a typical oscilloscope record indicating the pressure history produced by vibrations on the lower beam, and the ignition signal on the upper beam, in a 500 g/m^3 cornstarch dust-air mixture. Fig. 10 is the oscilloscope record for an upward propagating constant pressure flame in a 500 g/m^3 cornstarch dust-air mixture, triggering three of the four ionization probes positioned along the tube axis.

3.3.6 Instrumentation for the vertical tube

Dust dispersion, ignition of the dust-air mixture and any resultant flame propagation collectively take no more than one second to be completed in the closed tube. Given this short time for an experiment, it is essential to have all triggering devices and instruments for obtaining diagnostics, connected in such a way, so as to require minimum effort by the experimenter during the course of the test. Consequently, the entire instrumentation set-up is electronically linked together. An overall instrumentation block diagram is shown in Fig. 11.

Commencing of an experiment is effected by the manual pressing of the button on a hand held switch. This causes a short circuit in the condenser box and results in capacitors discharging through a resistive load, the 120 V DC provided by the Heathkit Regulated High Voltage Power Supply. The discharge activates the two solenoid valves, causing dust dispersion in the combustion chamber, and simultaneously sends out a pulse to the Thyrotron unit. In turn, the Thyrotron unit sends out two pulses. A 17.5 V pulse triggers the two channel non-storage Tektronix Oscilloscope (Oscilloscope 2), while a 5.5 V pulse is sent to the Digital Time Delay Generator. Following a preset time delay of 60 ms, the delay generator sends out a narrow 6 V output to be amplified by a Pulse Amplifier and to then trigger both the ignition system and the four channel storage Tektronix Oscilloscope (Oscilloscope

1). The output from the delay generator alone cannot trigger the TM-11A module of the ignition system and thus, it must be amplified in order to be able to do so.

The ignition system begins with the TM-11A Module and ends with the pyrotechnic igniter. A block diagram of the ignition system is provided in Fig. 12a and a photograph of the ignition system without the igniter, is provided in Fig. 12b. The TM-11A Module (30 $kV\ DC$) receives the amplified delayed output and triggers a high voltage switch ($12-24\ kV\ DC$). A high voltage condenser discharges across the switch the 20 kV, loaded from a Hipotronics High Voltage Power Supply ($0-60\ kV\ DC$). The discharge flows through a Pulse Current Transformer, across a 6 Ω resistance and on to the igniter. The resistance is necessary to decrease the intensity of the initial shock at ignition, which can cause some of the black gunpowder of the igniter as well as flammable dust particles surrounding the ignition source, to be dispersed away and decrease the probability of the combustible mixture igniting. A Pulse Current Transformer is used for sending a signal to Oscilloscope 2, which manifests itself as a vertical spike on the screen at the time of ignition (see Fig. 9). Ignition takes place 60 ms following activation of the solenoid valves.

Flame arrival at various positions along the axis of the test vessel is detected by four ionization probes. The ionization probes are biased at a 700 $V\ DC$ potential by a Portable High Voltage Power Supply ($0-12kV DC$). Voltage across the probes is accurately set by using a voltmeter (Avometer 8), connected in parallel to the Power Supply across the terminals of the ionization probe box. A block diagram of the instrumentation for the ionization probes, can be seen in Fig. 13. Signals from the four probes are recorded on the screen of Oscilloscope 1, which is triggered at ignition. A permanent record of the four probe signals is obtained, by taking a Polaroid photograph of the stored recording on the oscilloscope screen. To measure the average speed of the flame "front" with respect to laboratory coordinates, the distance between the location of any two ionization probes is divided by the time interval between the initial signal at each of these probes. A similar procedure is followed for obtaining the flame speed between ignition source and the ionization probe closest to it. Most studies on the field appear to indicate that propagating dust-air flames have a non- uniform flame "front". Instead, streaky filaments of flame follow regions where relatively rich concentrations of dust are present. Dust deposition after dispersion may insulate the electrodes of each ionization probe and, in extreme cases, cause no signal to be transmitted upon flame passage. On several occasions, very weak signals were picked up by some probes, especially at the final stages of flame propagation. This would indicate weak or non-isotropic flame propagation across the cross-section where the probe was located. On one trial, the flame totally avoided being detected at one ion probe location while it was detected at another position downstream of flame propagation. From these arguments, one must use flame "front" speed measurements with some caution.

The pressure-time history inside the combustion vessel is detected by using a fast-response piezoelectric pressure transducer (PCB 113A24). The transducer has a 1 μsec rise time and a 5 mV/psi nominal sensitivity. For the range of pressures developed during the experiments of the present study, the appropriate pressure transducer sensitivity used is 4.84 mV/psi. The transducer is DC coupled to one of the two channels of Oscilloscope 2 (the other being for the ignition signal). Since this oscilloscope is triggered as the solenoid valves are activated, the transducers register the pressure-time history in the vessel from the very beginning of the dispersion process. An open-shutter polaroid camera with a flash, must be used to obtain a permanent record of the pressure-time history in the vessel, because Oscilloscope 2 is non-storing. In the initial stages of this investigation, the oscilloscope channel used by the pressure-transducer, was instead used to detect the bottom flange dropping for constant pressure experiments (see Section 3.3.5).

3.4 Dust Fuels and Properties

Three different types of dust fuels were used for the present study. Primarily, the lean flammability behaviour of cornstarch in the two test vessels was extensively investigated. Following, samples of two different types of bituminous coal dust were used in experiments, so that comparisons of the lean flammability behaviour of the three dusts could be performed.

Cornstarch was selected as the main test dust in the dust-air flammability experiments for numerous reasons:

(a) It is readily available as a consumer product in pure form and in large quantities at a reasonable cost.

(b) Its properties are relatively well known from previous investigations [36,37,38] and its chemical composition is fairly simple.

(c) Results from its flammability behaviour can be compared with available benchmark data.

(d) The particles have a regular shape and fairly narrow size distribution.

(e) It is a major constituent of grains and other agricultural dusts stored in silos, thus making it very representative of many agricultural and carbonaceous dusts.

(f) It is relatively clean in its handling, readily dispersible and easily ignitable at fairly low concentrations.

Cornstarch is a natural polymer of the dextrose molecule. Typically, between 300 and 400 dextrose molecules form a chain. The basic chemical formula is $(C_6H_{10}O_5)_n$. Peraldi has obtained its heat of combustion and several other combustion parameters [38]. Lewis [39] has shown that cornstarch has a very high volatile content (above 90%). The shapes of cornstarch particles are fairly regular; they are mostly spherical in shape with some particles taking on ellipsoidal geometries. Fig. 14 shows a scanning electron micrograph of a cornstarch particle. The mean particle size based on a frequency average is 14.7 μm, with particles ranging from just a few microns up to 30 μm. Such small particles are normally cohesive and tend to agglomerate and form larger particles. Commercially available cornstarch usually contains roughly 10% moisture by mass [6]. This moisture between particles causes agglomeration, as well. To reduce agglomeration and facilitate a more uniform dust dispersion process, the dust was dried in an oven at $105^{o}C$, for 24 hours. Prior to being dried, the dust was well mixed with 1% by mass of fumed silica (cab-o-sil), a fluidizing agent. This fluidizing agent reduces the weak electrostatic forces which cause particles to be cohesive and thus reduces agglomeration. Smaller particles can remain suspended for longer periods of time and provide a larger specific surface area for volatiles release, compared to agglomerations of particles. Fig. 15 shows the particle size distribution of cornstarch particles for two random dust samples, one with and one without fluidizing agent. For the same concentration of dust-air mixture the peak explosion overpressure was shown to be noticeably higher when the dust was dried and admixed with fused silica than for the case when the dust was not dried and no fluidizing agent was added. The peak explosion overpressure is a relative measure of the amount of dust fuel which participates in combustion. Inevitably, the particle size of the dust cloud will determine the degree of burning. Table 2 summarizes the properties of cornstarch that are relevant to its combustion behaviour.

Once various aspects of the lean flammability behaviour of cornstarch dust were investigated, a similar investigation was carried out for two bituminous coal dust samples. The coal samples were provided by Energy, Mines and Resources, Canada, through their Cape Breton Coal Research Laboratory. Both dusts originate from the same region of Cape Breton, but from different mines. One sample is from the Devco No. 26 Colliery mine and the other is from the Devco Lingan 10-E mine. These Devco coal samples are among the most reactive of Canadian coals [40]. It should be noted that the Devco No. 26 mine is presently shut-down due to a destructive explosion that occurred at the site a few years ago. A lean flammability investigation was carried out for the two Devco coal samples, so that comparisons can be made with the very different agricultural cornstarch dust, and so that a better assessment of the relative explosion hazards presented by these two coals can be made possible.

The Lingan coal dust consists of a sample passed through a 325 mesh screen, containing a broad distribution of particle sizes with the maximum particle dimension being 44 μm. The No. 26 dust consists of a sample passed through a 200 mesh (70μm) screen and contains a somewhat broader distribution of particle sizes compared to that of the Lingan coal. Select properties of both these coal samples, as obtained by the Cape Breton Coal Research laboratory, are presented in Table 8. From the proximate analysis data, one can see that the moisture content of the two Devco coal samples is below 1%, much lower than the estimated 10% for commercially available cornstarch dust. As a result, the coal dust was heated overnight at 70°C only for experiments in the vertical tube where dust settling effects are more pronounced due to the high L/D of the vessel and to the small scale dispersion-induced turbulence present to suspend the dust. Both Devco coals have a much lower volatile matter composition, and a significantly larger percentage of fixed carbon compared to cornstarch dust. Unlike cornstarch dust, the shape of coal dust particles is non-spherical. At different stages of this investigation, some limited comparisons of the flammability behaviour were made, between cornstarch dust and one or both of the coal dust samples.

4 RESULTS FROM THE 180 LITRE CYLINDER AND DISCUSSION

4.1 General Description

Almost all flammability limit investigations of dust-air mixtures, have been carried out in confined pressure vessels of spherical or low L/D geometries and under constant volume conditions. The initial dust loading, in grams, divided by the volume of the vessel, in cubic meters, determines the nominal dust fuel concentration. The sample dust is placed in a receptable located within the vessel, is subsequently dispersed by a high pressure air blast and ignited after a pre-set time delay at atmospheric pressure. Dust dispersion and ignition cause a transient pressure rise within the vessel. The pressure rise is a result of the following phenomena: the introduction of the pressurized air which causes dust dispersion and raises the vessel's pressure to 1 atmosphere, the energy given-off by the igniter, and the energy released as a result of any dust combustion. The pressure-time history within the vessel is usually, as in this case, detected by a calibrated pressure transducer and transmitted to a recording device, such as an oscilloscope. As the oscilloscope is triggered at the onset of dust dispersion, the initial rise in pressure is caused by the dispersion air while a secondary discrete pressure rise results from the combination of ignition and any flame propagation (see Fig. 4).

4.2 Experimental Data Obtained on the 180 litre Cylindrical Vessel

Prior to attempting the establishment of any flammability limit criterion, it is necessary to compare raw data results. The approach has been to carry out a broad flammability study relating the results obtained from the present study to well-established benchmark data in the field, for all the particulate materials used. It is necessary to confirm the adequacy and reliability of the apparatus, dispersion system, ignition source, diagnostic techniques and operating procedure. With L/D near unity for the constant volume 180 litre vessel, the Δp_{max}, and $(dp/dt)_{max}$ values, are readily deduced from the pressure-time record of an experiment. In order to compare the present data of $(dp/dt)_{max}$ with those obtained from other vessels, it is necessary to scale the rate of pressure rise with the apparatus size. The "cubic law" [30] is used and the K_{st} factor is introduced. For the cornstarch dust and the two Devco coal dust samples, the Δp_{max} and K_{st} values are compared with pertinent benchmark data. However, it is unfortunate that most other investigations have not been concerned with the flammability behaviour of the dusts near their lean limit. As a result, some critical parameters that lean limits are very sensitive to, such as ignition source characteristics and moisture content, were given little or no consideration at all by other researchers.

Primarily, a dust mixture well within the flammability limits (250 g/m^3 cornstarch) was burned in the cylindrical vessel. The peak overpressure recorded was 5.6 *bar*. Nagy et al. (1961) obtained overpressures of 5.6 *bar* for the same dust concentration in a 1.23 litre Hartmann bomb [12]. Previous work performed in McGill by Bond et al. [41] in a 333 litre sphere, and in the same 180 litre vessel used for the present study, indicated overpressures of 5.4 *bar* and roughly 4.2 *bar*, respectively. Cocks [42] reported a value of 3.6 *bar* for the same dust concentration in a 20 litre sphere. A relatively large scatter of results is expected for dust combustion where the uniformity of the dust cloud varies with apparatus and dispersion system. The discrepancy between results in the 180 litre vessel can be attributed to different dust preparation methods, significantly weaker ignition source, and possibly different dispersion pressure. Nevertheless, the result obtained in the present apparatus compares very favorably with the other results previously mentioned. When it comes to comparing dust combustion properties near the lean limits, very limited data exists from other investigations. Despite this limitation, one can observe how the lean flammability combustion data from this investigation appears in perspective to the few lean dust concentration results available and to the many results obtained from investigations concerned with relative rich dust fuel-air mixtures. A comparison of the present results for the normalized peak explosion overpressure, $\Delta p_{max}/P_o$, the peak rate of pressure rise, $(dp/dt)_{max}$, and the vessel size normalized peak rate of pressure rise, K_{st}, in cornstarch dust-air mixture as a function of cornstarch concentration, is shown in Figs. 16-18, respectively, with previous results obtained by other researchers. The scales of both axes for all of the above three figures are magnified near the origin.

For most other investigations, the emphasis was in cornstarch concentrations of over 100 g/m^3, while in the present case 100 g/m^3 was one of the maximum concentrations used. No particular attention was paid by others to the extremely sensitive nature of the lean flammability behaviour of dust-air mixtures. In a previous investigation in the same 180 litre vessel conducted by Bond et al. [41], ignition was effected by an exploding wire and the dust was not dried. Presently, the cornstarch dust used was dried, causing a reduction of humidity between particles and a pyrotechnic igniter of relatively higher energy and longer burn profile was used. As a result, Bond observed negligible pressure rise in attempting to burn 150 g/m^3 cornstarch dust in air while normalized peak explosion overpressure values near 0.5 were observed in the present study for cornstarch concentrations below 100 g/m^3. Present results tend to be in reasonably good agreement with results obtained from the 333 litre vessel in all of Figs. 16-18. The cornstarch data plotted was obtained using a 500 ms delay between dispersion and ignition, for better comparison with Fresko's and Bond's data which were obtained using the same time delay. Results obtained in vessels with volume significantly below 180 litres, indicate significantly higher values for all three explosion parameters at cornstarch concentrations less than or equal to 100 g/m^3. This large difference between results obtained in the 1.23 litre vessel and the 180 litre cylinder, may be partly attributed to the difference in the cornstarch used and the specific ignition-dispersion procedure followed for the two different types of vessels. In the Hartmann 1.23 litre bomb [12] a continuous transformer spark discharge is activated before dispersion. The dust initially rises as a dense cloud and is ignited prior to it being uniformly dispersed, resulting in the ignition of a cloud whose real concentration is significantly above the nominal dust concentration in the vessel. Using the identical pyrotechnic igniter and method of dust preparation in the 53 litre vertical tube, $(\Delta p_{max}/P_o)$ values are higher for cornstarch concentrations at, or under 100 g/m^3. This is due mainly to magnified ignition effects in the smaller 53 litre vessel. The large difference in combustion parameters between the 180 litre cylinder and the 1.23 litre Hartmann type vessel, as is evident from Figs. 16 and 18, is expected due to the unsuitability of such small vessel volumes for reliable lean dust flammability research. Thus, the present combustion data for cornstarch dust in the 180 litre vessel is consistent with relevant benchmark data.

To further establish the reliability of the data obtained from the present vessel, and to assess the relative flammability of the two different Devco coal dust samples tested, comparisons are made with the "standard" Pittsburgh Seam bituminous coal dust. Figs. 19 and 20, respectively compare the results of $(\Delta p_{max}/p_o)$ and K_{st}, obtained in the 180 litre vessel for different coal dust concentrations, with results obtained by Hertzberg [24] in a 20 litre vessel using the "standard" Pittsburgh coal dust. The Hertzberg data used are obtained using pyrotechnic igniters of 5.0 kJ minimal calorimetric energy, and effective energy [35] ($\epsilon_{eff} = \frac{5}{2} V \Delta p_{max}$) of 2120 ± 220 J. The effective energy of one of the pyrotechnic igniters used for the present experiments was found to be over 3600 J, which should correspond to a nominal calorimetric energy of more than 5 kJ. Hence, comparisons of the present results with Hertzberg are most appropriately performed if one selects to compare those results which were obtained using the 5.0 kJ igniter [24]. Despite the differences in chemical composition, size of apparatus, ignition source, dispersion system, of one temporarily disregards the 5.3 litre coal dust results, Figs. 19 and 20 demonstrate reasonable agreement in obtained combustion parameters as a function of concentration for all three coal dusts. More particularly, the Devco No. 26 and Lingan 10-E coal dusts, behave in a very similar fashion for the leanest concentrations tested.

4.3 Criterion for Determining Lean Flammability Limits in the 180 L Cylinder

After having confirmed the reliability of data obtained for the cornstarch Dust and coal dusts tested in the 180 litre vessel, one can now attempt to establish criteria for deciding lean flammability limits for this vessel. In selecting the flammability criteria, the peak explosion overpressures were found to decrease rapidly with decreasing concentration. Finally, at some point, the overpressures levelled off and essentially registered the overpressure generated by the pyrotechnic igniter itself. Peak overpressures generated by igniters alone, under identical test conditions (dispersion turbulence) as when dust is placed, varied from about 5 to 10 kPa. A maximum overpressure of 20.7 kPa was selected as the lean flammability limit criterion. This value was chosen for two main reasons. First, this limit criterion is significantly higher from the maximum observed overpressure generated by any igniter tested. It provides a small buffer region whereby overpressures produced by marginal dust burning nearest to the ignition source, would not be considered as a sign of a sustained flame propagation. Second, this value was chosen because it corresponds to the pressure generated by a quiescent mixture of 4.0% hydrogen in air in the present vessel. Coward and Jones [8] reported 4.0% to be the lean upward propagation limit of hydrogen in air. Very similar pressures were obtained for limit mixtures of 5.0% methane in air. The lean flammability limit of a dust, at any particular ignition delay time after dispersion, is taken to be the minimum nominal dust concentration where at least one trial produces a Δp_{max} of at least 20.7 kPa.

4.4 Effects of Ignition Delay in the 180 Litre Cylinder and Lean Flammability Limit Results

The parameters which can affect dust-air combustion, especially for compositions near the lean limits, are numerous. For a given dust sample, given test vessel, dispersion system and dispersion pressure, and fixed initial thermodynamic state, there remain two very important parameters to be decided upon. They are the time delay between the onset of dispersion and ignition, and the ignition source energy and burn profile. Hertzberg has performed systematic investigations to determine the influence of ignition source, on various aspects of the combustion behaviour of dusts and gases, across the entire flammability range [24,35,43]. He has demonstrated that the observed lean flammability limits of dusts can be lowered significantly by increasing the energy content of the pyrotechnic igniters used. For the present investigation, it was decided that it would be best to fix the ignition source and to look at some effects in the combustion behaviour, of time delay between onset of dispersion and ignition. After an examination of Hertzberg's results, the level of ignition energy of the pyrotechnic igniter used in the 180 litre vessel, was rendered to be adequate to ensure a proper lean flammability investigation of the dust fuels used (as opposed to the relative ignitability of a dust for a given ignition energy). As well, the relatively long burn profile ($> 25\ ms$) of these igniters [6], increases the probability that a sufficient amount of randomly moving dust particles will traverse the ignition source region and ignite, providing the necessary initial flame kernel.

As was discussed in section 2.4, 2.5, the ignition will affect the degree of turbulence present and may affect the concentration of dust suspended within the vessel, at ignition. The dispersion of dust in the 180 litre vessel is a transient process and takes a finite amount of time for a uniform dust distribution to be achieved. Thus, prior to determining the lean flammability limit of a dust, it is necessary that the dust-air mixture be ignited at the most appropriate time delay after dispersion. This determination of "optimum" time delay for each dust, was accomplished in one of two ways. In one way, a dust concentration near stoichiometric proportions, or the average concentration to be used in a set of experiments, was chosen. With this chosen dust concentration, a set of experiments in which the time delay between dispersion and ignition was varied, was conducted. The Δp_{max} and $(dp/dt)_{max}$ values were obtained at each time delay, and the "optimum" delay was selected to be the delay where the maximum value of Δp_{max} was achieved. Delay time increments of 100 ms were used. This optimum delay was then used in the determination of the lean flammability limit of the dust, using the 20.7 kPa peak explosion overpressure criterion. In the other way, the "optimum" time delay was determined indirectly. The lean flammability limit of a dust was determined for a set of time delays, 100 ms apart. The time delay where the lowest lean flammability limit was observed, corresponded to the "optimum" time. Since this was the lowest nominal dust concentration at which a Δp_{max} value of at least 20.7 kPa was obtained, it implies that the time delay used must have been such as to have produced the best turbulence and dust distribution in air combination.

The maximum explosion overpressure developed in a given vessel should be a function of the energetics of the dust sample, its physical properties, such as particle size distribution and moisture content, and the initial thermodynamic state of the mixture. Thus, for a fixed nominal dust concentration in a given vessel, any increase in Δp_{max} value should correspond to an improvement in the quality of dispersion. It is then reasonable to assume that the highest Δp_{max} values are produced, when ignition occurs at the time when the sample dust has been most effectively dispersed throughout the vessel. However, one must not forget the existence of turbulence at the time of ignition of the dust-air mixture. As a result of dust dispersion via an air blast, one introduces a certain amount of dispersion induced turbulence in the vessel. After dispersion, turbulence is necessary to entrain and suspend the dust particles within its eddies. Even though this turbulence immediately begins to decay after the onset of dispersion, there exists a finite amount of it still present at ignition which may affect the combustion process. The random motions of the turbulent eddies can serve as multiple points for ignition ahead of the main burning region, effectively accelerating the combustion rate. Turbulence may reduce the heat losses from the burning region(s) via a faster burning rate, while for near limit mixtures it counteracts buoyancy effects, resulting in more uniform combustion of the given volume. In the determination of "optimum" time delay, it is beyond the scope of this investigation to quantify the interactions of turbulence, buoyancy and quality of dust dispersion. Nevertheless, some limited qualitative observations on the effects of time delay to the Δp_{max} and $(dp/dt)_{max}$ values for some dusts, are reported.

Bond et al. [41] investigated the influence of turbulence on cornstarch dust-air explosions in the same 180 litre vessel used by this author as well as in a 333 litre spherical vessel. Definite differences were reported in the Δp_{max} and $(dp/dt)_{max}$ values obtained as a function of time delay, for cases where there was turbulence introduced in the vessel, in addition to the dispersion induced turbulence, and the case of no additional turbulence introduced. It was found that for two cornstarch dust concentrations tested of 300 g/m^3 and 600 g/m^3, the general trend is that increasing the level of additional turbulence, decreases both Δp_{max} and $(dp/dt)_{max}$ in the cylindrical vessel. The decrease in both Δp_{max} and $(dp/dt)_{max}$ may be due to turbulent quenching. Opposite trends in results are obtained in the 333 litre sphere. This may be partially a result of more severe heat losses to the walls in the cylindrical bomb since the flame is already in contact with the cylinder wall, prior to the mixture near the ends of the vessel being consumed. It is thus, difficult to generalize the effects of turbulence on the burning rate since it appears that vessel geometry and details of the turbulent structure affect the burning rate. With and without additional turbulence, maximum values for Δp_{max} and $(dp/dt)_{max}$ were observed for cornstarch, at time delays significantly below 1.0 s. The highest value of Δp_{max} for cornstarch dust, with no added turbulence other than the dispersion-induced turbulence, appeared at a time delay of 400 ms, while the Devco No. 26 coal dust attained its highest value for Δp_{max} at a 300 ms ignition delay.

In Figs. 21 and 22, Δp_{max} and $(dp/dt)_{max}$ from the cylindrical bomb, are plotted as a function of ignition delay time for concentrations of 250 g/m^3 cornstarch dust and 200 g/m^3 coal dust (Devco No. 26). Beyond the "optimum" delay time of each dust, the Δp_{max} values appear to decay in an almost linear fashion, with increasing time and decreasing turbulence in the vessel. $(dp/dt)_{max}$ values for coal dust decrease linearly from about 7500 kPa/s at a few milliseconds ignition delay after dispersion, down to under 1000 kPa/s when 1 sec has elapsed before ignition occurs. In other words, the burning rate which is a direct reflection of $(dp/dt)_{max}$ appears to be dominated by the dispersion-induced turbulence present at ignition. As the turbulence level decreases immediately after dispersion to a more quiescent state with elapsed time, so does the burning rate for this coal dust sample. On the other hand, the peak value of $(dp/dt)_{max}$ for cornstarch dust appears at a ignition delay time of 500 ms, after which time $(dp/dt)_{max}$ values quickly decay, with decreasing dispersion-induced turbulence. Potential reasons for the decay in both Δp_{max} and $(dp/dt)_{max}$ values, are the decreasing level of turbulence in the vessel and dust particle settling with elapsed time after dispersion. Even though the burning rate of the coal dust is decreasing steadily and linearly for all increasing time delays between dispersion onset and ignition, the Δp_{max} value attains its peak at 300 ms delay. This indicates, that the level of dispersion-induced turbulence alone, cannot directly determine the appropriate conditions for the highest Δp_{max} to be achieved. The peak values for Δp_{max} and $(dp/dt)_{max}$ are 100 ms apart. The optimum burning conditions of a dust in the vessel are most likely determined from the coupling of turbulence level present and the quality of available dust concentration suspended, at ignition.

The effectiveness of the air blast used for dispersion to entrain and swirl the dust around the vessel, decreases with time. The question of when the transient dispersion-induced turbulence can no longer suspend the dust, is very complex to answer. In contrast, it is relatively simple to estimate the free fall distance of individual particles with elapsed time, by assuming the typical settling velocity of the dust particles to be equal to their stokes free fall velocity. The magnitude of this velocity can provide some indication of the amount of dust still in suspension at ignition. For the largest cornstarch particle size of 30 μm, this terminal velocity is roughly 4 cm/s. Thus for time delays between dispersion and ignition of under .5 seconds, almost all the cornstarch particles should still be in suspension. Even though one can estimate the free-fall velocity of individual dust particles, one cannot know the concentration gradients available within the dust cloud, at ignition. Further, agglomerations of particles can decrease the effective amount of dust suspended, at a faster rate than could individual particles falling at their own free-fall velocity. Once ignition occurs under these constant volume conditions, the expanding hot region will create a turbulent flow field ahead of the flame "front", which will distort both the turbulence and the suspended dust distribution that was present at ignition. It is not possible to estimate the free-fall velocity of the highly non-spherical coal dust particles using the Stokes free- fall assumption since it does not apply to non-spherical geometries. However, based on the relatively large particle size of this coal dust (< 70 μm), one would expect that if one waits too long after dispersion, the available coal dust concentration at ignition may be significantly below the intended one. Intuitively, it appears that the proper ignition delay time for the much larger coal dust (Devco No. 26) particles of roughly the same specific gravity (1.35) as cornstarch (1.5), should be less than that for cornstarch particles. This is demonstrated by the determined "optimum" delay times.

As mentioned earlier, the "optimum" time delay between dispersion and ignition for some dusts in the 180 litre vessel, was determined to be the delay at which a peak explosion overpressure of at least 20.7 kPa was produced, by burning of the lowest concentration of the particular dust. Using this approach, the "optimum" ignition delay for the Lingan 10-E coal dust was found to be 100 ms after dispersion. Considering that most of the particles for this sample of coal dust (< 44 μm) should be larger than the biggest observed cornstarch particles (30 μm), one expects its "optimum" time delay to be below that found for cornstarch. Questions arise about the applicability of "optimum" delays obtained from the method of using relatively rich dust mixtures, to lean flammability limit investigations. In attempting to resolve such questions, the "optimum" t_D for cornstarch was determined using both of the described methods for its determination. The lowest dust concentration which produced a Δp_{max} of at least 20.7 kPa was found to be at a t_D of 200 ms. This t_D of 200 ms was 200 ms shorter than the "optimum" t_D that was obtained by its correspondence to the peak value of Δp_{max} from the combustion of 200 g/m^3 cornstarch dust in air, over a range of time delays. It must be noted that reproducibility of results for lean mixtures, has been shown to be inferior to that of non-lean mixtures. Hence, obtaining the "optimum" t_D from the method of lowest lean flammability limit of a particular dust, is subject to a certain extent to the fluctuations in Δp_{max}, resulting from the number of trials at the nominal concentrations attempted at each t_D. It may be worthwhile to determine the optimum "t_D" for all dusts used in a lean limit investigation by both methods and then compare the results to decide the final t_D to be used. The "optimum" t_D selected for lean flammability investigations of cornstarch in the 180 litre vessel is 200 ms. One should take note, however, that the lean limit for cornstarch at a t_D of 400 ms is only 5 g/m^3 higher which is not very significant if one considers the large scatter observed in Δp_{max} results. The optimum "t_D" of all the dust fuels used are tabulated in Table 3. The apparent lean flammability limits of cornstarch dust and Lingan 10-E coal dust, as a function of ignition delay, t_D, are tabulated in Table 4 and plotted in Fig. 23. From 100 to 400 ms ignition delay, the lean limit concentration for cornstarch dust is fairly constant rising from 75 gm/m^3 at 100 ms and remaining at 80 g/m^3 until 400 ms ignition delay. With increasing t_D past 400 ms, the lean limit of cornstarch appears to increase fairly rapidly to 95 g/m^3, at the 600 ms delay tested. On the other hand, there is almost a linear increase in lean limit concentration for coal dust (Lingan 10-E) with increasing time delay for ignition, from 100 ms to 600 ms. Due to the unsatisfactory reproducibility of results in this vessel for the combustion of lean dust-air mixtures, it may not always be meaningful to quote a single number as the absolute lean flammability limit of a dust. Rather, an interval of concentrations for the lean limit would be preferable. To be conservative, however, the stated value (or range) of lean flammability limit must incorporate the minimum nominal concentration of dust observed, at any t_D, which satisfied the 20.7 kPa Δp_{max} criterion. Consequently, the lean flammability limits in air, of cornstarch dust and Lingan 10-E coal dust, as obtained from the 180 litre vessel, are $75 - 80$ g/m^3 and 40 g/m^3, respectively.

In order to establish if the criterion used for determining lean flammability limits of dust fuels in the 180 litre cylinder is adequate, one must further examine the results obtained. As the lean flammability limit is approached with decreasing fuel concentrations, the observed values for Δp_{max} and $(dp/dt)_{max}$ should rapidly decline and attain values near those produced by the igniter itself. The results are displaced numerically for cornstarch in Tables 5a through 5e, and for Devco Lingan 10-E coal dust in Tables 6a through 6f. The tabulated results show the Δp_{max} and $(dp/dt)_{max}$ values for given nominal dust-air mixtures, at particular ignition delay times. If one plots the Δp_{max} and $(dp/dt)_{max}$ at the "optimum" t_D as a function of nominal dust concentration, the typical trends are illustrated for cornstarch dust-air mixtures in Fig. 24 and 25, respectively, and for coal dust-air mixtures (Lingan 10-E) in Figs. 26 and 27, respectively. Looking at Δp_{max} versus concentration for cornstarch dust in Fig. 24, and for coal dust (Lingan 10-E) in Fig. 26, one sees that Δp_{max} increases with increasing dust concentration. Hertzberg et al. [24] observed the identical trends in their study of pulverized coal dust flammability limits. A drastic change of slope of the curves, in the vicinity of the flammability criterion (20.7 kPa) is clearly evident. At concentrations near the flammability limit, one expects sudden changes in the energy released from combustion. A much higher Δp_{max} is expected for flammable mixtures where a self sustained flame is present, compared to that obtained from a mixture where concentration is below the lean flammability limit and where there is no self-sustained flame propagation. For cornstarch dust at its "optimum" ignition delay of 200 ms, the maximum rate of change in Δp_{max} is displayed at around 75 g/m^3 dust concentration. As indicated earlier, 75 g/m^3 is the minimum concentration of cornstarch dust which satisfies the lean flammability criterion of 20.7 kPa peak explosion overpressure. The intersection of the curve in Fig. 24 with the limit criterion very near 75 g/m^3 cornstarch dust concentration, indicates remarkable consistency of the criterion used to expected combustion behaviour. Fig. 25 indicates a drastic change in slope for $(dp/dt)_{max}$ at a cornstarch concentration of 75 g/m^3. Recall, however that the criterion for determining the lean flammability limit is based on Δp_{max} and not on $(dp/dt)_{max}$. Fig. 26 indicates a drastic change in slope for Δp_{max} at a coal dust (Lingan 10-E) concentration of 40 g/m^3. In Fig. 26, the Δp_{max} curve intersects the 20.7 kPa Δp_{max} criterion very near 40 g/m^3. Once again, this demonstrates very good agreement between the criterion used to establish lean flammability limits and the actual combustion behaviour. The $(dp/dt)_{max}$ curve (Fig. 27) for the Lingan coal dust, indicates an increase in the burning rate with increasing concentration but due to the large scatter in results, no discernible drastic change in slope is evident at the limit of 40 g/m^3.

To further appraise the method for determination of lean flammability limits of dust-air mixtures, in the present investigation, one must compare the present results with those obtained from other studies. The cornstarch results are compared in Table 7 with flammability limit data measured in the 1.23 litre Hartmann bomb [30], the 5 m^3 explosion vessel [36] and with a first approximation for the lean flammability limit concentration based solely on the higher heating value [7]. Results from the Hartmann bomb can be dismissed immediately due to a soft flammability criterion, inadequate procedure for the tests, and the general inapplicability of such small vessels in studying dust air combustion. The very good agreement between the 180 litre vessel results and the 5 m^3 results is to be noted. The theoretical estimate for the lean flammability limit of cornstarch based on higher heating value information is 103 g/m^3; it appears to be a satisfactory first approximation considering all the other factors which can affect lean limits for dusts such as particle size, volatile matter, ignition energy, and so on.

Flammability limit data from constant volume combustion, along with some selected properties (particle size, proximate analysis, heating value) of different coal dust samples are compared in Table 8. The lean flammability limit of 40 g/m^3 for the two Devco coal dust samples tested in the 180 litre cylinder, appears to be the lowest from all the other reported coal dust lean limits. Both the Devco Lingen 10-E and Devco No. 26 coal dust samples, were obtained from the same Cape Breton region of Nova Scotia. Proximate analysis data (Table 8) demonstrate the many similarities in the composition of these two coal dust samples. The higher limit concentration of 67 g/m^3 obtained by Feng [40] in a 1.2 litre cylinder for the No. 26 coal dust can be partly attributed to a different ignition source and drying procedure used, and once again, to the inapplicability of such small test vessels for dust combustion. Hertzberg et al. [19,24], determined the lean limits of several coal samples in smaller 7.8 litre and 20 litre vessels. Hertzberg's criteria for the limits of flammability differ from the criterion used in the 180 litre cylinder. A large variation in the proximate analysis data is evident for the variety of coal samples tabulated. Hertzberg reports that the lean limits of the coal samples tested in the 7.8 litre vessel, are inversely proportional to the volatile matter in the samples [19]. Equivalently, samples with the highest combined percentage of fixed carbon and ash, have the highest lean limits, since flame propagation is not facilitated as a result of the small content of volatile matter present. The reported lean limit for the most volatile Gilsonite is 65 g/m^3, compared to the 450 g/m^3 limit reported for the least volatile Reading coal. The Devco coal samples have much higher volatile matter and lower fixed carbon compared to Pocahontas and Reading coal samples, which explains the lower lean flammability limits observed in the present investigation. The volatile matter and fixed carbon in the Devco coal samples and the Pittsburgh "standard" coal dust, are not very different. Therefore, the significant difference in the reported limit concentrations must be largely due to the different apparatus, test procedure, ignition source, and propagation criteria, used by Hertzberg and in this investigation. Furthermore, Hertzberg reports that for the lower volatile coals, Pocahontas and Reading, more energetic igniters are necessary and larger test vessels are to be utilized in order to avoid overdriving effects of the combustible mixture. If these recommendations were to be implemented, the lean limits for such coal dusts should be lowered and would approach the lean limit of the Devco coal samples. The theoretical lean limit estimated by the higher heating value for each dust sample, gives comparable results to the measured lean limits, except for the least volatile dusts, Pocahontas and Reading.

In short summary, it appears that the criterion used for the present investigation in the 180 litre vessel to determine lean flammability limits, produces comparable results to other vessels. There is very good agreement for the flammability limit of cornstarch dust air mixtures, in the 180 litre ($75 - 80\ g/m^3$) and the 5 m^3 cylinders. Less satisfactory agreement was observed between the two Devco coal dusts in the 180 litre cylinder, and other coal samples in smaller vessels. Lean flammability limits of Lingan 10-E and No. 26 coal dusts ($40\ g/m^3$), were significantly below other coal dust results obtained from other investigations ($65 - 450\ g/m^3$). However, the adequacy of the 20.7 kPa Δp_{max} criterion for the 180 litre cylinder, appears to be supported by the actual combustion behaviour which was deduced from Δp_{max} data, as a function of dust concentration at the "optimum" ignition delay time. The greatest rate of change in Δp_{max} with dust concentration at the "optimum" t_D, was observed to intersect with the flammability limit criterion very near the determined lean limit.

5 RESULTS FROM THE 53 LITRE VERTICAL TUBE AND DISCUSSION

5.1 General Considerations

The standard apparatus used to study dust explosions is usually the constant volume bomb of spherical, or low L/D geometry, such as the 180 litre cylinder. In such vessels, ignition takes place centrally and the combustible mixture is consumed volumetrically. More often, the standard or sole diagnostic used, is the pressure-time history developed by the combustion process. For the second part of this investigation, a 52.7 litre vertical tube with L/D near 10 is used to investigate lean flammability limits of some dust-air mixtures, under both constant volume and constant pressure conditions. Ignition occurs either at the top or bottom cover flange, depending on the intended direction of flame propagation. Unlike the 180 litre cylinder, this vertical tube allows for distinct flame propagation along the vertical axis of the vessel. Due to the geometry of the apparatus, an effective dust dispersion throughout the vessel cannot be achieved by the usual air blast into a dust receptable. As a result, a very different dispersion system is used (see section 3.3.2) whereby pressurized air disperses the dust through fine holes from a small diameter vertical tube, running along the entire wall height of the apparatus.

Since the combustion tube can be operated closed or open and has a large value of L/D, one must decide on the method to use for determining if the combustible mixture can sustain flame propagation. In view of the large L/D of this tube compared to the 180 litre cylinder, and the fact that dust flammability investigations under constant pressure are to be conducted, pressure measurements of the combustion process are clearly inadequate as the sole diagnostic means. Subsequently, the main diagnostic in the dust flame tube consists of ionization probes which detect the passage of the combustion front. Four such probes have been installed in the present experiments, at different locations along the tube axis. Traditionally, the criterion used for determining whether or not a sustained flame propagation has occurred in a given experiment, is the visual observation in a darkened room (or with a photo multiplier) of upward flame propagation in a tube over a distance of 1 to 2 *meters* from the ignition source, under constant pressure conditions. Flammability limits are not necessarily restricted to the upward direction, but to the downward and horizontal directions, as well. In the present investigation, only upward propagation limits are investigated under constant pressure, while both upward and downward limits are examined under "constant volume" conditions. It was not practical to investigate horizontal propagation limits. The criterion for inflammation is when the dust-air flame propagates along the tube and triggers the ionization probes. A mixture is judged to burn when the flame has managed to propagate at least three quarters of the length of the tube; this is roughly when it reaches the third ionization probe in the upward direction, and beyond the third probe for the downward direction. Even though the flammability criterion is based on the distance of flame travel along the tube, the pressure-time history in the vessel was detected by a piezoelectric pressure transducer and recorded on an oscilloscope.

5.2 Experimental Data Obtained in the Closed 53 Litre Vertical Tube

Before attempting to determine flammability limits for the dust-air mixtures in this high L/D vertical tube, it is necessary to verify the effectiveness of the apparatus and dispersion system used, in yielding results that are valid and reproducible. This is achieved by demonstrating that the present results are compatible with those of other researchers doing similar work. $\Delta p_{max}/p_o$ results from the present study are placed side by side with those of others [17,41,42,44,45], in Figs. 16 and 28, for cornstarch dust-air mixture under constant volume conditions. The present data is compared with data from a spherical .333 m^3 bomb, a .180 m^3 cylinder [41], a .156 m^3 horizontal tube (L/D = 7) [44], and a .025m^3 vertical tube (L/D = 5)

[45], all previously obtained at McGill using the same cornstarch and similar dust preparation procedures before experimentation. One would expect that there should exist significant differences in the Δp_{max} data obtained from such very different vessel geometries, dispersion systems, turbulence intensities, and distributions of dust in the vessel. However, there appears to be quite good agreement for all the data shown in both Figs. 16 and 28. The present vertical tube is essentially a cascade of two identical tubes as the one used by Pu et al. [45]. In Pu's results, it is uncertain if the Δp_{max} data is for nominal dust concentrations or actual dust participating in combustion (corrected for the amount of dust that has been shown to stick to the walls, or left behind in the dispersion system). In addition, it is very likely that a higher more effective dust dispersion pressure was used which can better break-up and suspend dust particles, resulting in slightly higher Δp_{max} values compared to the present data.

The Δp_{max} values obtained from the .180 m^3 cylindrical, .333 m^3 spherical and .156 m^3 (L/D = 7) vessels, are all higher than those obtained from the present vertical tube. This may be simply an indication of the higher heat losses prevalent in the present test tube which has the highest L/D from all the other vessels. For the dust concentrations tested in the present apparatus, there appears to be no discernable deviations in the Δp_{max} data obtained from upward and downward propagating flames. While it is difficult to compare results from different laboratories since the particle size and other properties of the cornstarch used would generally be different, remarkable agreement in results is demonstrated between the present vertical tube and Cocks' 20 litre vessel.

It is worthwhile to compare the burning rates as characterized by the rates of pressure rise dp/dt, obtained in the present experiments with those obtained in other McGill vessels. Due to the high L/D for the vertical tube, the dp/dt chosen is a representative value of the combustion pressure-time history. It is neither a maximum nor an average. One does not understand local fluctuations in dp/dt well enough to properly interpret the results, so a representative value of dp/dt is chosen after a global assessment of the pressure-time history. Fig. 29 shows a series of typical pressure-time curves and the manner in which the representative value for the burning rate is chosen. dp/dt data for both upward and downward propagating cornstarch dust-air flames, are plotted in Fig. 17 along with $(dp/dt)_{max}$ data from the .180 m^3 and .333 m^3 vessels. Higher values of dp/dt are observed for the present investigation up to 175 g/m^3 dust concentration, compared to the $(dp/dt)_{max}$ values from other investigations. Between 200 g/m^3 and 400 g/m^3, the rate of increase in dp/dt with increasing dust concentration appears to follow the general trend and decreases, attaining values below those from the other vessels. In order to better compare the present dp/dt data with those from other bombs, it is necessary to use the K_{st} factor. The K_{st} factor is defined as $K_{st} = (dp/dt)_{max}\ V^{1/3}$. It was developed for spherical bombs or cylindrical bombs with L/D near unity. The scale factor $V^{1/3}$ is characteristic of the length of flame travel. Thus, $V^{1/3}$ is not applicable for long tubes and this factor should be replaced by the distance between the ignition source and opposite end of the tube (1.86 m). In Fig. 18, the modified K_{st} values for the present vertical tube for both upward and downward propagating flames, are plotted as a function of cornstarch dust concentration, along with K_{st} values from several other vessels. For all cornstarch dust concentrations up to 400 g/m^3, the K_{st} increases sharply for the vertical tube and takes on higher values than those from the .333 m^3 sphere and the .180 m^3 cylinder. The larger values in K_{st} for the vertical tube are due to the large value for length of flame travel in this vessel. Between 200 g/m^3 and 400 g/m^3, the K_{st} curves for the vertical tube, the 1.23 litre Hartmann type of apparatus, and the .180 m^3 cylinder, approach each other and intersect one another in some cases. A quick observation of Figs. 16 and 18, reveals the existence of a larger scatter in K_{st} factor than $\Delta p_{max}/P_o$, as a function of cornstarch dust concentration. It is difficult to come up with any representative value of the K_{st} factor for cornstarch from the scatter in data that results from all the different apparatus sizes and geometries, dispersion methods, ignition sources and dust samples used by different researchers. The larger K_{st} values for the vertical tube are due to the replacement of the scale factor, $V^{1/3}$, by the maximum length of flame travel in the tube. This length of flame travel for such a high L/D vessel is significantly larger than the cube root of the volume in the spherical or cylindrical vessels, with L/D near one. Hence, larger K_{st} factors are expected for the vertical tube, especially for the lean concentrations where the flame actually propagates a fraction of the total length of the tube.

The adequacy of the present vertical tube and its dispersion system has been demonstrated, by the reasonable agreement in $\Delta p_{max}/P_o$ results obtained for the constant volume combustion of cornstarch dust- air mixtures with results from other very different vessels and dispersion systems. It must be noted, that in comparing dust-air combustion results, the dust concentrations quoted are usually based on the nominal loading, that is the mass of dust placed in the apparatus divided by the vessel's volume. In general, however, for each apparatus and dispersion system, the actual dust concentration suspended at the time of ignition will be less than the nominal dust concentration. Thus, one should not expect identical combustion results (Δp_{max}, $(dp/dt)_{max}$) for a given nominal dust concentration tested in different vessels.

5.3 Effects of Ignition Delay in the Vertical Tube

The time delay for ignition to occur after the solenoid valves have been activated to initiate dust dispersion, is most critical for this high L/D vertical tube. While the initial pressure in the discharge vessel decides the initial dispersion turbulence intensity, the delay time for ignition after dispersion will reflect the residual turbulence level at the time of ignition. One would expect a rapid decay in the turbulence intensity produced by the pressurized air leaving the fine holes (order of 1 mm) of the present dispersion system. On the other hand, the air blast used to disperse the dust in the 180 litre cylinder, produces relatively larger scale turbulence which is not as easily dissipated as the fine scale turbulence in the vertical tube. The effectiveness of the dispersion-induced turbulence in entraining dust particles within its eddies, decreases rapidly following the onset of the dispersion process. Furthermore, the probability increases that dust particles will hit walls and other obstacles of the combustion volume, with elapsed time after dispersion, and get stuck there or drop to the bottom. These potential phenomena, together with the ever present sedimentations of particles as a result of gravity, cause the concentration of the dust-air mixture to be highly transient in this vertical tube. If enough particles have dropped out of suspension in some region of the tube, the available dust concentration may be significantly below the nominal dust concentration. Such an occurrence takes on additional significance for lean flammability investigations and relatively slow moving constant pressure flames. In such cases, the available dust concentration at points in the tube furthest from the ignition source may not be sufficient to sustain flame propagation and hence, will cause the flame to quench. In effect, this may give the false impression that a flame cannot propagate for a certain nominal dust concentration, whereas, the flame could have propagated if ignition had taken place sooner after dust dispersion.

Once again, it becomes very important to determine the "optimum" t_D at which the suspended dust concentration in the tube will be closest to the nominal condition. It is expected that highest values for Δp_{max} will be observed, when all or most of the dust has been effectively dispersed throughout the tube, and participates in combustion. Given the high L/D of the vertical tube and its particular dispersion system, one would expect the optimum "t_D" to be significantly lower than that for the same dust in the 180 litre cylinder with L/D near unity. Pu, and Lee [6,45] have conducted some extensive investigations on the effects of turbulence on constant volume explosions of cornstarch dust-air mixture. Their experiments were performed in one of the two identical vertical sections placed in cascade, to make up the present vertical tube. Much can be learned from the two investigations, since the same dispersion system, initial dispersion pressure and similar dust preparation techniques, were used as for the present study. Observations indicate that the amount of dust unavailable for combustion strongly depends on ignition delay time, t_D. It was found that for a t_D below 100 ms, a very small mass of dust particles got stuck to the wall or got a chance to drop to the bottom (about .5 g for one vertical section). In addition, the amount of dust which remained trapped in the dispersion system, was found to be about 1 g for the highest cornstarch dust concentrations tested in the present study. The discharge time of the compressed air from the dispersion bottle is about 100 ms (most of the dust dispersion occurs in the first 50 ms). Dust explosion characteristics will inevitably depend on the actual amount of dust that participates in combustion and the dispersion-induced turbulence present at ignition.

Lee et al. [45] have demonstrated that for ignition delay times larger than the dust dispersion time of 100 ms, the burning rate, as indicated by $(dp/dt)_{max}$, drops sharply with the increasing decay rate of the dispersion induced turbulence. Since turbulence affects the burning rate, it can drastically accelerate the rate at which an explosion develops. For convenience, plots of $(dp/dt)_{max}$ and Δp_{max} for different cornstarch dust concentrations as a function of t_D, have been replotted in Figs. 30 and 31, respectively. The same dispersion bottle gauge pressure of about 10 atm is used throughout and the dust concentrations given are obtained by subtracting the dust left in the dispersion system after an experiment. For different dust concentrations, peak values for $(dp/dt)_{max}$ are obtained at a t_D of about 75 ms. For too short a delay, insufficient amount of dust has been dispersed into the combustion volume to provide a strong ignition flame kernel for subsequent flame propagation. In general, higher burning rates are observed with increasing dust concentration at the same t_D. Fig. 31 indicates that peak values for Δp_{max} are obtained at ignition delay times between $75 - 100$ ms. The decay of Δp_{max} with increasing t_D (decreasing turbulence intensity) is not as severe as the decay of $(dp/dt)_{max}$ (Fig. 30). For the leanest case (of 276 g/m^3) there is hardly any decay in the Δp_{max} and $(dp/dt)_{max}$ with increasing t_D. Higher decay rates are observed for higher dust concentrations which would imply that dust settling plays a dominant role. It is suspected that for higher dust concentrations, the dust dispersion process is not as effective in breaking up the dust, and thus, the dust discharged into the chamber is in large agglomerate forms which settle quickly. When the dust is fully broken up to its nominal particle size of 15 μm without agglomeration, it will settle slowly at its Stokes free fall velocity ($1 - 2$ cm/s) and the amount burned will be practically independent on the delay time or turbulence level. The observations of Lee and Pu indicate an "optimum" t_D of about 75 *ms* for cornstarch dust-air mixture in their single vertical tube.

One would now like to know the most appropriate, or "optimum", t_D to be used for the present investigation where the vertical tube consists of two identical sections as to the ones used by Pu and Lee. In some of her investigations, Pu [6] performed experiments in the identical 1.86 *meter* vertical tube used in the present study. It was determined that flame propagation velocities in the 1.86 *meter* tube were higher than those in the .93 *meter* (single section) tube. Consequently, the time of combustion, or flame propagation along the entire tube length, is only slightly longer for the 1.86 *meter* tube compared to the .93 *meter* tube. If the time a flame takes to propagate throughout the entire vessel volume is far less than the time dust particles, anywhere in the vessel, will take to drop any significant distance compared to the vessel's dimensions, sedimentation effects can be ignored. Of course, the flame speed will depend on the type and concentration of dust to be used. Flame speeds for both upward and downward propagating cornstarch dust-air flames under constant volume conditions, are typically of the order of several meters per second ($4 - 20$ m/s). The entire flame propagation duration for cornstarch is under half a second, as detected by the ionization probes. For the largest nominal cornstarch particle size of 30 μm, the Stokes free fall velocity is roughly 4 cm/s. Thus, it would appear that for constant volume cornstarch dust-air flames, sedimentation effects can be neglected for any t_D under, say, .5 *seconds*. However, it is essential to recall that the rate at which dust adheres to the walls of the combustion chamber, has been shown to increase significantly with increasing t_D [6]. Furthermore, dust particles tend to form agglomerations which fall far faster than a few cm/s. Since the optimum t_D for the .93 *meter* tube was shown to be about 75 *ms*, and the time for flame propagation along the entire 1.86 *meter* tube length is slightly larger than in the .93 *meter* tube, the most appropriate t_D for the 1.86 *meter* tube should be slightly less than 75 *ms*. An "optimum" t_D of 60 *ms* was chosen for the present investigation.

Sedimentation effects are more significant for constant pressure cornstarch dust-air flames, where the flame speeds can be near or below 1 m/s. Different ignition delays were used for a nominal cornstarch dust concentration of 400 g/m^3, to provide some indication of the effects of t_D on flame propagation under constant pressure conditions (Table 9). Results from Table 9 indicate that the t_D should be no larger than 150 *ms*. No conclusive differences are evident for t_D's of 60, 100, and 150 *ms*, where the flame propagated roughly three quarters of the length of the tube. Nevertheless, in order to ensure a high degree of dispersion-induced turbulence which is desirable for dust entrainment, the same "optimum" t_D of 60 *ms* used for the constant volume experiments of cornstarch dust-air mixtures was used for the constant pressure experiments of cornstarch.

The average particle sizes of the Deyco coal dust samples are much larger than for cornstarch dust, and any agglomerates of the coal dust particles will tend to be even larger. Consequently, coal dust particles would tend to drop at a faster rate than cornstarch particles and may adhere to the walls of the combustion volume in larger amounts compared to cornstarch, with elapsed time after dispersion. The minimum acceptable t_D to be used is about 60 *ms* for sufficient dust dispersion in the combustion volume. Therefore, in experimentation with both cornstarch dust and coal dust, under both constant volume and constant pressure conditions, a 60 *ms* t_D was used.

5.4 Experimental Results of flame Propagation in the Closed Tube

Using the flammability limit criterion previously established for the vertical tube (flame travel of at least 3/4 of the length of the tube), one attempted to determine the lean flammability limits, under constant volume, for cornstarch dust-air mixture and Lingan coal dust-air mixture. Both upward and downward propagating flames were investigated. Flame detection along the tube was made possible by the triggering of the ionization probes. Having a knowledge of the location of all four probes, the arrival of the flame "front" at different positions in the vertical tube can be determined. As well, by dividing the distance between probes (and between the igniter and first probe), with the time the flame takes to travel that distance, one obtains average flame "front" speeds for specific regions in the tube. Since the tube is kept closed for the duration of the experiment, it is possible to obtain the pressure-time history in the vessel during the combustion process.

Tables 10 to 13 summarize the results for Δp_{max}, dp/dt and flame speeds achieved for the cornstarch and Lingan 10-E coal dust in the closed vertical tube for upward and downward flame propagation. The lean flammability limit of cornstarch dust-air mixture for both upward and downward propagating flames in the closed tube, is 200 g/m^3 dust concentration in air, as is evident from Tables 10 and 11, respectively. The criterion for flammability is 140 cm of flame travel from the ignition end. For the upward direction three probes were triggered, corresponding to 132 cm of flame travel from the bottom, at a minimum concentration of 200 g/m^3. On the other hand, for the downward direction, three probes of flame travel (102 cm) is too short according to the 3/4 tube length criterion. Subsequently, the flammability limit for the downward direction is decided by the minimum dust concentration in air for which all four probes are triggered, corresponding to a flame travel of 147 cm down the tube. Considering the non-uniform flame "front" of lean dust-air mixtures, and the arbitrary nature of the flammability limit criterion, the described method for deciding flammability limits in the upward and downward directions, was deemed adequate. At the 200 g/m^3 flammability limit for cornstarch, Δp_{max} and dp/dt for the upward direction are 299 kPa and 13.2 bar/s, respectively, while for the downward direction Δp_{max} and dp/dt are 284 kPa and 14.1 bar/s, respectively. There appears to be remarkable agreement in the combustion characteristics of cornstarch dust-air mixture in the closed tube, for both directions of flame propagation. In a previous investigation in the same closed tube, Jarosinski et al. [29] observed that a flame was able to propagate up the length of the tube, at a cornstarch dust concentration in air of 200 g/m^3. Craft [44] found 200 g/m^3 to be the minimum cornstarch dust concentration in air for which a flame could propagate most of the length in his horizontal tube. He observed a Δp_{max} of about 450 kPa. The higher heat losses from the present tube and the different dispersion system used, can account for some of the deviation in Δp_{max}. However, within experimental uncertainties, it appears that the lean flammability limit of cornstarch dust in air in a closed tube, is about 200 g/m^3 and is independent of direction of flame propagation, if one uses flame propagation over three-quarters of the length of the tube as the flammability limit criterion. For Lingan coal dust-air mixture in the closed vertical tube, the maximum flame "front" travel detected was 82.5 cm in the upward direction, corresponding to the position of the second probe (Table 12). Only 52.5 cm of flame travel was detected for downward propagating coal dust-air flames in the closed tube. In both flame propagation directions, the maximum distance travelled by the flame in coal dust-air mixture, was far below the flammability criterion of 140 cm. As a result, it was not possible to determine any lean flammability limit for the Lingan 10-E coal dust in this vertical tube with the present flammability criterion. A Δp_{max} of 207 kPa was observed for a coal dust concentration of 350 g/m^3, which is a whole order of magnitude larger than the 20.7 kPa flammability limit criterion used in the 180 litre cylinder. Despite this significant Δp_{max}, coal dust-air flames were not even able to propagate half the tube length, for the concentrations tested. This result is not what one would expect if one recalls that in the 180 litre cylinder, the lean flammability limit for coal dust was 40 g/m^3, much lower than that for cornstarch dust which was about 70 – 75 g/m^3.

For a better understanding of the lean flammability behaviour of each dust in air, it may be worthwhile to conduct a closer comparative examination of the results obtained in the vertical tube. If one plots the Δp_{max} and dp/dt data as a function of cornstarch concentration, for lean dust-air mixtures (less than or equal to 200 g/m^3 cornstarch), the results are shown in Figs. 32 and 33, respectively. The Δp_{max} results appear to be independent of direction of flame propagation, while a marginally higher burning rate is observed for downward propagating cornstarch dust-air flames. One would expect upward flame propagation to be more vigorous since the flame's rate of ascent will be enhanced by the rising and expanding product gases. Any dust settling, produces a downward flow in the tube. This downward flow is a function of many parameters, but most notably the size and weight of the falling particles. One possible explanation for the slightly lower burning rates observed for upward propagating cornstarch dust-air flames, is the hindering of the burning rate as the unreacted downward flow encounters the rising hot flame. The high volatile-content cornstarch dust particles readily release their volatile matter as they are approached and preheated by radiation and other heat transfer modes from the downward propagating flame. The insensitivity of Δp_{max} to direction of flame propagation may be attributed to the relatively high flammability of the cornstarch dust. Flame propagation velocities must be significantly above the buoyant rise velocity of the hot gases for Δp_{max} to be direction independent. In both Figs. 32 and 33, the same trend of decreasing Δp_{max} and dp/dt with decreasing dust concentration is evident, as was the case for lean mixtures in the 180 litre cylinder and in Hertzberg's lean coal dust-air results [24].

Figs. 34 and 35 display the variations in Δp_{max} and dp/dt, respectively, as a function of coal dust (lingan 10-E) concentration. The Δp_{max} for coal dust (Lingan 10-E) rises slowly with increasing dust concentrations, for both flame propagation directions, and stays at a low level, reflecting of course that only a part of the dispersed dust was buried (less than half the tube length), as contrasted with the cornstarch dust where Δp_{max} is steep and the maximum level is much higher. Fig. 34 indicates that upward flame propagation for coal dusts is slightly more effective than downward propagation. This could possibly be due to the downward settling of the coal dust into the upward advancing flame, thereby enriching the effective concentration that the flame sees compared to a downward flame. As particles approach the rising hot flame, they will begin to emit volatile matter which will react with oxygen. Only after devolatilization can the homogeneous gas-phase combustion reactions proceed [19]. For downward flame propagation, the flame chases the settling particles which may drop to the bottom or stick to the vessel's walls, prior to the hot flame reaching them. In effect, less particles will be available to react in such a situation, which explains the lower Δp_{max} observed for downward propagating flames. As the coal dust concentration increases, Δp_{max} attains a steady level for both directions of flame propagation. One possible explanation for this phenomenon is that the devolatilization rate has become too slow compared to the rate of combustion reactions in the gas phase, thereby limiting the amount of fuel which actually reacts. Sharp differences in the dp/dt behaviour as a function of coal dust concentration are exhibited in Fig. 35, with changes in the direction of flame propagation. While Δp_{max} increases and attains a steady level with increasing dust concentration for upward propagating coal dust-air flames, dp/dt appears to decay in an exponential manner with increasing dust concentration. The immediate decrease in burning rate with increasing coal dust concentration for upward flame propagation, is believed to be largely due to the adverse downward induced flow caused by the increasing mass of falling dust particles. While the amount of coal dust burned with increasing concentrations tested appears to approach a fixed level, the rate at which this amount burns decreases as the increasing mass of excess unreacting dust travels through the burning region, providing a heat sink. For downward propagating flames dp/dt increases with increasing dust concentration, reaching a maximum level between $200 - 300$ g/m^3 coal dust, and decreases rapidly with further increases in dust concentration. Settling dust particles do not affect downward propagating flames in the same way as upward propagating flames. With increasing coal dust concentration up to 300 g/m^3, more fuel reacts in downward propagation, producing higher Δp_{max} and dp/dt values. For the concentrations tested above 300 g/m^3, Δp_{max} remains constant while the burning rate, or dp/dt, drastically decreases for downward coal dust-air flames. Once again, excess amount of unreacting dust at the higher concentrations behaves like a heat sink and cools the flame, reducing the burning rate.

To compare the present coal dust results with coal dust results obtained from other investigations, the $\Delta p_{max}/p_o$ and K_{st} data obtained in the vertical tube are plotted in Figs. 19 and 20, respectively. Once again, K_{st} for the vertical tube is defined as the product of the representative dp/dt with the characteristic length of flame travel. It is evident that the high L/D vertical tube results behave very differently compared to coal dust results from vessels with L/D near one. Other than the leanest of concentrations tested, the Δp_{max} and K_{st} data from the vertical tube, are significantly below other coal dust results. The very different geometry in the high L/D vertical tube compared to the 180 litre cylinder and Hertzberg's [24] 20 litre vessel, gives rise to a different type of burning. A distinct flame propagation is possible in the vertical tube where ignition takes place at one end, whereas a volumetric type of burning occurs in the low L/D vessels with central ignition. The higher (S/V) of the vertical tube allows for more heat losses from the burning region to the cold walls. Small scale easily dissipated dispersion-induced turbulence is available for dispersing and entraining the dust in the vertical tube, compared to the large scale turbulence introduced for dust dispersion in the 180 litre cylinder and Hertzberg's vessel. Finally, dust settling and flame inhibiting downward induced flows, appear to play dominant roles in the combustion characteristics of coal dust-air mixtures in the vertical tube. As a result, the determination of lean flammability limits of the dust-air mixtures in the present tube is subject to many adverse effects, eminating from the geometry and dispersion system of the vessel. The Δp_{max} and K_{st} data from the vertical tube, are significantly below other coal dust results.

It would be interesting to directly compare the Δp_{max} and dp/dt data for the Lingan coal dust and cornstarch dust, since all data was obtained in the same vertical tube with identical experimental procedure. Figs. 36 and 37, respectively show the variations in Δp_{max} and dp/dt as a function of dust concentration, for both cornstarch dust and Lingan coal dust and for both directions of flame propagation. Cornstarch dust is almost entirely composed of volatile matter with very little fixed carbon and ash and the nominal size is about 15 μm. The Lingan coal dust is specified at 325 *mesh* ($< 44\ \mu m$)), has a relatively high content of fixed carbon and ash, and has far less volatile matter than cornstarch dust. As a result, the release of volatiles for reaction with oxygen in the gaseous phase, is better facilitated by the highly volatile and relatively small cornstarch dust particles. Furthermore, dust settling effects which appear to play a dominant role in inhibiting the combustion of coal dust-air mixtures in the vertical tube, are not as evident for cornstarch dust-air mixture. More dust burns with rising cornstarch concentrations resulting in increasing Δp_{max} values for cornstarch, whereas the amount of coal dust that burns remains at a relatively low level, as indicated from the Δp_{max} record. The lowest Δp_{max} are obtained for downward propagating coal dust-air flames. As might be expected, the dp/dt behaviour for cornstarch dust is very different from that of coal dust (see Fig. 37). The burning rates for cornstarch dust-air mixture are generally much higher than for coal dust-air mixture in the same tube. As explained earlier, this is probably due to the cooling phenomenon caused by the non-reacting mass of coal dust and downward flow which inhibit flame propagation by lowering the burning rate.

The trajectories in the closed vertical tube for upward and downward directions of flame propagation, are shown in Figs. 38a and 38b, respectively for cornstarch dust and Figs. 39a and 39b, respectively, for Lingan 10-E coal dust. The corresponding flame speed versus position traces are shown in Fig.s 40a and 40b for cornstarch dust and Figs. 41a and 41b for coal dust. It should be noted that in all of Figs. 39 to 41, data has not been plotted for the dust concentrations that triggered only one probe. The trajectories of the flame for cornstarch dust-air mixture (Figs. 38a and 38b), indicate that propagation for the full length of the tube could readily be achieved for all but the leanest (below 200 g/m^3) dust concentrations. Within experimental scatter, there does not appear to be any consistent pattern in the variation of flame speed as a function of cornstarch dust concentration or direction of flame propagation. Figs. 40a and 40b demonstrate that cornstarch flames accelerate to a maximum at about the middle of the tube length, attaining speeds of about 10 m/s and higher, and quickly decelerate beyond this point as the flame approaches the blind end flange opposite the ignition source. Typical flame speeds in a closed tube with diameter beyond a few centimeters create a turbulent flow ahead of the combustion wave. The expanding hot gases compress the unreacted mixture in the closed tube. As the flame propagates into the precompressed turbulent region of reactants, it accelerates and increases the flow velocity ahead of it which creates more turbulence, further accelerating the flame "front" and so forth. The turbulent eddies of combustible mixture maintain their initial random motions as they are overtaken by the flame. Burned gas eddies which project ahead of the main burning region serve as multiple ignition sources for the unreacted mixture, and thus, accelerate the combustion rate. In a short tube such as the present vertical tube, the combustion "front" quickly approaches the end of the tube, and the precompressed reactants offer increasing resistance to the expanding hot gases. This is believed to cause the observed deceleration in the flame speed near the end of the tube, while the burning velocity for the highly volatile cornstarch dust should remain constant. The flame trajectories for Lingan 10-E coal dust (Figs. 39a and 39b) indicate that for most dust-air concentrations the flame can propagate to roughly half the tube length. For no coal dust concentration was there a sustained flame propagation detected beyond half the tube length. As with cornstarch dust-air mixture, there does not appear to be any definite trend in the variation of flame speed as a function of coal dust concentration. However, some of the data indicates that the arrival time of the flame at the probe locations tended to be shorter for richer coal dust-air mixtures. A large scatter in flame speeds between probes is evident for both cornstarch dust and coal dust.

After a careful examination of the results obtained in the closed vertical tube for cornstarch dust and Lingan 10-E coal dust, one realizes that the flammability behaviour for the two dusts is very different. The differences in the physical and chemical properties of these two types of dust cause pronounced dissimilarities in flame propagation characteristics. Determination of lean flammability limits under constant volume has been shown to be highly dependent on the apparatus and criterion used. If the 20.7 kPa Δp_{max} criterion is used to determine lean flammability limits in the vertical tube, very lean dust-air mixtures appear to be able to sustain flame propagation, compared to the 180 litre Hartmann type vessel. In the vertical tube, over 20.7 kPa is observed for the Δp_{max} of 50 g/m^3 cornstarch dust in air and 15g/m^3 Lingan 10-E coal dust in air. Both these concentrations are far below the lean limit concentrations for cornstarch dust and coal dust of 75 g/m^3 and 40 g/m^3, respectively, obtained in the 180 litre vessel. The Δp_{max} created by the igniter alone in the vertical tube has been shown to be significantly more than 20 kPa. Since the same igniter energy is introduced in both vessels, it is expected that higher Δp_{max} will be observed in the vertical tube which has less than one third the volume of the 180 litre cylinder. Therefore, the 20.7 kPa criterion is not really meaningful for the 53 litre vertical flame tube which as a high L/D ratio. On the other hand, the length of flame travel criterion used for determining flammability limits in the vertical tube, yields very different results compared to the 180 litre vessel. It is important to recall that no coal dust-air flame could propagate 3/4 of the length of the tube, while the lean flammability limit for cornstarch dust in the same test tube was determined to be 200 g/m^3, much higher than the 75 g/m^3 limit determined in the 180 litre cylinder.

A self-sustained flame propagation in dust-air mixtures appears to take on very particular meanings, depending on the apparatus and procedure used to determine flammability limits. Choosing a propagation criterion must be consistent with the purposes for which the limit is being determined. From the present investigation, it is evident that the lean flammability limit of a dust-air mixture is not a fundamental property of the mixture.

5.5 Experimental Results of Flame Propagation in the Vertical Tube with One Open End

The flammability limits of dust-air mixtures under constant volume conditions, have been studied in the 180 litre cylinder and the 53 litre closed vertical tube. It is now necessary to determine if any changes arise in the lean flammability behaviour of the same dust-air mixtures, when the test vessel is open to the atmosphere at one end. The bottom flange of the 53 litre vertical tube is freely floating and begins to drop immediately after the onset of dust dispersion. The displaced flange effectively opens the bottom end of the tube to atmospheric pressure and thus, disallows any pressure build-up within the vessel during combustion The time scale of combustion in open tube experiments is approximately an order of magnitude longer than that in a closed tube. This is a direct result of the role played by the expansion of the hot combustion gases in flame propagation under constant volume conditions. The compressive effects of the expanding combustion products are relieved through the open end of the tube in the constant pressure experiments. For a flammable dust-air mixture, the flame will propagate up the tube after ignition at the bottom and trigger all the ionization probes in its path. Using a t_D of 60 ms in this vertical tube, one will attempt to determine the lean flammability limits of different dusts in air under constant pressure conditions.

The leanest cornstarch dust concentration which could sustain flame propagation for at least three quarters of the open flame tube corresponds to 400 g/m^3. This is in very good agreement with a previous study conducted by Jarosinski et al. [29], in which a value of 380 g/m^3 was quoted as the flammability limit for cornstarch dust in the same vertical tube under constant pressure conditions. There are numerous reasons for this small discrepancy in flammability limits reported for the same duct, in the same apparatus with identical dispersion system. The calculated tube volume of 53.3 litres used in the Jarosinski et al. paper is slightly larger than the more accurately measured value of 52.7 litres in the present experiments, making Jarosinski's actual lean limit for cornstarch to correspond to 385 g/m^3. Another source for the discrepancy rests with the criterion used to decide a sustained flame propagation. A flame travel of only 115.5 cm would trigger the last of three ionization probes mounted on Jarosinski's tube, while the flame would be required to travel an additional 16.5 cm in the present investigation, to trigger the third out of a total of four ionization probes mounted on the tube. Further, Jarosinski used much longer electrodes for his ionization probes, which can be triggered easier than the present ones used, by the highly non-contiguous lean dust flame "front". As a result of the above differences between the two investigations, one would expect Jarosinski et al. to report lower lean flammability limits for dust-air mixtures. It should also be noted that Jarosinski dried his cornstarch dust overnight at $40°C$, while for the present investigation cornstarch was dried for 24 hours at a much higher temperature of $105°C$. However, for both these investigations, the lean flammability limit of cornstarch dust-air mixture is very different when determined in the constant volume cylinder ($70 - 75$ g/m^3), the closed vertical tube (200 g/m^3), and the open vertical tube. The differences in lean limit concentration for cornstarch in the vertical tube at constant volume and constant pressure, could be explained by the observation that when a flame is pushed by hot gases, it can propagate with a lower burning velocity [46]. In sharp contrast, Proust [28] reports a lean flammability limit of 70 g/m^3 for cornstarch dust obtained in an open tube, using a fluidized bed for dust suspension. This is the identical result for flammability limit obtained under constant volume, in the 5 m^3 vessel [36] and very near the 75 g/m^3 limit for the 180 litre cylinder. The method used by Proust to assess flammability, is the visual observation of any dust burning past the half way point (1.5 m) of his vertical tube and not the usual three quarters of tube length travel by the flame "front". From visual records provided, it is apparent that the quality of flame propagation is very poor for some dust-air cocncentrations above 70 g/m^3, which he considers as being able to sustain flame propagation. If Proust's flammability criterion is to be used for the present investigation, the lean limit for cornstarch in the open tube would undoubtedly be lower. A propagating flame was readily detected by the second ionization probe, corresponding to roughly half the tube length, for the tested dust concentrations as low as 350 g/m^3 cornstarch. It is possible that limited dust burning may exist at the half tube level even for dust concentrations below 350 g/m^3. However, based on constant volume results (Table 10) where flame propagation is facilitated by the expanding hot gases, it is very unlikely that any dust burning will occur in the open tube above the half tube level, at 70 g/m^3. There must exist fundamental differences in the dust-air environment in the two different vessels for such a large discrepancy in dust flame propagation. One obvious difference is the turbulence level at the time of ignition. Dust suspension by the fluidized bed technique introduces far less turbulence in the vessel than do jets of pressurized air used for dust dispersion in the present vertical tube. The dramatic differences in cornstarch dust flame propagation in the two vertical tubes may be attributed to the quenching effects resulting from the high level of dispersion-induced turbulence in the present tube. However, further study is necessary to accurately determine the causes for such a large discrepancy in reported flammability limits for cornstarch in open tubes.

The flame speeds as a function of the tube length are plotted in Fig. 42, for different cornstarch dust concentrations. There is no evident pattern to flame speed with dust concentration and for almost all cases, the flame tends to accelerate marginally in the first section of the tube and then decelerates as it reaches its limit of propagation and quenches. Flame speeds vary around 1 m/s with minimum and maximum observed speeds of 0.5 m/s and 2 m/s, respectively. The closed tube results for cornstarch dust flame speeds are a whole order of magnitude faster and the flame accelerations more conspicuous, as the expanding hot gases compress the reactants under the constant volume conditions. Proust observed flame propagation velocities in the vicinity of 0.5 m/s for laminar conditions. When air, in excess of that necessary to create the dust suspension was added in the tube, the flame speeds observed by Proust were of the order of 1 m/s, similar to those from the present investigation.

Determination of the lean flammability limit of each of the two Devco coal dusts, Lingan 10-E and No. 26, was then tried under constant pressure conditions in the vertical flame tube. No sustained flame propagation in either of the coal dusts could be achieved, regardless of the concentration tried. While there was ignition and acoustic vibrations could be heard, the flame did not even trigger the first probe located 37.5 cm above the ignition source. In retrospect, this behaviour by the two Devco coal dusts in the vertical tube under constant pressure, was not entirely unexpected. Recall that no sustained flame propagation past the half way point of the tube length was observed for the Lingan coal dust in the closed tube. For the more flammable cornstarch, sustained flame propagation was only observed at 400 g/m^3, which is twice its closed tube lean flammability limit. Without the expanding combustion products assisting flame propagation, under constant pressure conditions, one would not anticipate coal dust flames to travel three-quarters of the length of the tube. The results of experiments conducted by Jarosinski et al. [29] with finer, (5 μm), Devco No. 26 coal dust particles, indicate a lean flammability limit of 280 g/m^3 in the same open tube. Smoot and co-workers [47] found that the rate of flame propagation in fine coal dust-air mixtures is controlled by the rate of streamwise molecular diffusion of oxygen and volatiles, together with heat conduction from the hot gas to the particles. Unlike cornstarch dust which has over 90% volatile content, the two coal dust samples used have a relatively small content of volatile matter and comparatively large amounts of fixed carbon and ash. Heat conduction from the hot gas to the dust particles cause volatiles to be released. As the falling coal dust particles encounter the rising hot flame, they absorb heat from the flame. If the volatile release rate from the dust particles approaching the flame is insufficient, the burning velocity will drop below the limit burning velocity and the flame will quench. For the same dust concentration, fine particles provide a much larger specific surface area for volatiles release than do coarse particles. In addition to the lower volatile yield, coarse particles induce a far more effective downward draft to hinder the rising flame than do fine particles.

These arguments may explain why no flame propagation was detected for the coarse coal dust-air mixtures investigated. Note that the lean flammability limit of the fine coal dust, obtained in the open tube, is below that of cornstarch dust even though cornstarch has a much higher volatile content. This is consistent with the lower lean limit than cornstarch dust observed for both the coarse Devco coal dusts in the closed 180 litre vessel. It then appears, that the downward flow induced by the settling of large coal dust particles in the vertical tube, plays the dominant role in determining why no flame was able to propagate more than half the tube length under any tested conditions, in coarse coal dust-air mixtures. Such adverse effects of dust settling do not appear to be as prevalent in the very different geometry of the low L/D 180 litre cylinder.

6 SUMMARY AND CONCLUSIONS

6.1 Synthesis of experimental results

A systematic investigation has been carried out in a 180 litre cylindrical Hartmann-type dust explosion vessel and in a high L/D 53 litre vertical flame tube, to determine the lean flammability limits of different dust-air mixtures. An accurate and reliable knowledge of the flammability limits of fuel-air mixtures can provide a better assessment of their fire and explosion hazard in mining and other industrial environments. For this reason, the high volatile-content cornstarch dust, representative of many agricultural dusts processed in mills or stored in silos, and two samples of the most hazardous of Canadian coal dusts, Devco No. 26 and Devco Lingan 10-E, were used as the fuels for the present investigation. The 180 litre cylindrical vessel and the 53 litre closed vertical tube, were used to determine lean flammability limits under constant volume conditions. The high L/D of the vertical tube allowed for distinct flame propagation, and permitted the study of both upward and downward propagation limits of dust-air mixtures. Furthermore, by opening the bottom end of the vertical tube to the environment at ignition, it was possible to study the lean flammability limits of upward propagating dust-air flames under constant pressure conditions.

Unlike homogeneous gases which can readily diffuse and mix with their oxidizer environment, a dust remains concentrated in its initial placement container and hence, must be dispersed prior to ignition of the combustible mixture. An air blast into the dust receptable located at the bottom of the cylinder disperses the placed dust throughout the 180 litre vessel, while in the vertical tube, the dust is entrained from its placement chamber by pressurized air and dispersed effectively in the 53 litre volume, through jets emitting from fine holes of a hollow pipe running along the entire length of the tube. The creation of the dust suspension is a highly transient process. As the dispersion-induced turbulence begins to be rapidly dissipated immediately after the onset of the dust dispersion process, its effectiveness in entraining dust particles and maintaining them in suspension is quickly decreased. As a result, individual particles and relatively large agglomerations of particles will begin to settle to the bottom or stick to the walls of the vessel. It is necessary to effect ignition at the time when the dust has been most effectively dispersed throughout the vessel. The effects of time delay must thus be considered in any dust-air flammability investigation. It is inevitable that the effects of time delay between dispersion and ignition will be highly dependent on the dust properties and the initial and boundary conditions, which determine to some degree the dispersion-induced turbulence intensities and its decay rate. The most appropriate, or "optimum" ignition delay for each dust in the 180 litre cylinder, was determined to be the ignition delay time where the highest peak explosion overpressure, Δp_{max}, was obtained from the combustion of a given concentration of dust in air, over a range of time delays. Alternately, the "optimum" delay was the delay at which the lowest concentration of dust-air mixture was able to produce a Δp_{max} of at least 20.7 kPa. The "optimum" ignition delays used in the 180 litre cylinder for the three different dusts ranged from 100 to 400 ms. The ignition delay used for all experiments in the vertical tube was 60 ms, shorter than any ignition delay used in the cylindrical vessel, due to the quicker dissipation of the small scale dispersion-induced turbulence in the vertical tube and to its relatively high L/D. A pyrotechnic igniter with relatively long burn time and of high calorimetric energy, was used for igniting the dust-air mixtures in both vessels. Having examined Hertzberg's [24] results where the lean flammability limits of dusts in air were lowered significantly by increasing the energy content of the pyrotechnic igniters used, the level of ignition energy of the present pyrotechnic igniter was rendered adequate to ensure a proper lean flammability investigation of the dust fuels tested (as opposed to the relative ignitability of a dust for a given ignition energy).

Prior to the determination of lean flammability limits, it was necessary to establish appropriate limit criteria. A Δp_{max} of 20.7 kPa in the 180 litre low L/D cylindrical vessel, was deemed to be a reasonable criterion for assessing a sustained flame propagation in a dust-air mixture. The lean flammability limit at constant volume for cornstarch determined in this way, was found to be 75 – 80 g/m^3, which is in very good agreement with earlier measurements in a larger scale 5 m^3 vessel. This appears to confirm the suitability of the 180 litre explosion vessel for flammability limit studies. On the other hand, the much lower lean limit of 40 g/m^3 obtained in the 1.23 litre Hartmann apparatus, is misleading due to the approach of the dust flame thickness to the integral vessel dimension, a softer propagation criterion, and the overall unsuitability of such small vessels for dust combustion research. The flammability limit under constant volume for the Devco No. 26 and Lingan 10-E coal dust samples was determined to be 40 g/m^3 in the 180 litre cylinder. It should be noted that 40 g/m^3 was the lowest lean limit reported compared to some other coal dust samples found in the literature [19,24].

The criterion used to establish flammability limits in the 53 litre high L/D vertical tube, was the detection of a propagating flame by ionization probes located roughly at three quarters of the length of the tube, in both upward and downward directions of flame propagation. Under these conditions, the lean flammability limit for cornstarch dust in the closed tube for both directions of flame propagation, was found to be 200 g/m^3 and in the open tube, the upward propagation limit was 400 g/m^3. The closed tube results for cornstarch, compare favorably with those obtained in other relatively high L/D vessels, including a horizontal tube (L/D of 7) [44], if the same limit criterion is used. The series of experiments made in the same apparatus, but in the different conditions of constant volume and constant pressure, confirm the existence of two different lean flammability limits. Using the less turbulent fluidized bed technique to create the dust suspension and with the limit criterion being the observation of any dust burning past half the tube length, Proust [28] reports a much lower constant pressure lean flammability limit for cornstarch dust, of only 70 g/m^3. It is difficult to account for the evidently large discrepancy in results. No dust-air mixture was detected to have sustained flame propagation past half the tube length in the closed tube and past a quarter of the tube length in the open tube, for the

Devco Lingan 10-E coal dust concentrations tested. Similar results were obtained for the Devco No. 26 coal dust in the vertical tube.

A comparative examination of the Δp_{max} and dp/dt results for the Lingan 10-E coal dust in the high L/D vertical tube, with cornstarch in the same tube and other coal dust samples in vessels of almost spherical geometries, displayed significant deviations in results. Despite the lower lean limit compared to cornstarch dust observed for both Devco coal samples in the low L/D cylindrical vessel, one was not able to determine any flammability limits for coal dust in the vertical tube using the 3/4 of the length of the tube flame travel criterion, even though it was possible to do so for cornstarch. The Δp_{max} results indicate that only a limited amount of coal dust burns for the concentrations tested, and the burning rate, as is evident from dp/dt and K_{st} data, decreases drastically with the higher concentrations. This is believed to be a direct result of the large downward induced flows in the long vertical tube, created by the relatively large coal dust particles settling. The coal dust samples tested have much lower volatile matter and a much higher fixed-carbon content, compared to cornstarch. The induced downward flow together with the unreacted (or slowly devolatilizing) mass of coal dust, may cool the flame, slowing down the burning rate and hindering further flame propagation. It appears reasonable, that lean flammability limit determination in high L/D vertical tubes, is limited to dusts with a large content of volatile matter or very small easily devolatilizable and slowly settling particles.

6.2 General concluding remarks

The lean flammability limit of a dust-air mixture has been shown to take on several very different values. It has been found to be highly dependent on the experimental conditions used in its determination as they pertain to the volume and degree of confinement of the apparatus, the method of dust dispersion, the ignition delay time, and ignition source characteristics. Further, the flammability behaviour of the dust will ultimately be decided by the physical and chemical properties of individual particles and their dynamic behaviour as they approach the flame.

Experimental measurements of flammability limits, are to a large degree arbitrary because of the criteria used to determine them. Instead of a simple statement as to whether or not a mixture can sustain flame propagation, it may be necessary to specify the quality of the sustained flame propagation. Choosing a propagation criterion must be consistent with the purposes for which the limit is being determined. The different experimental conditions of constant volume and constant pressure have been shown to yield drastically different results for lean flammability limit of the same dust. While the direction of flame propagation did not seem to affect the lean flammability limit in the closed vertical tube, buoyancy together with large scale effects may play more active roles in actual explosion scenaria. The direction of flame propagation in a large scale industrial site, will most likely affect the amount of dust necessary to be initially suspended for a self-sustained flame to exist. A flame travelling in a horizontal channel may entrain settled dust, in addition to the one already suspended, enriching the effective dust concentration the flame encounters and allowing the flame to propagate in an environment which initially may have not been able to sustain flame propagation. One is led to conclude that the lean flammability limit of a dust-air mixture cannot be defined as a fundamental property of the dust-air mixture itself.

Furthermore, due to the very subjective and arbitrary nature of the determination of lean flammability limits, it would be unwise and potentially hazardous to rely on any single value quoted from the literature, in accurately assessing the danger posed by a specific dust-air environment.

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APPENDIX A

TYPICAL COMBUSTION PROCESS

While the exact combustion process of all dust particles is not yet fully known, the following steps have been accepted as describing, in part or in full, the combustion process of carbonaceous dusts [48]:

1) Evolution of Volatiles: Volatile gases are driven away from the particles by heat from the ignition source or other burning particles.

2) Surface Melting: The particle surface softens, melts, vaporizes and boils surrounding itself with a boundary layer of combustible vapor.

3) Pyrolysis: Additional heating pyrolyses the particle to drive off decomposition products; themselves often combustible.

4) Gas Phase Ignition and Burning: When the vapors around the particle are produced at a sufficient rate to maintain a flammable mixture, they will ignite by autoignition or by pilot ignition from a nearby flame. A diffusion flame will stabilize around the particle and accelerate its vaporization and decomposition. The flame will extinguish when the rate of vapor evolution or oxygen diffusion into the boundary layer is insufficient to maintain a flammable mixture. This process eventually leads to the final stage.

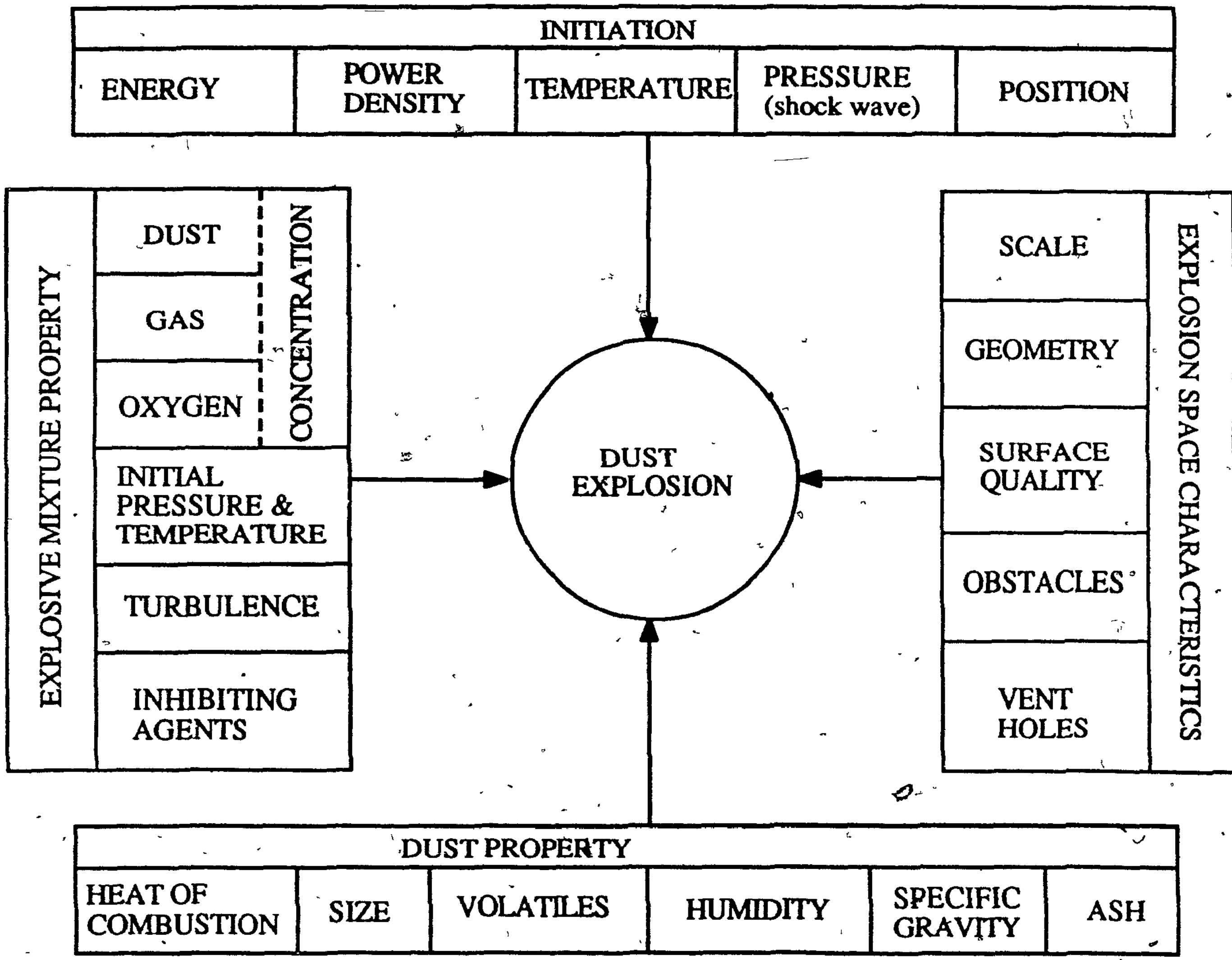


Fig. 1. Major factors influencing dust explosions.

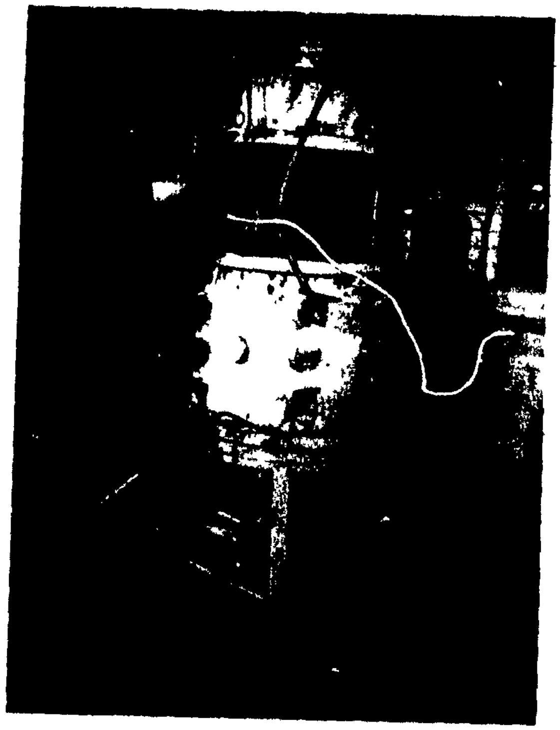


Fig. 2. Photograph of the 180 L cylindrical vessel.

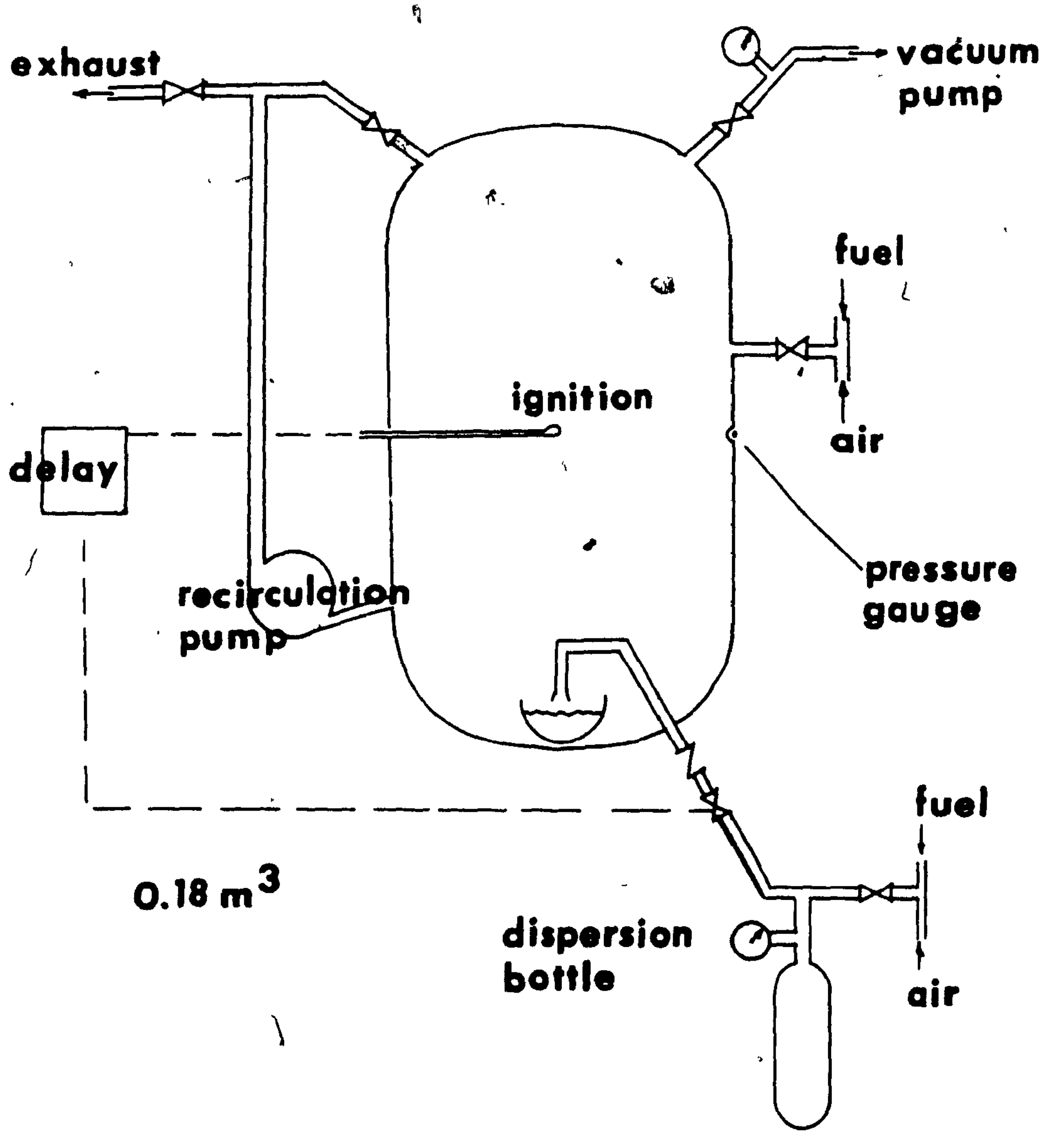


Fig. 3. Schematic diagram of the 180 L cylindrical vessel.

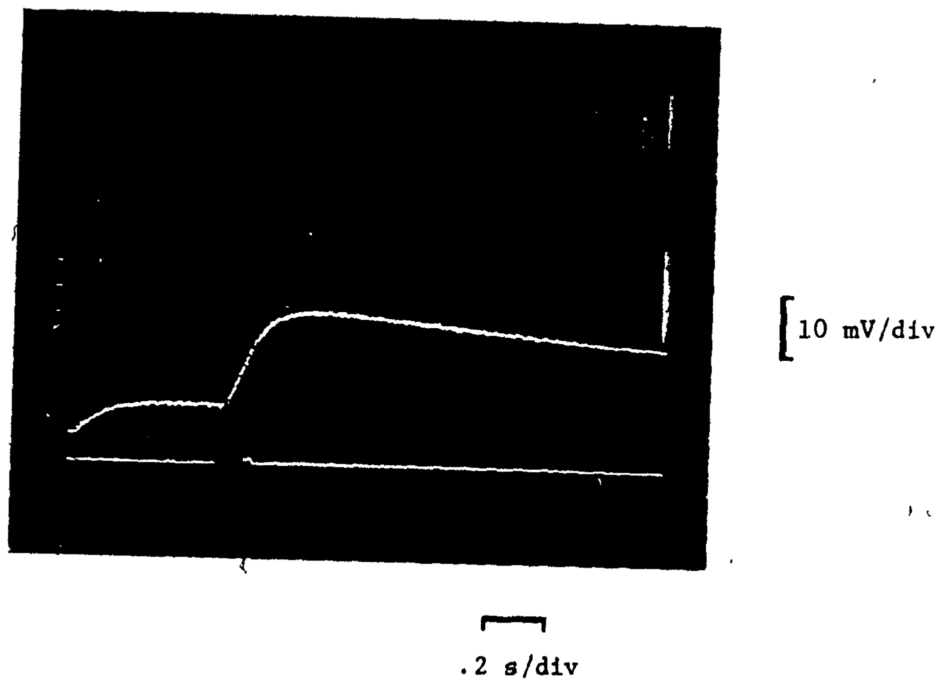


Fig. 4. Typical pressure-time record of a dust-air explosion ($70\ g/m^3$ Lingan 10-E coal dust) under constant volume.

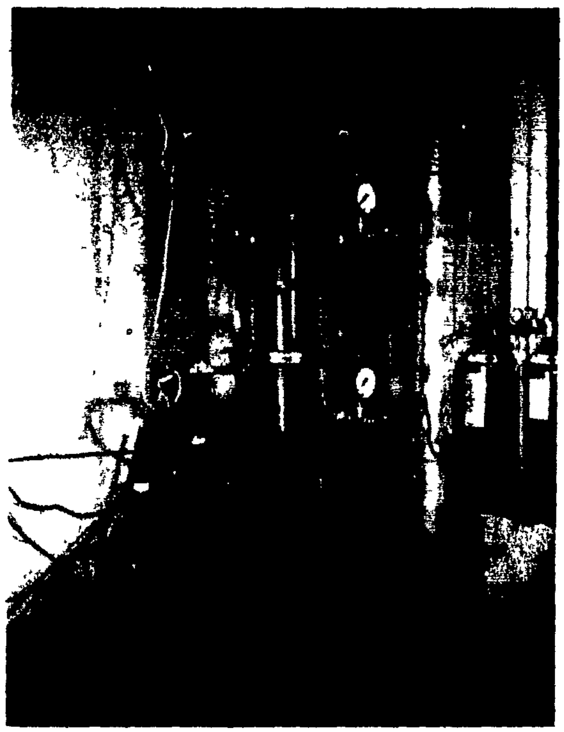


Fig. 5. Photograph of the 53 L vertical tube.

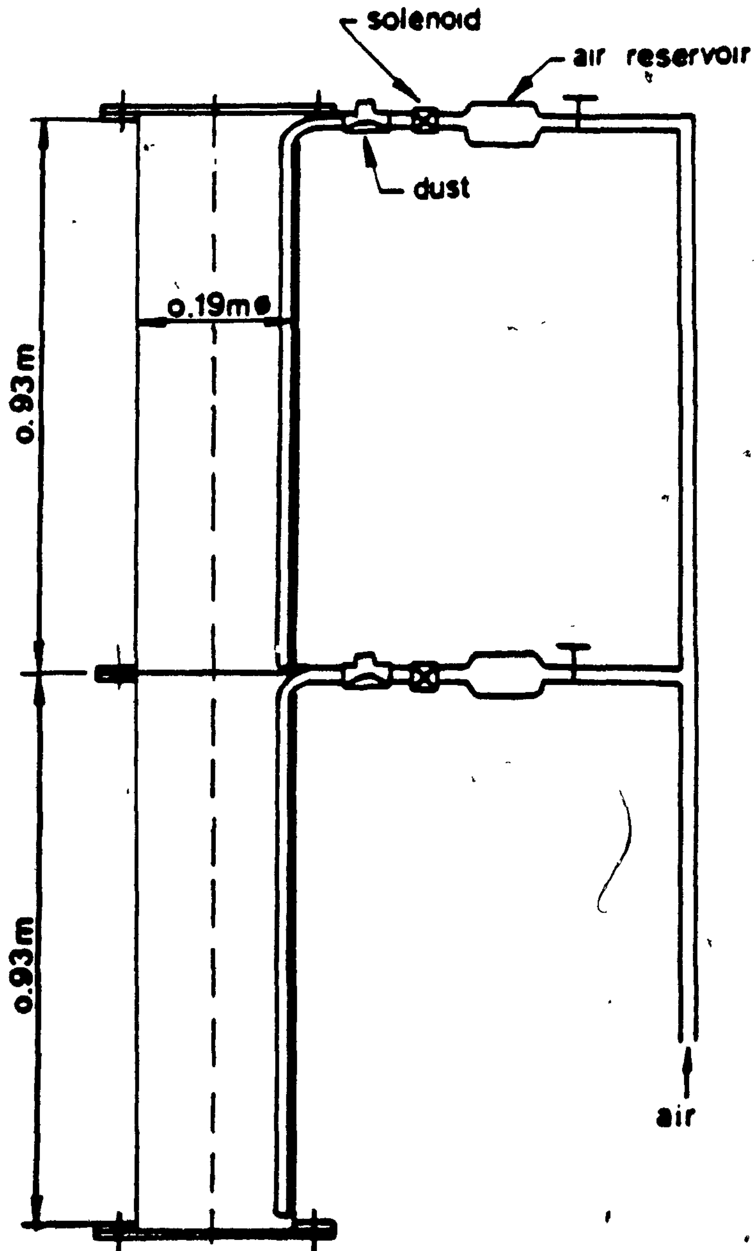


Fig. 6. Schematic diagram of the 53 L vertical tube.

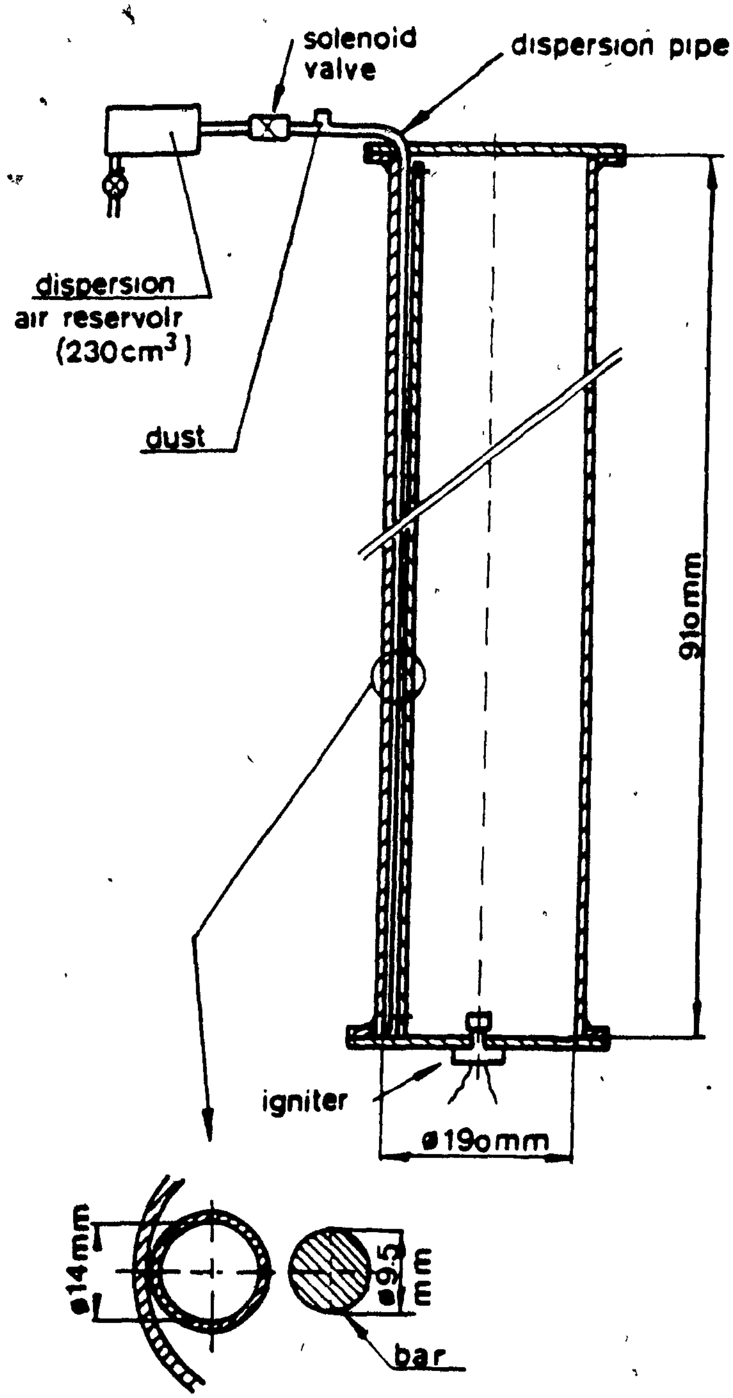


Fig. 7. Schematic diagram of the bottom section of the vertical tube with its dust dispersion system.

Fig. 8a. Photograph of the open end of the vertical tube.

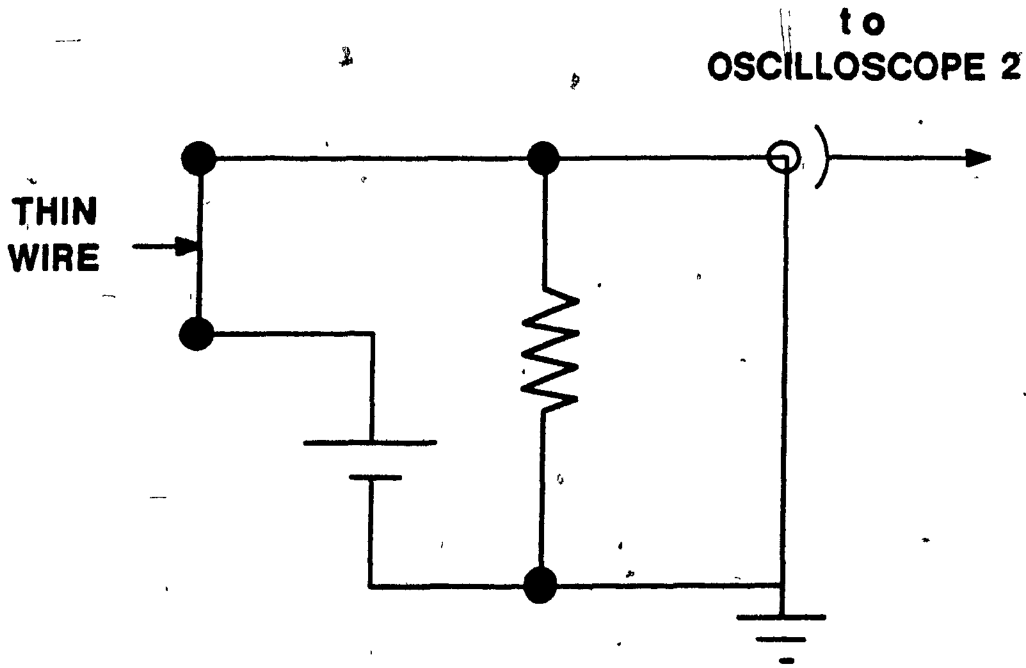


Fig. 8b. Flange dropping circuit.

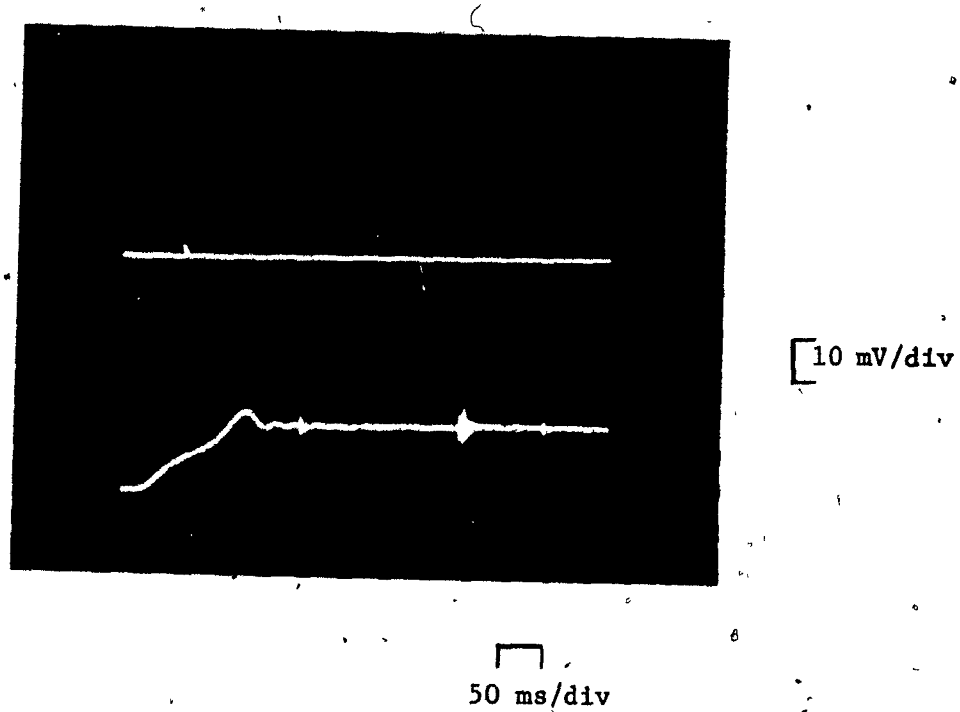


Fig. 9. Typical pressure-time trace caused by vibrations in the open tube resulting from flame propagation in a cornstarch dust-air mixture (500 g/m^3).

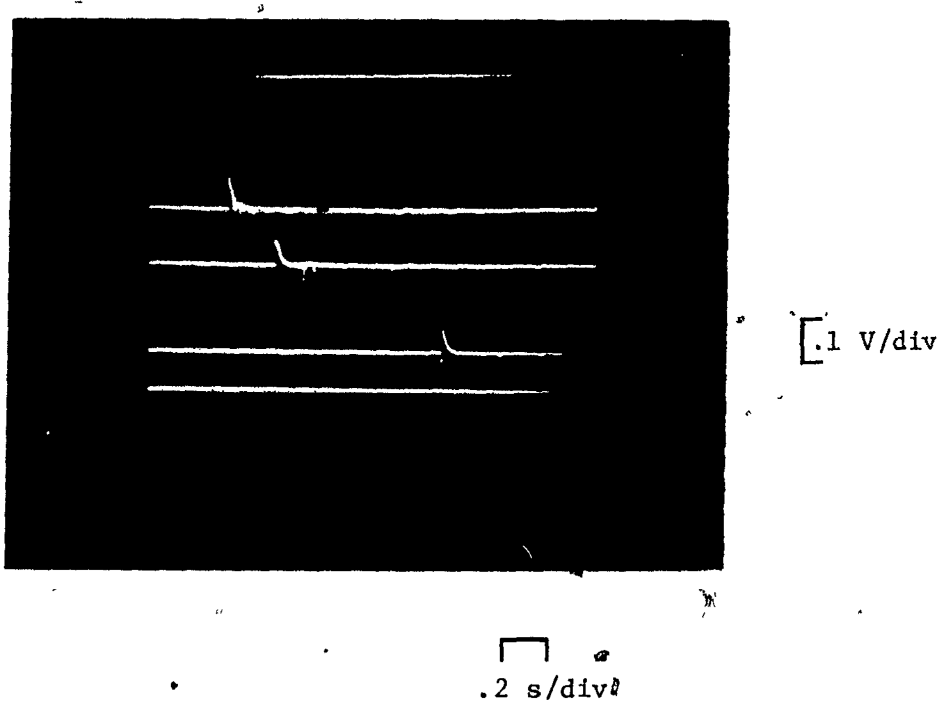


Fig. 10. Triggering of 3 out of 4 ionization probes in the open tube by an upward propagating cornstarch dust-air flame (500 g/m^3).

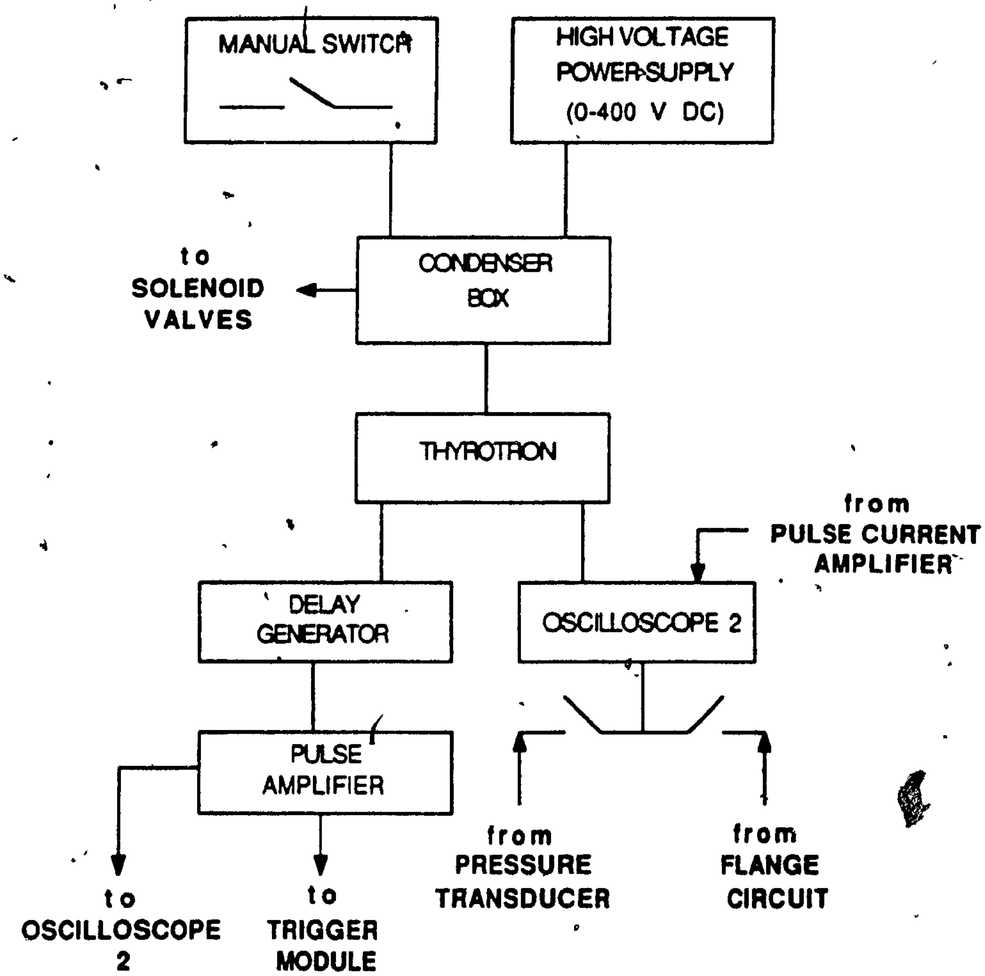


Fig. 11. Overall instrumentation block diagram for vertical tube.

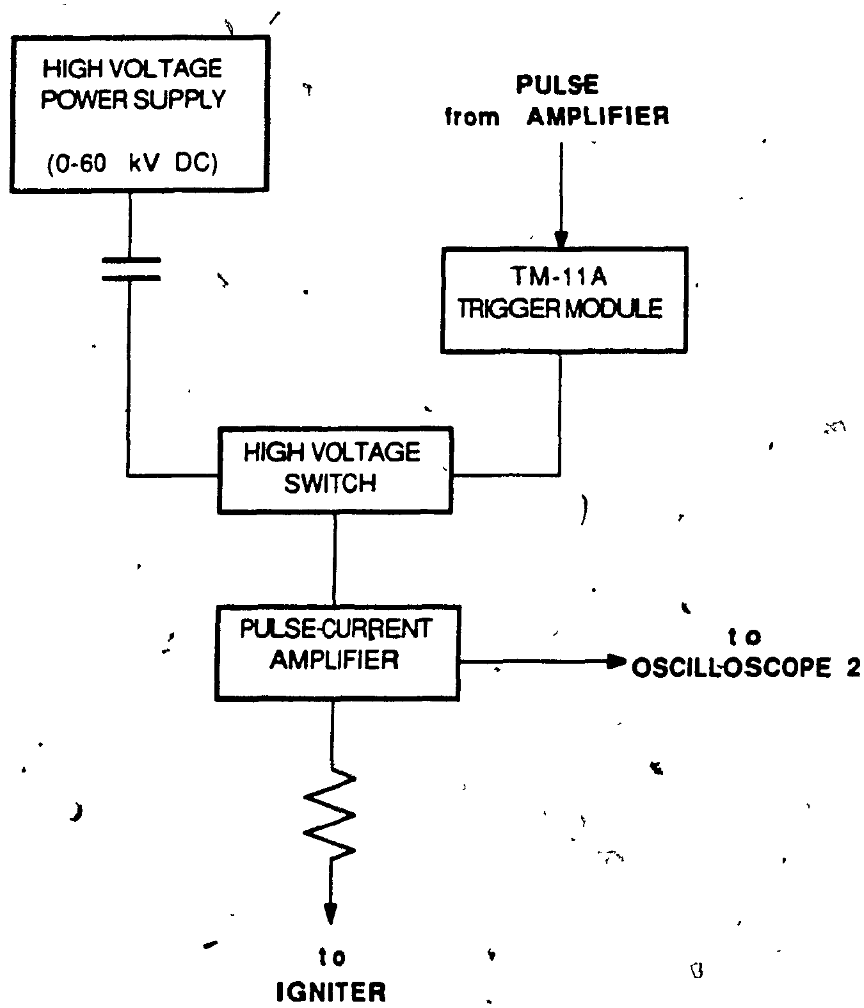


Fig. 12a. Block diagram of the ignition system for the vertical tube.

Fig. 12b. Photograph of ignition system for vertical tube.

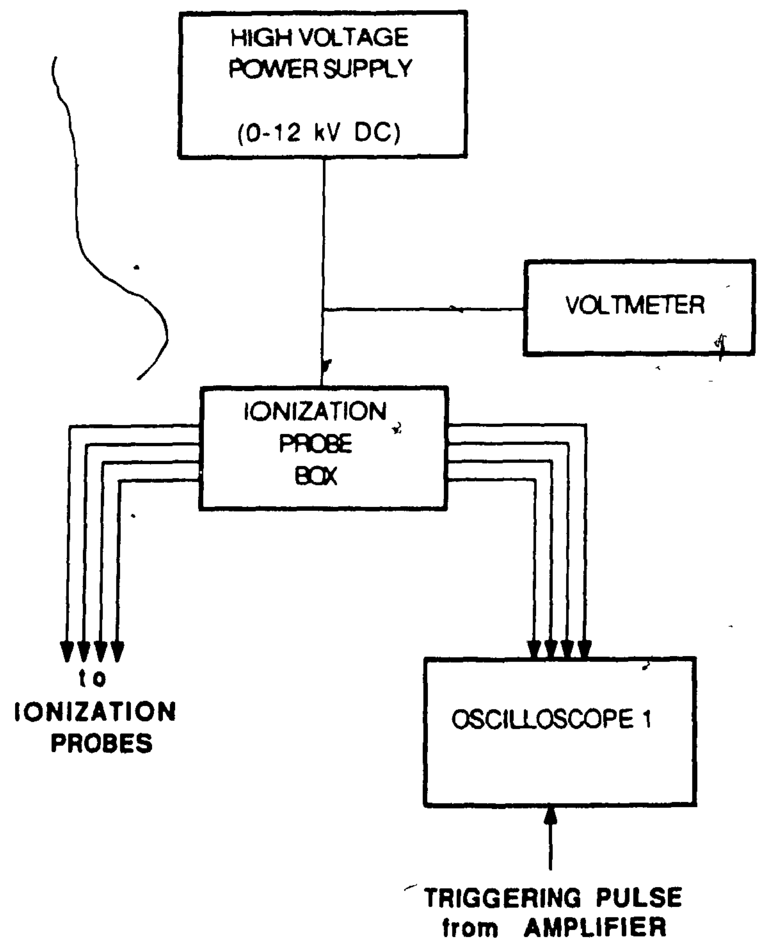


Fig. 13. Block diagram of the instrumentation for the ionization probes.

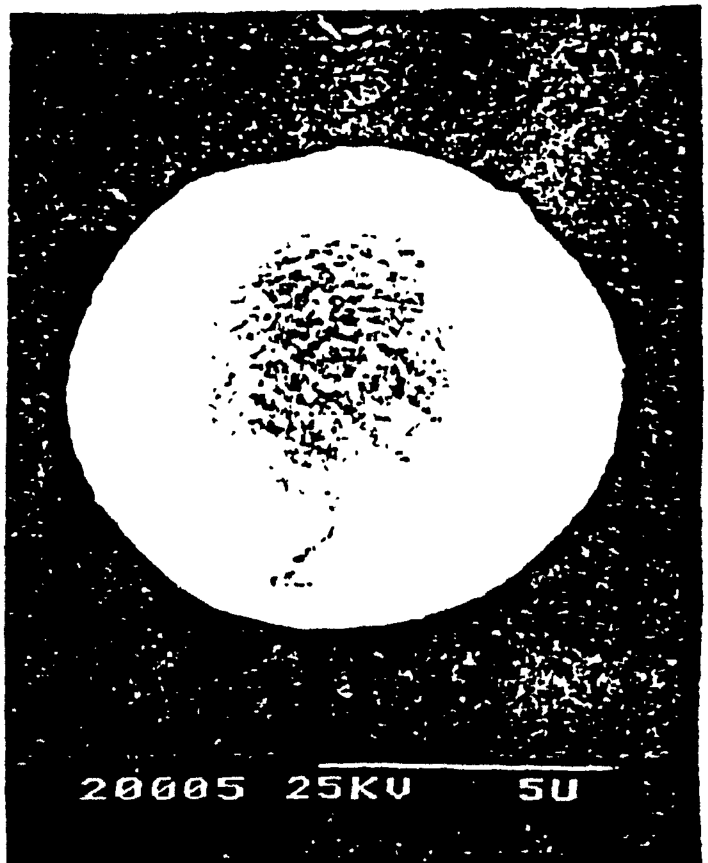
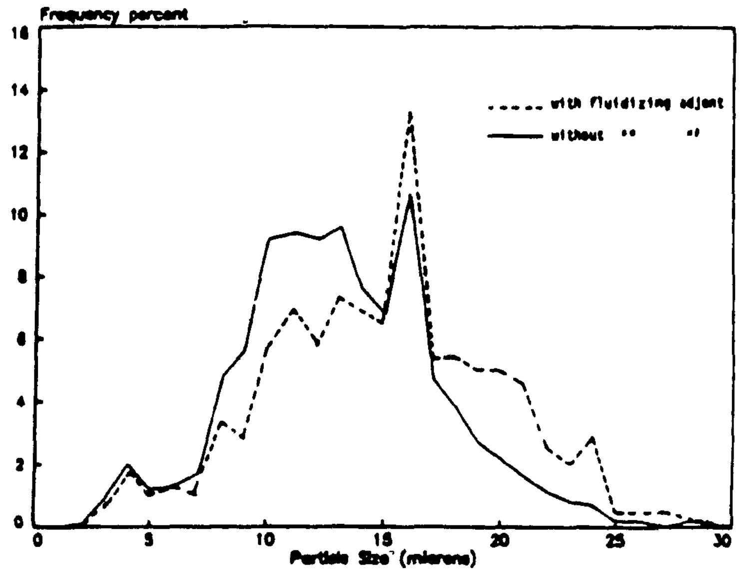


Fig. 14. Scanning electron micrograph of a cornstarch particle.

Particle Size Distribution of Cornstarch



Particle size determined by Image Analysis.

Particle Size Distribution of Cornstarch

Frequency Percent for Particle Size Interval (Microns)

Lot	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14
Cornstarch #1	0.0	0.1	0.9	2.0	1.2	1.5	1.7	4.8	5.6	9.2	9.4	9.2	9.6	7.6
Cornstarch #2**	0.0	0.1	0.7	1.7	1.0	1.2	1.0	3.3	2.8	5.6	6.9	5.7	7.3	6.8
	14-15	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**	**24-25**	**25-26**		
Cornstarch #1	6.8	10.7	4.7	3.8	2.7	2.2	1.6	1.1	0.8	0.7	0.2	0.2		
Cornstarch #2	6.4	13.3	5.3	5.4	5.0	4.9	4.5	2.5	2.0	2.8	0.5	0.5		
	26-27	**27-28**	**28-29**	**29-30**	***Mean**	**Dev.**	**Min.**	**Max.**						
Cornstarch #1	0.0	0.2	0.1	0.0	12.7	4.3	1.8	31.9						
Cornstarch #2	0.5	0.3	0.2	0.2	14.7	5.1	1.8	42.5						

*Mean = arithmetic mean
Dev. = standard deviation
Min. = minimum particle size
Max. = maximum particle size

**Sample #2 contains 1% fumed silica fluidizing adjent

Fig. 15. Particle size distribution of cornstarch dust.

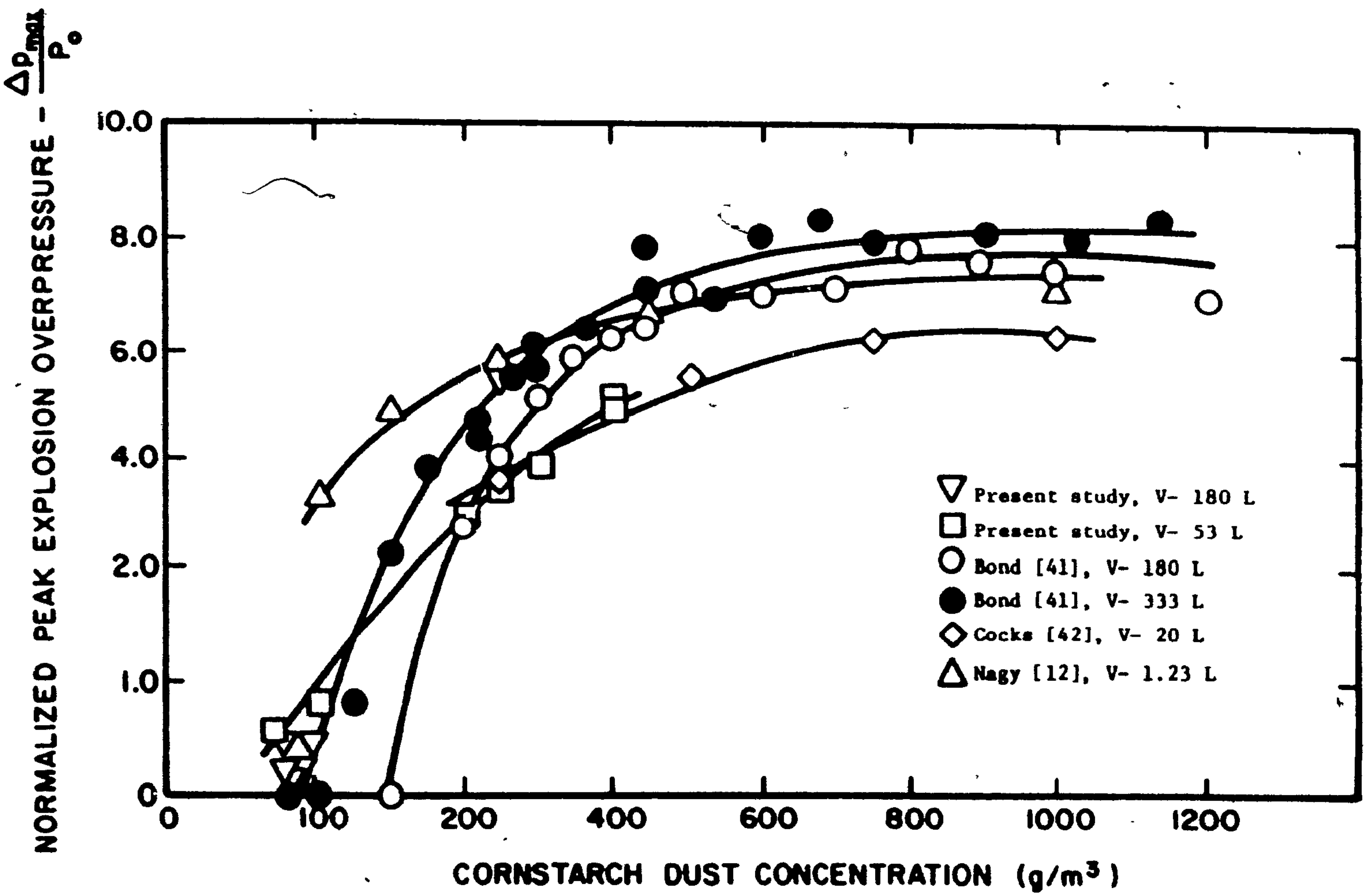


Fig. 16. A comparison of the results for the normalized peak explosion overpressure in a cornstarch dust-air mixture as a function of the cornstarch concentration.

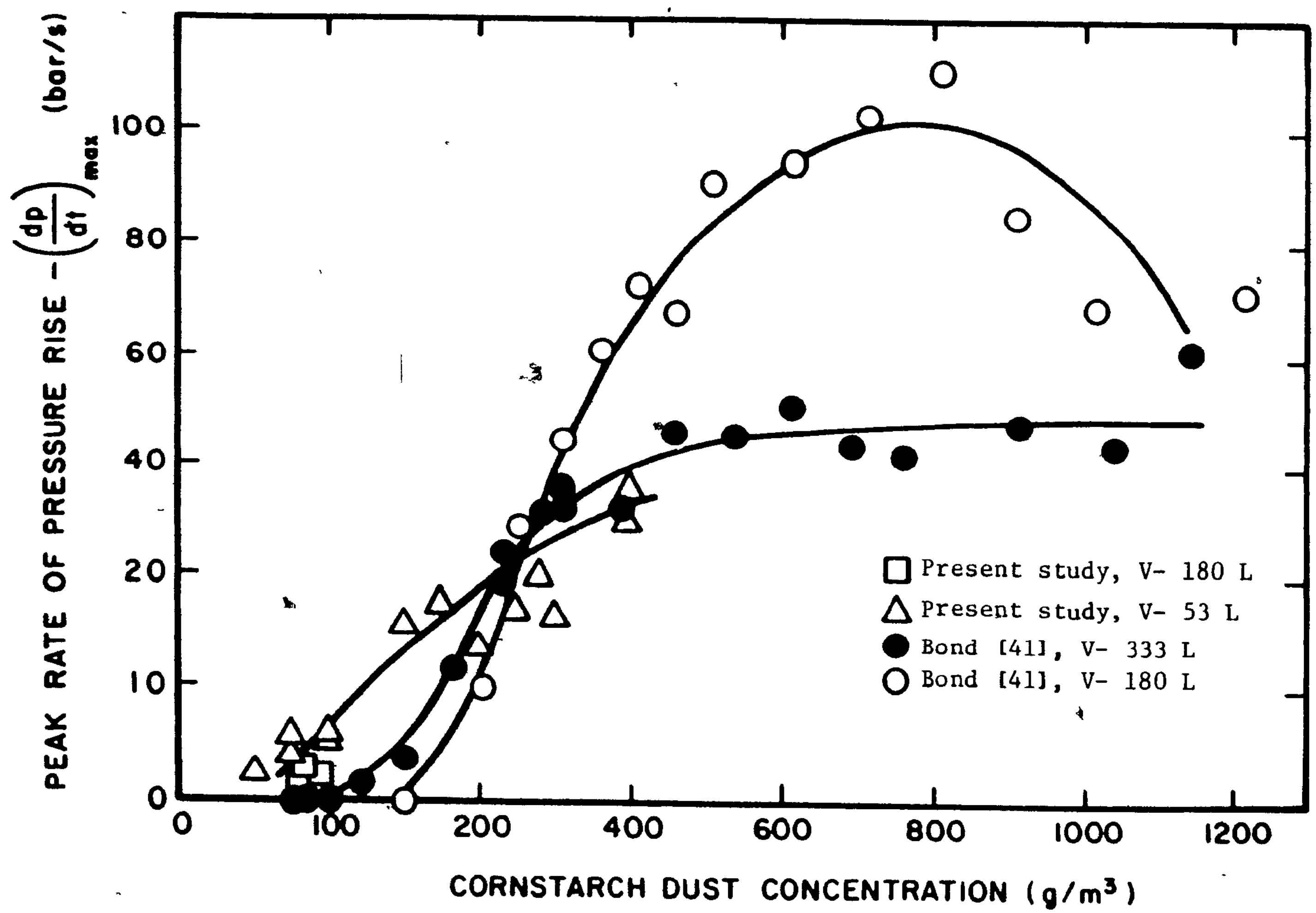


Fig. 17. A comparison of the results for the peak rate of pressure rise in a cornstarch dust-air mixture as a function of the cornstarch concentration.

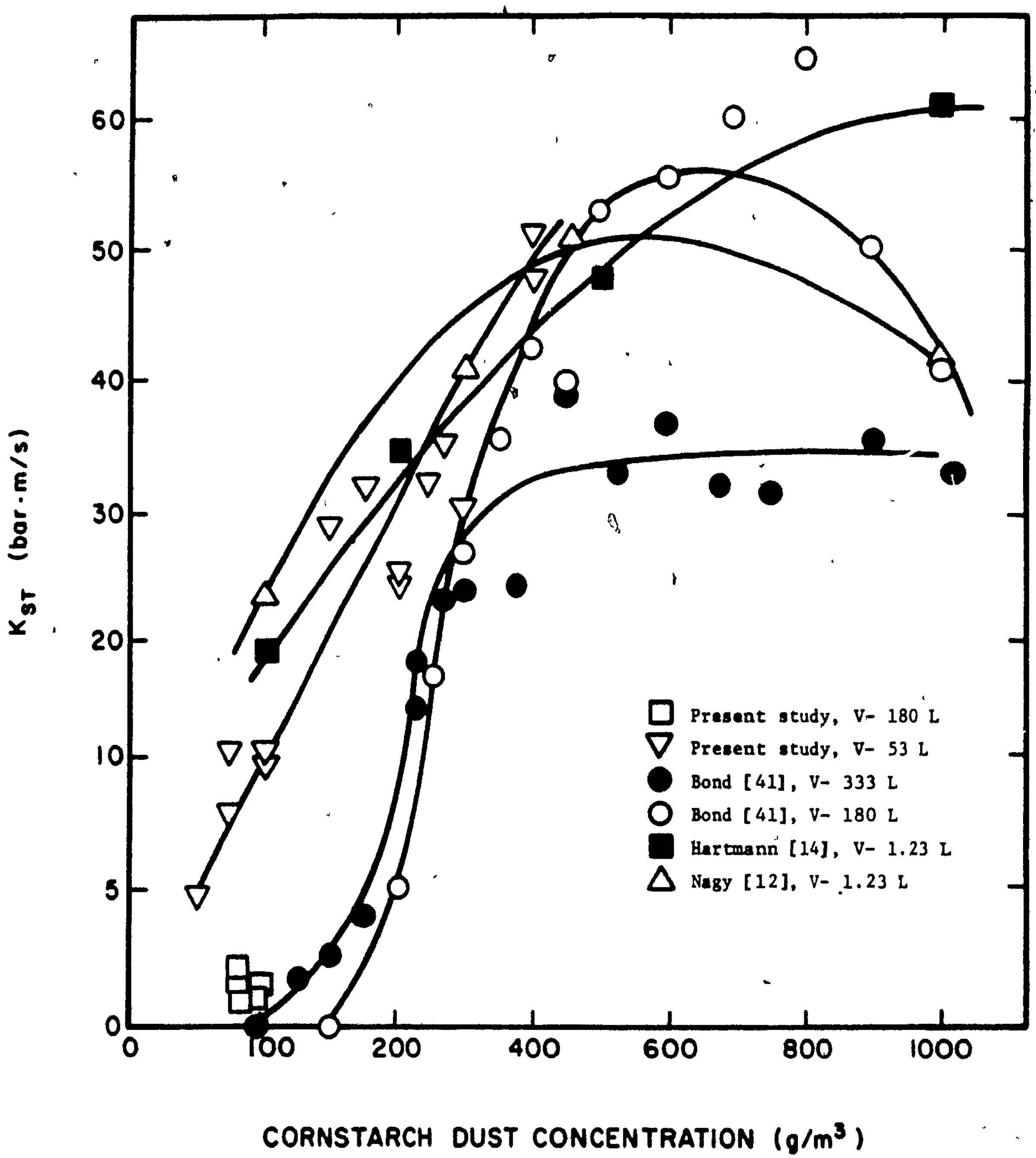


Fig. 18. A comparison of the results obtained for the K_{st} factor in a cornstarch dust-air mixture as a function of the cornstarch concentration.

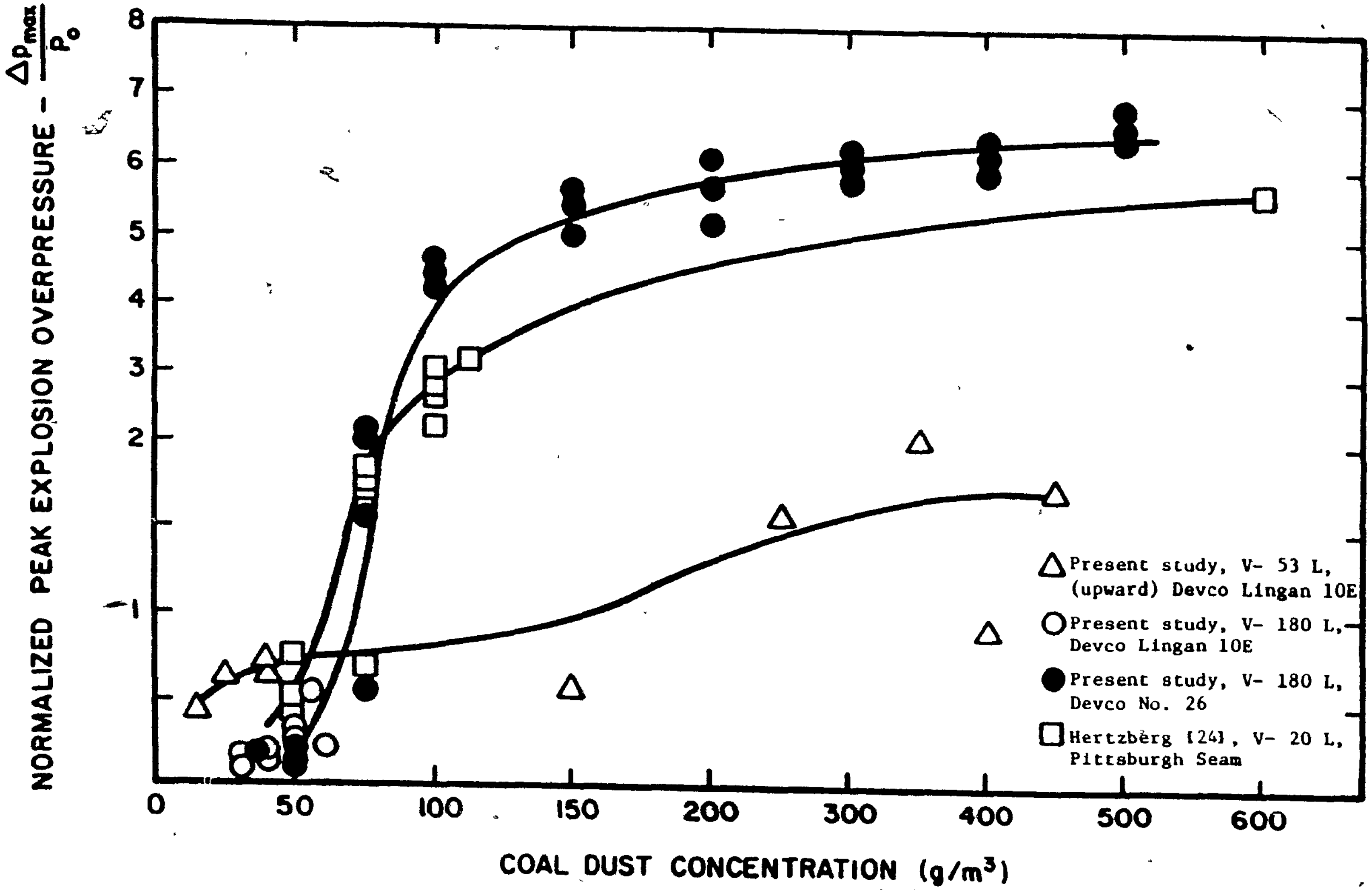


Fig. 19. A comparison of the results for the normalized peak explosion overpressure in a coal dust-air mixture as a function of the coal dust concentration.

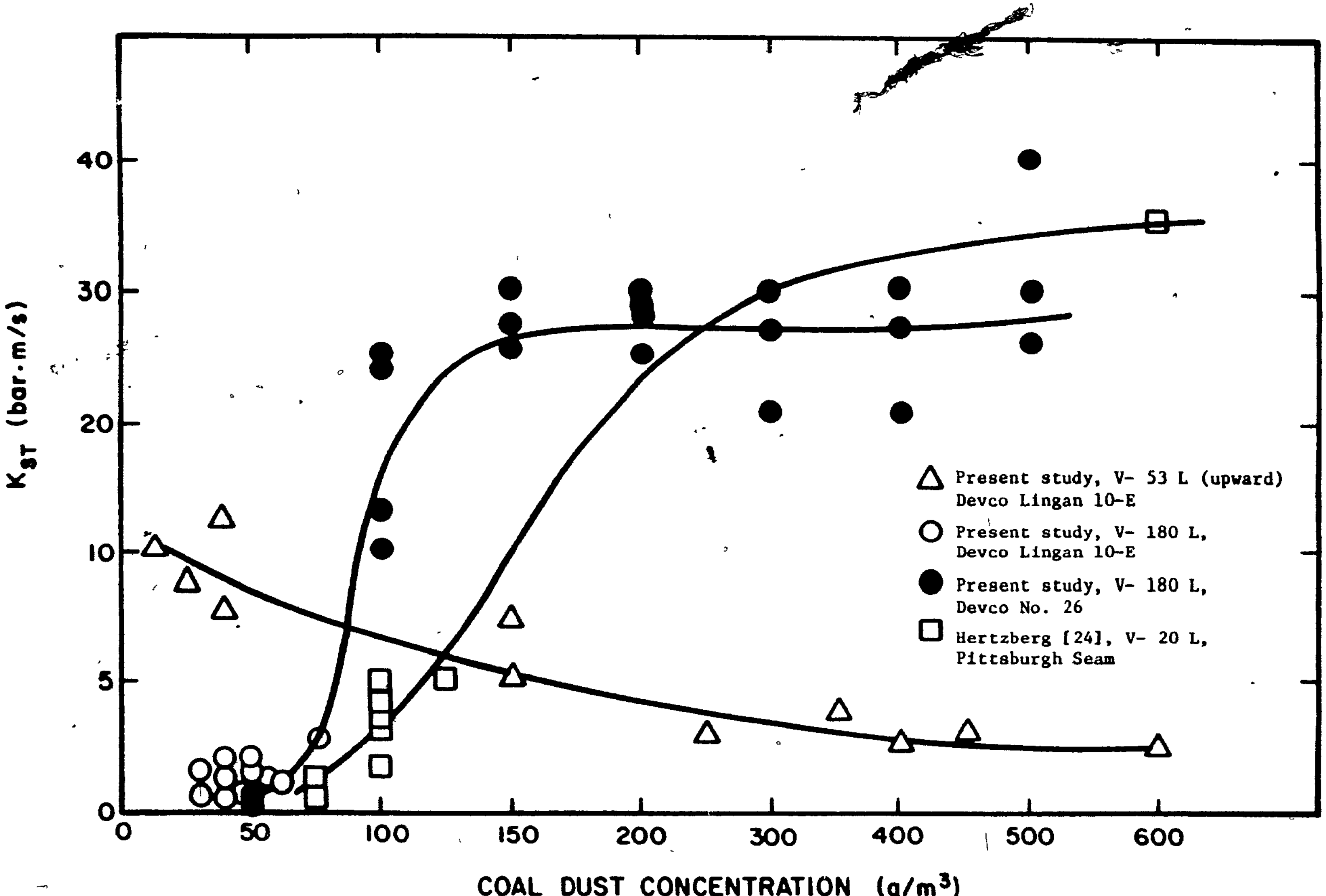


Fig. 20. A comparison of the results obtained for the K_{st} factor in a coal dust-air mixture as a function of the coal dust concentration.

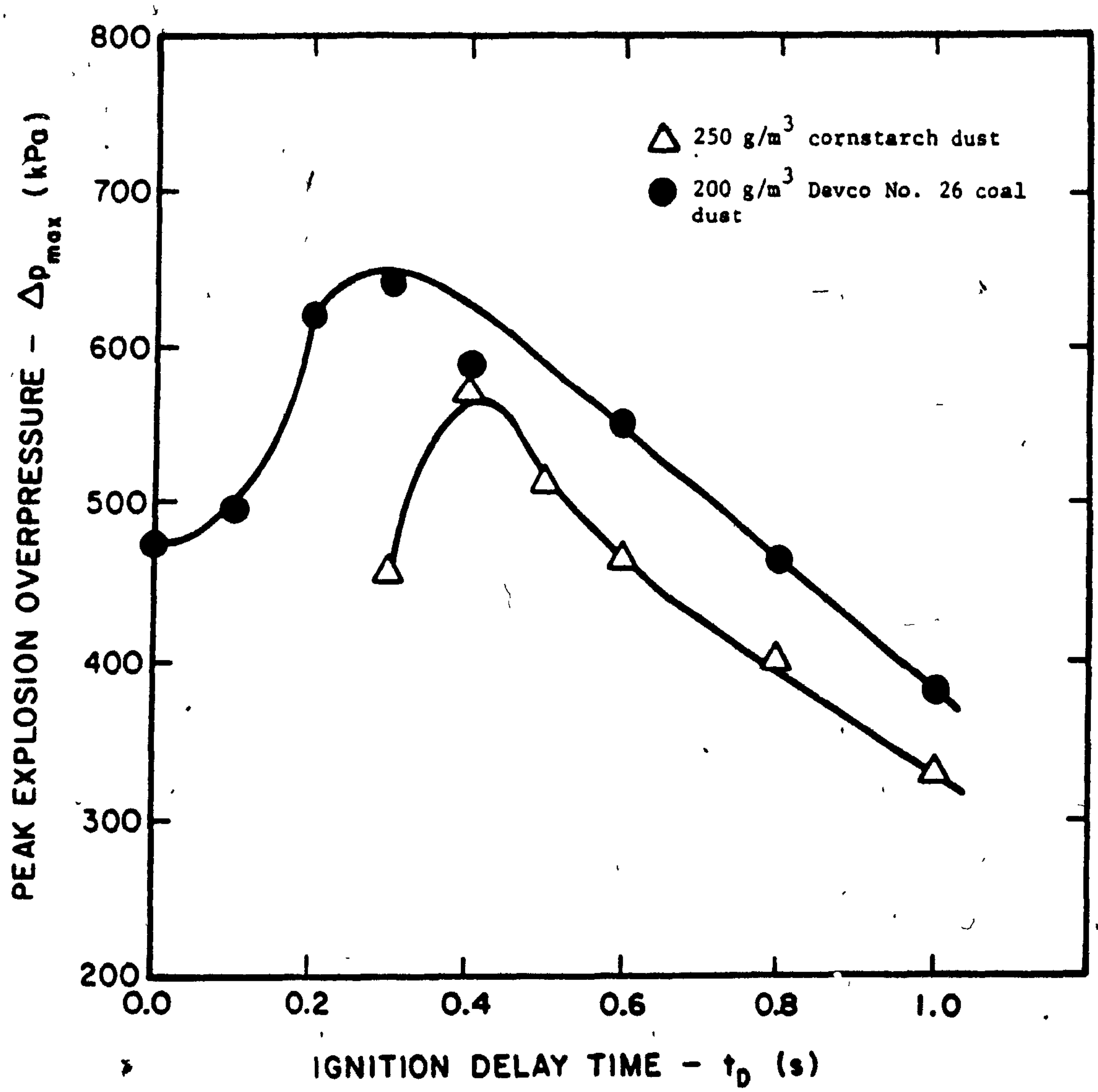


Fig. 21. The variation in peak explosion overpressure with ignition delay time for a cornstarch dust-air mixture and a coal dust-air mixture in the 180 L vessel.

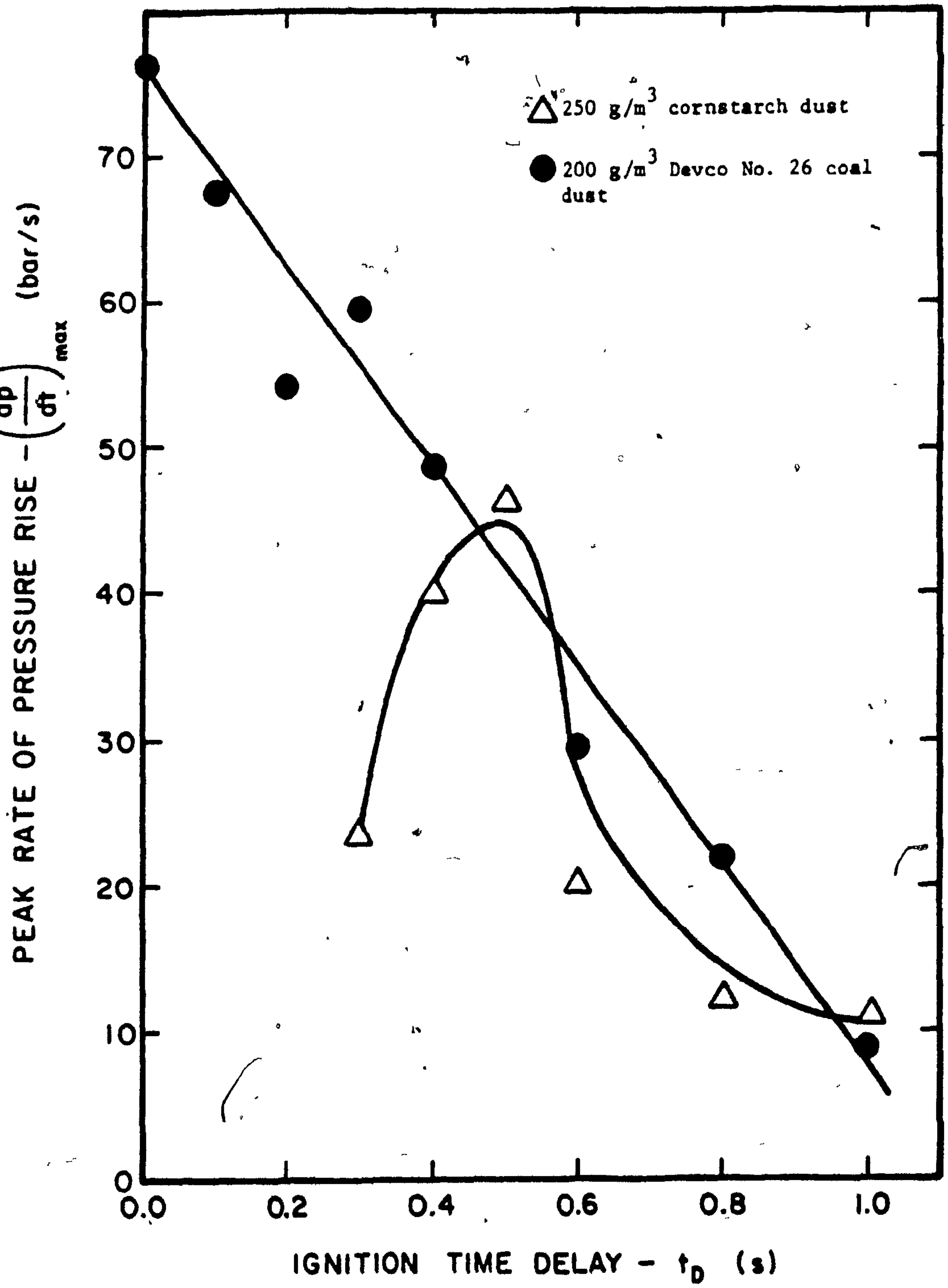


Fig. 22. The variation in peak rate of pressure rise with ignition delay time for a cornstarch dust-air mixture and a coal dust-air mixture in the 180 L vessel.

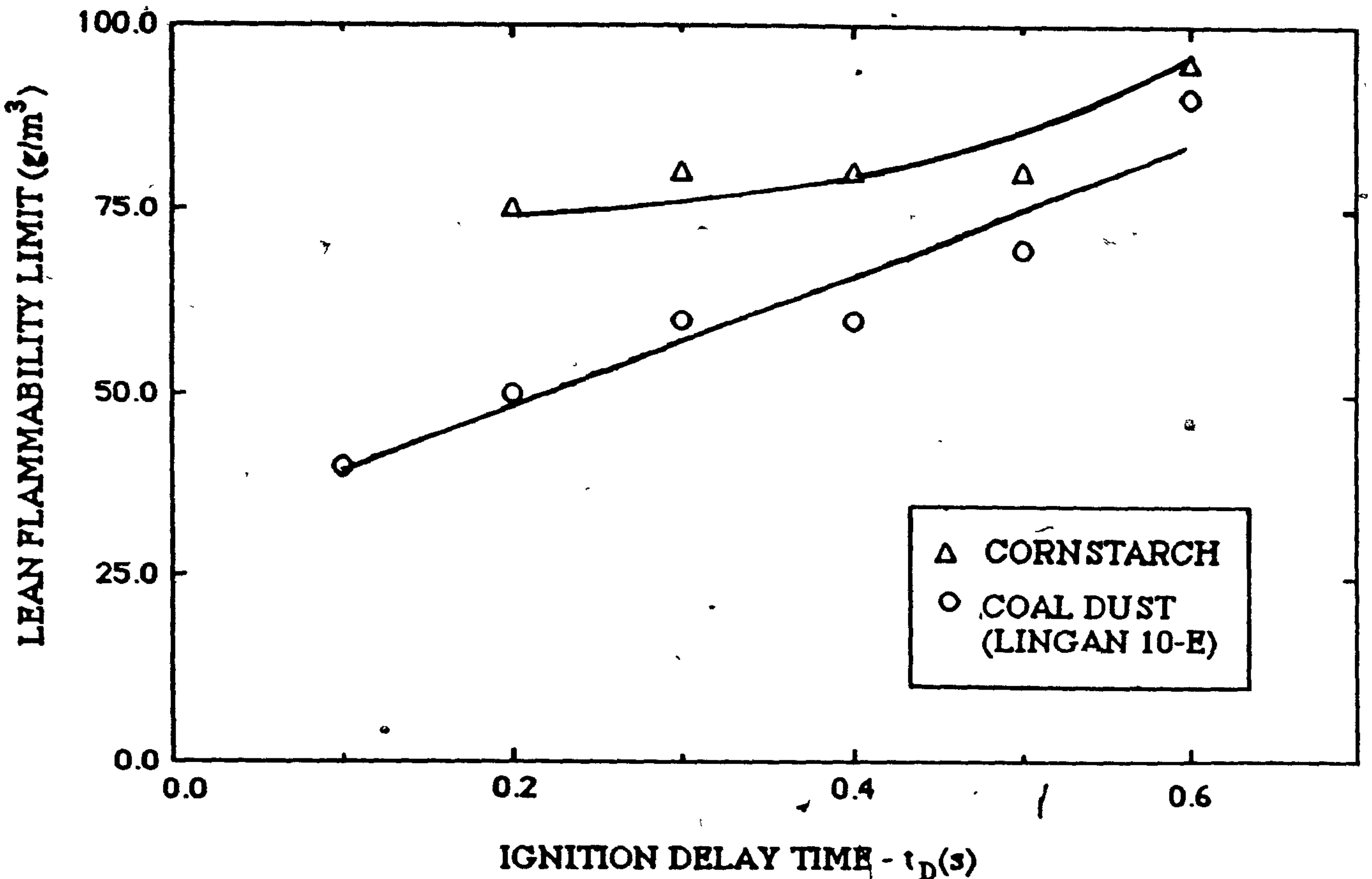


Fig. 23. The variation in apparent lean flammability limit, as a function of ignition delay time, for cornstarch dust and Devco Lingan 10-E coal dust.

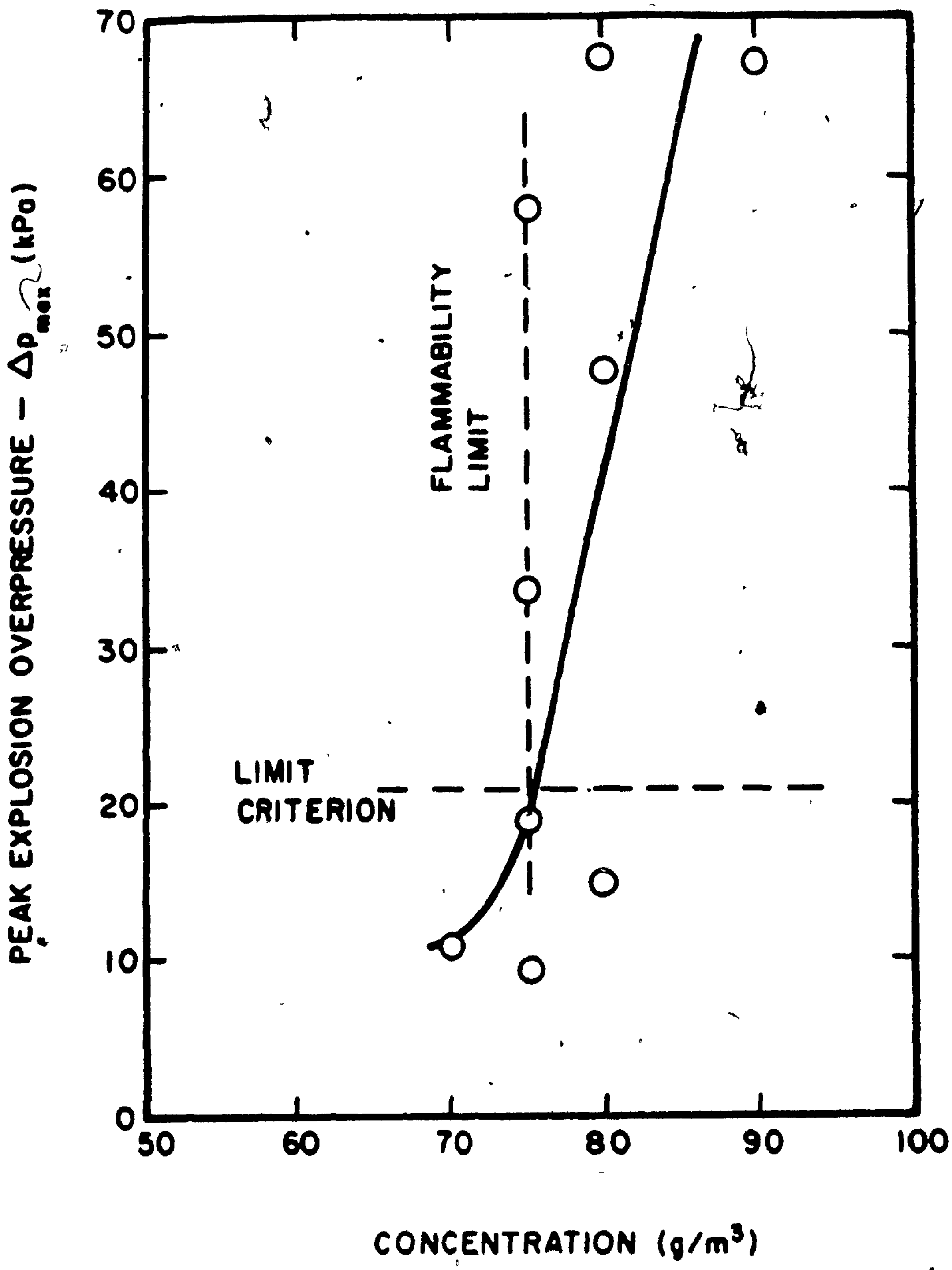


Fig. 24. Peak explosion overpressure as a function of cornstarch dust concentration at "optimum" ignition delay time of 200 ms.

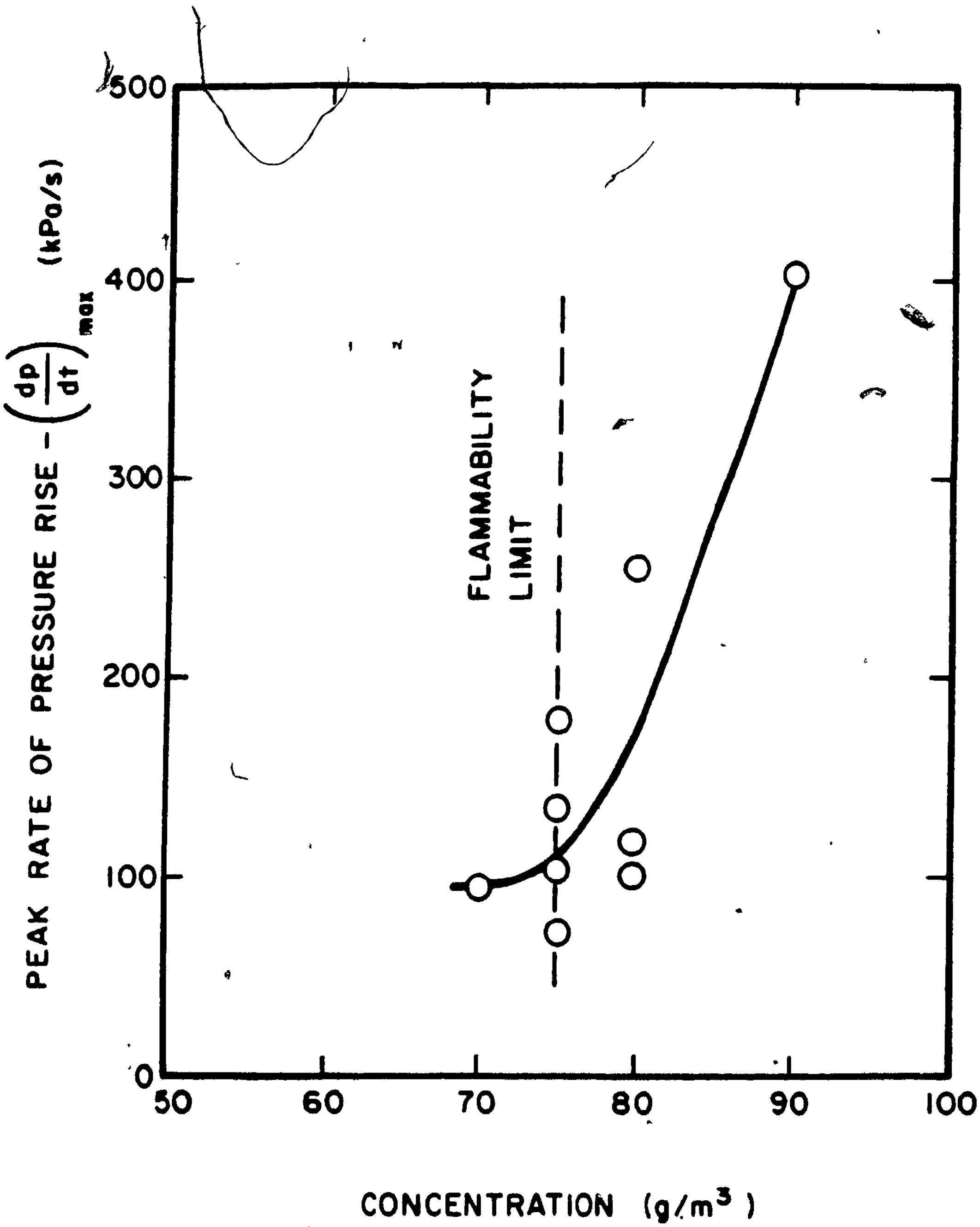


Fig. 25. Peak rate of pressure rise as a function of cornstarch dust concentration at "optimum" ignition delay time of 200 ms.

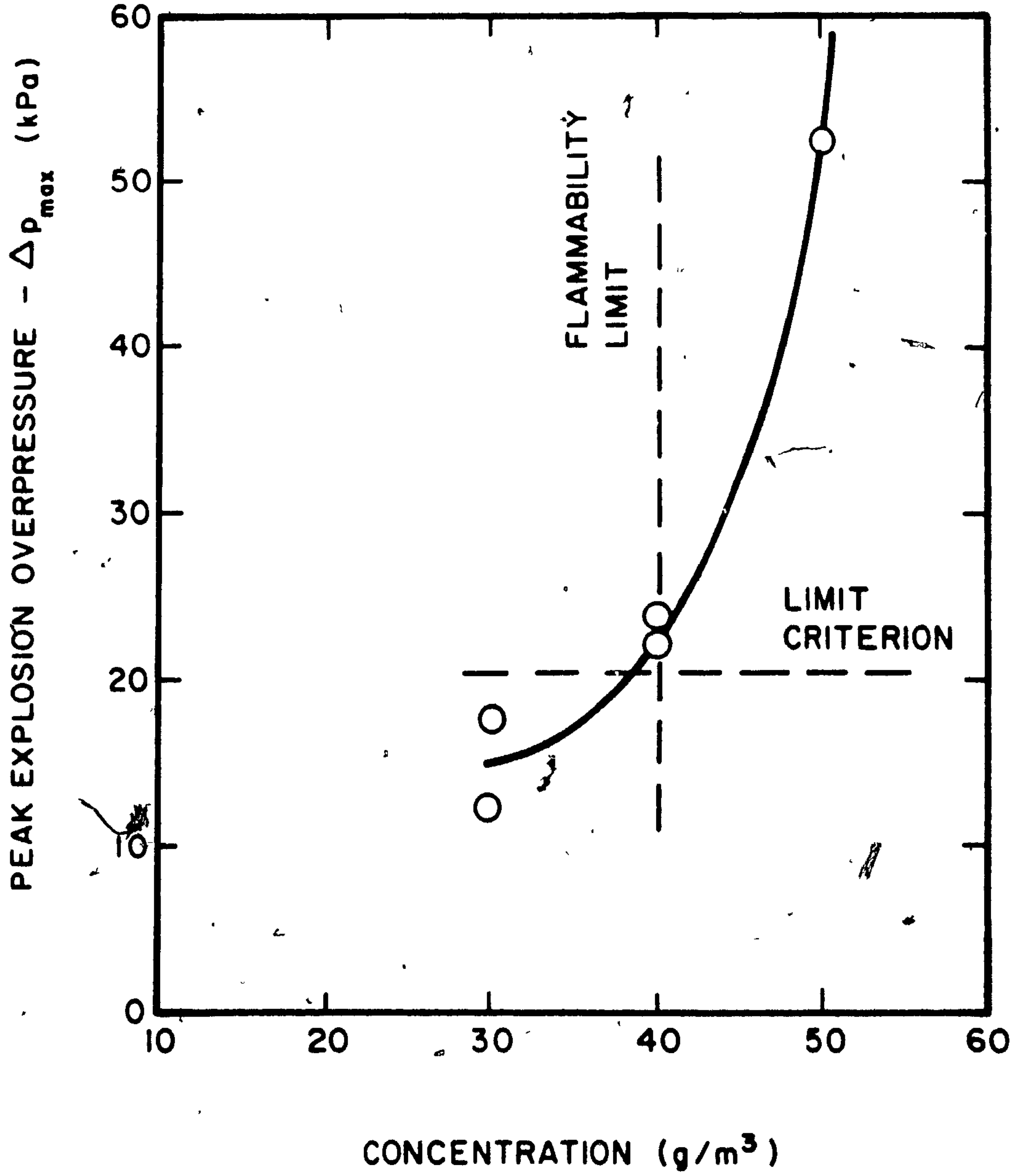


Fig. 26. Peak explosion overpressure as a function of coal dust (Lingan 10-E) concentration at "optimum" ignition delay time of 100 ms.

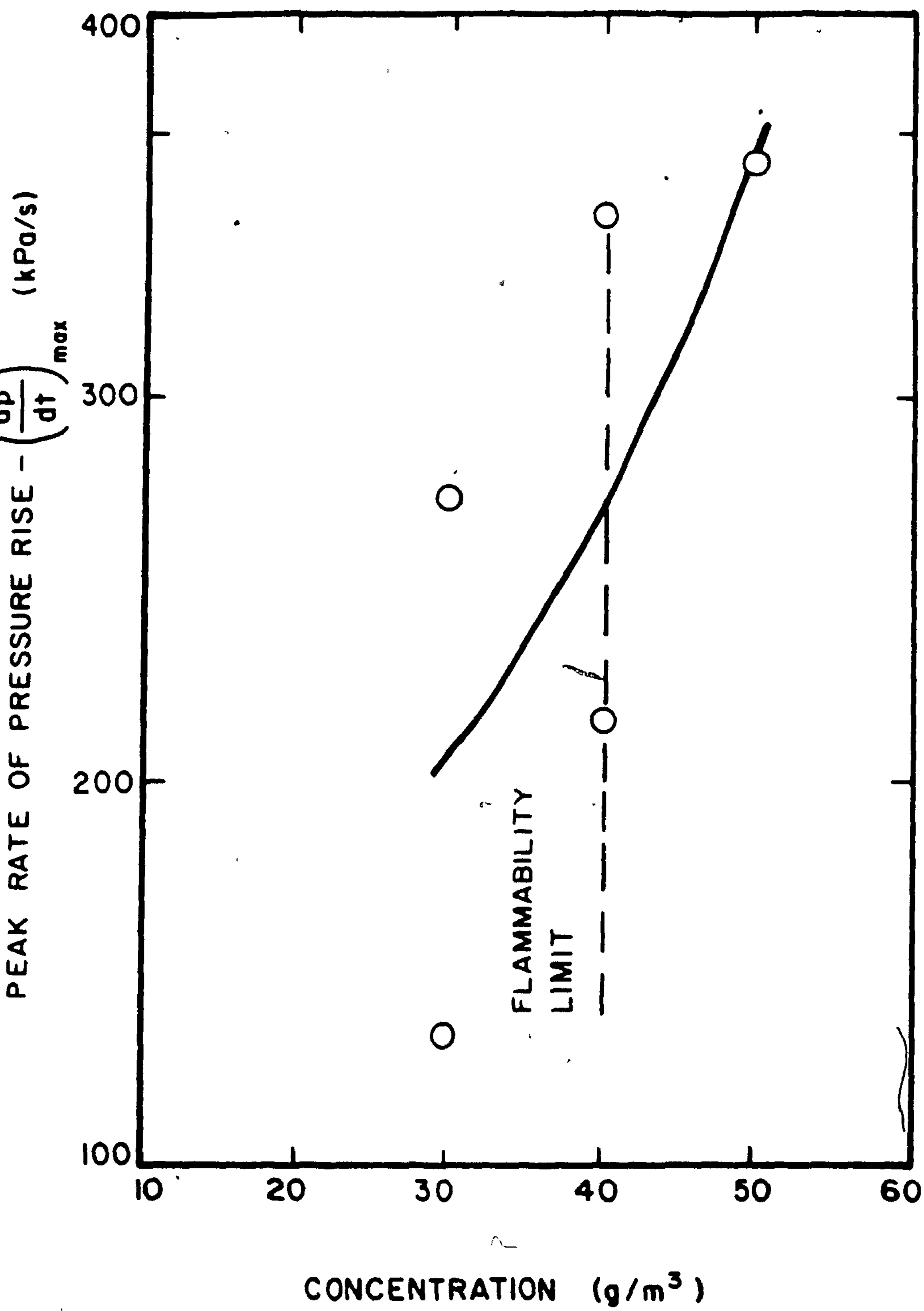


Fig. 27. Peak rate of pressure rise as a function of coal dust (Lingan 10-E) concentration at "optimum" ignition delay time of 100 ms.

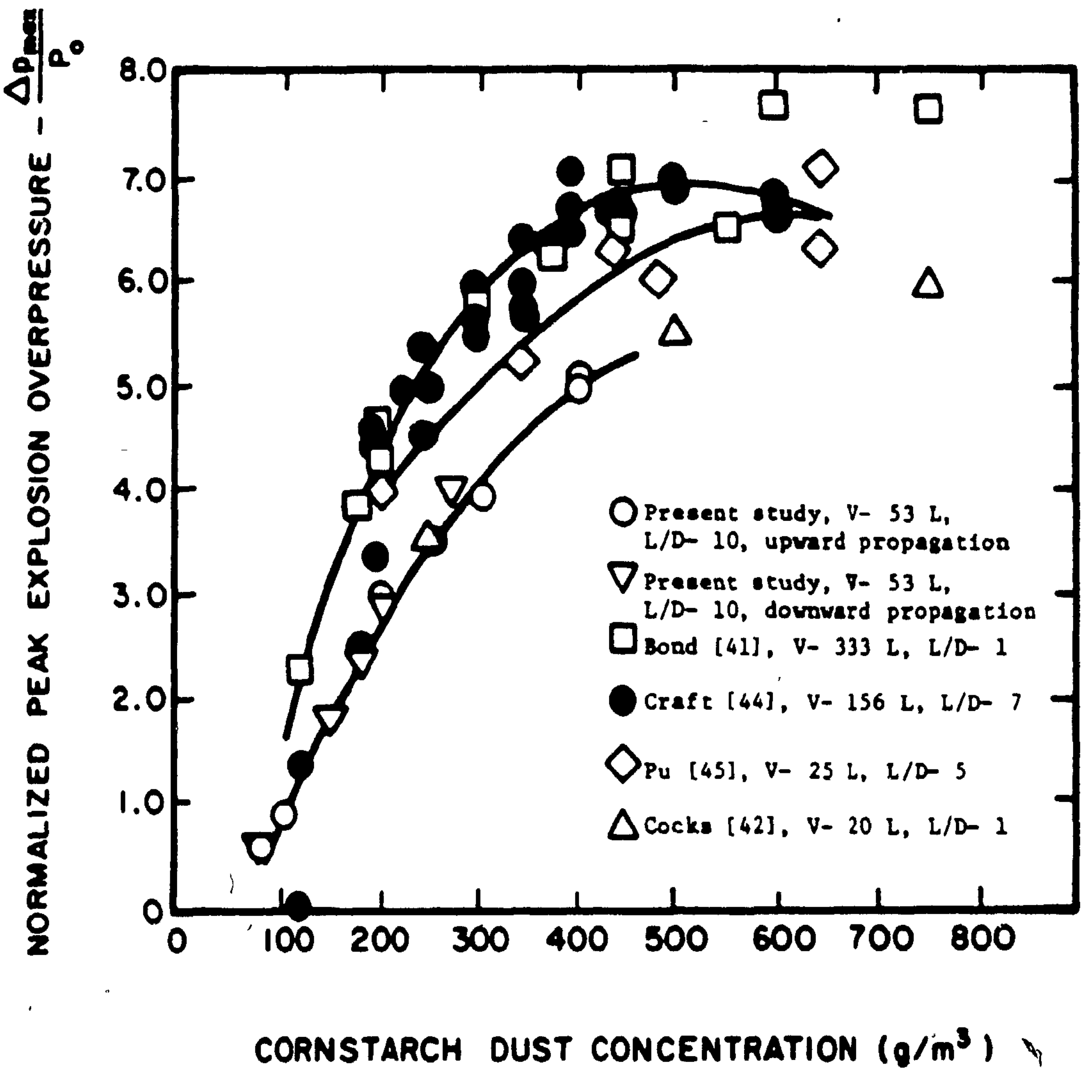


Fig. 28. A comparison of the results for the normalized peak explosion overpressure in a cornstarch dust-air mixture as a function of the cornstarch concentration.

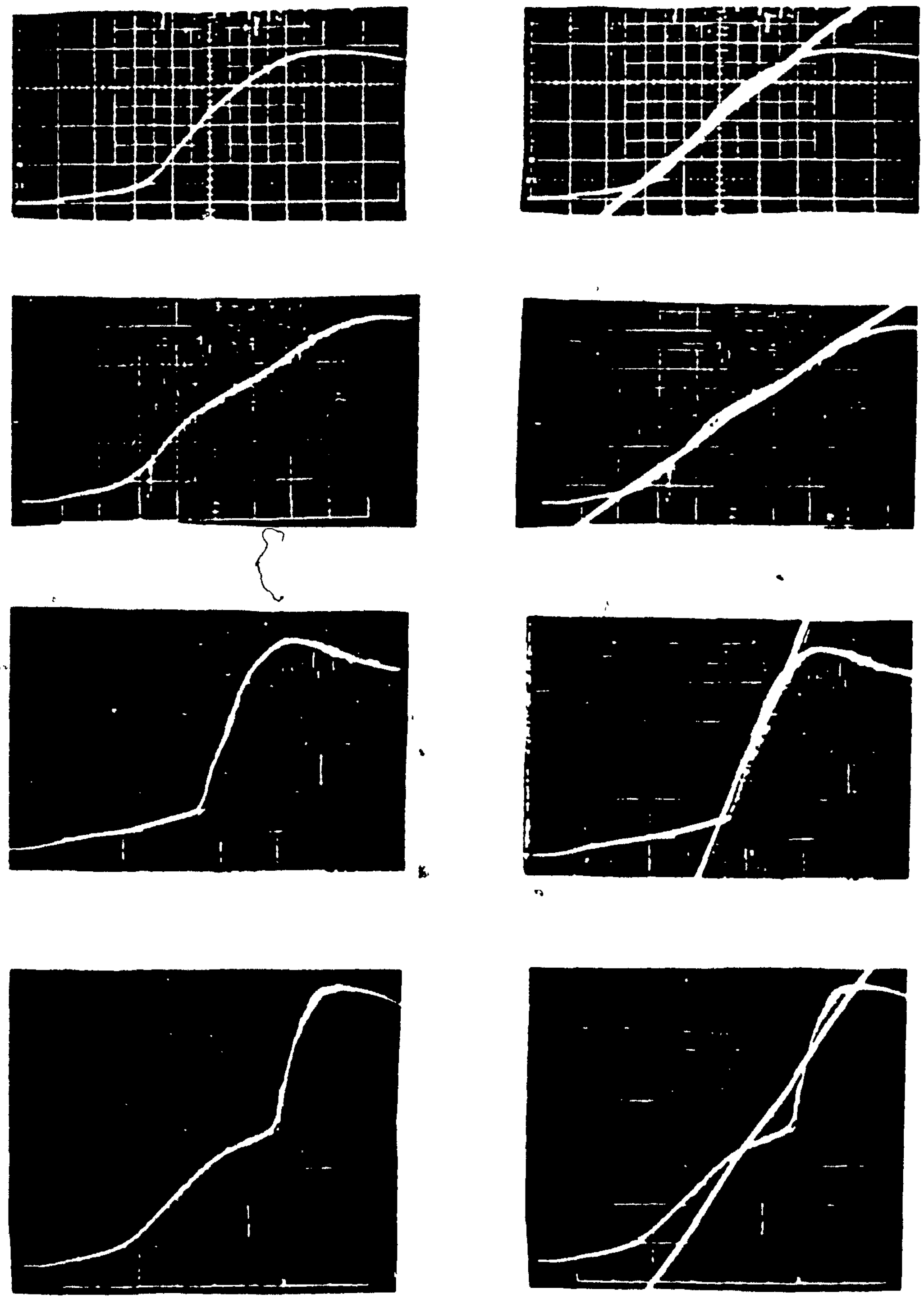


Fig. 29. Experimental traces of the variation of pressure with time (obtaining representative value of peak rate of pressure rise in vertical tube).

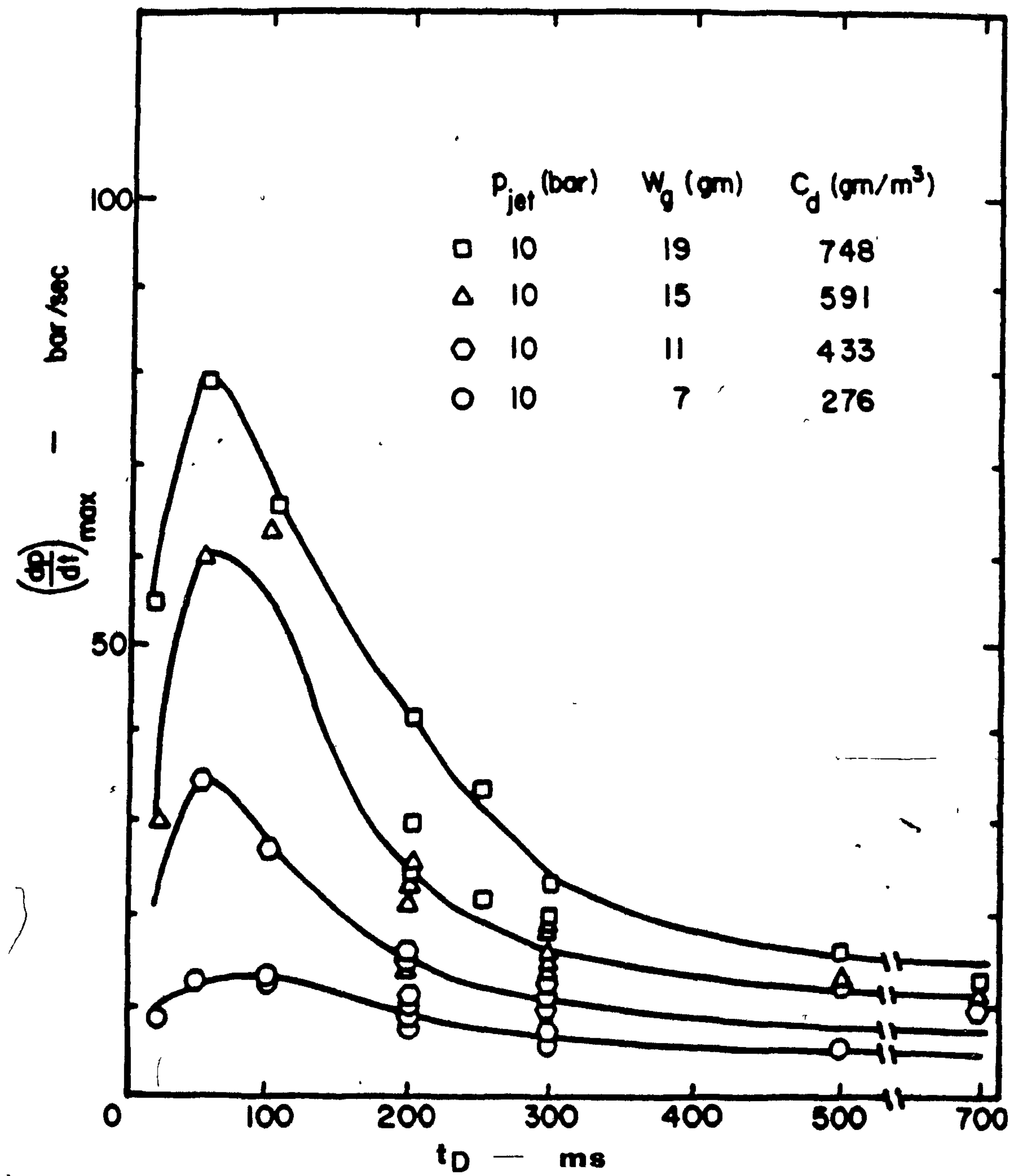


Fig. 30. Experimental results [45] for the variation of the peak rate of pressure rise with ignition delay time in a 25 L tube.

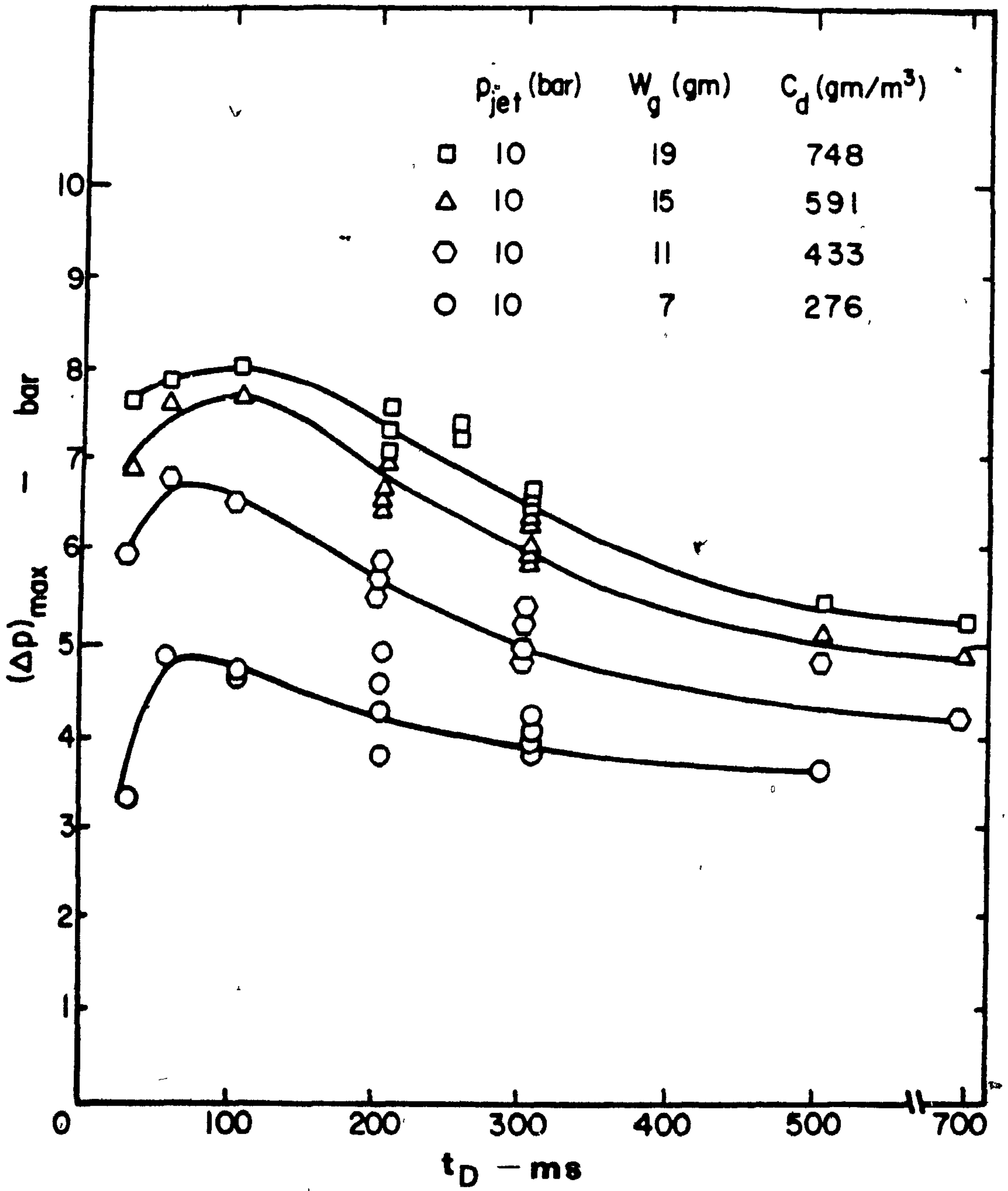


Fig. 31. Experimental results [45] for the variation of peak explosion overpressure with ignition delay time in a 25 L tube.

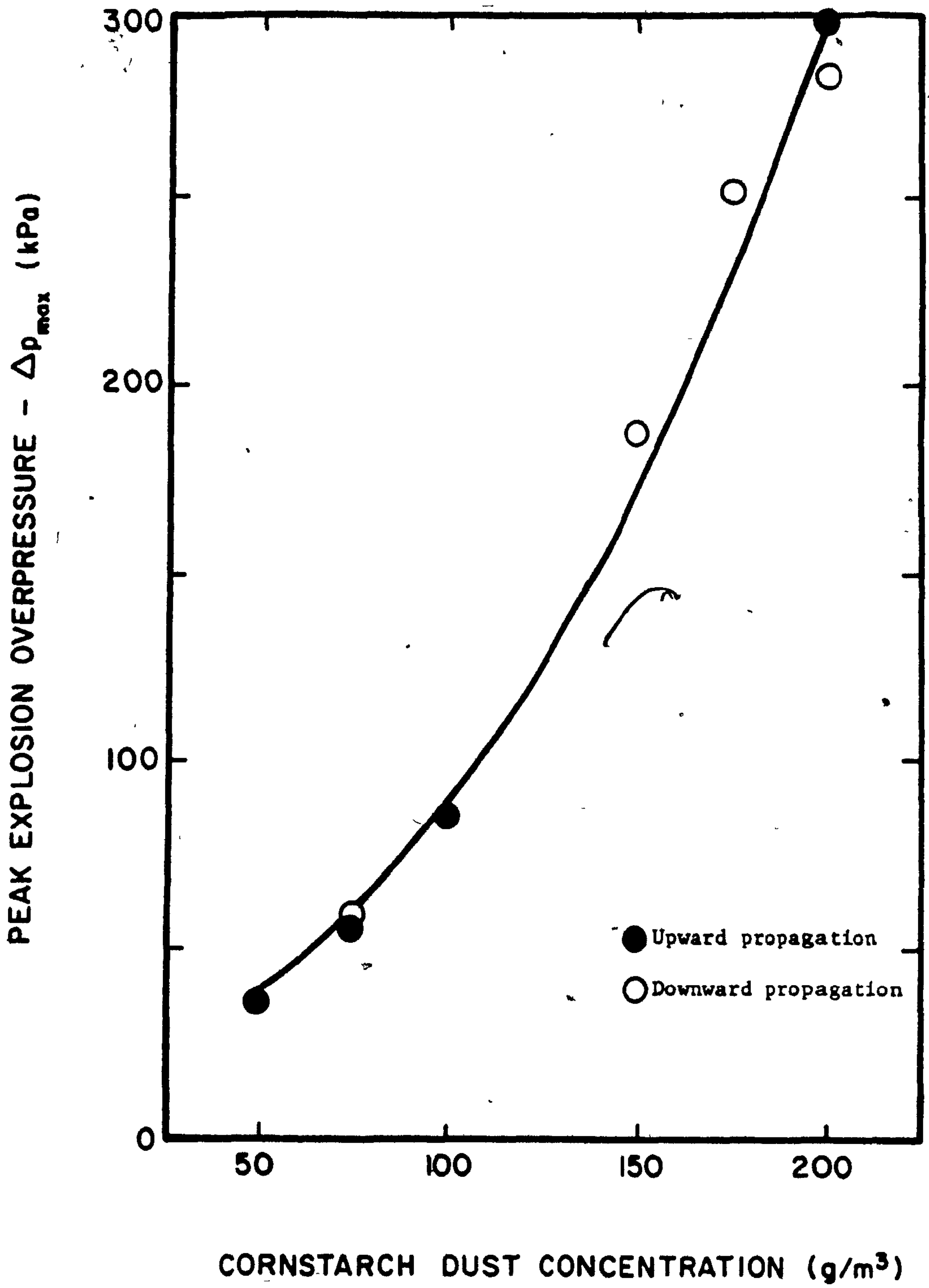


Fig. 32. The variation in peak explosion overpressure as a function of cornstarch dust concentration in the vertical tube for upward and downward flame propagation directions.

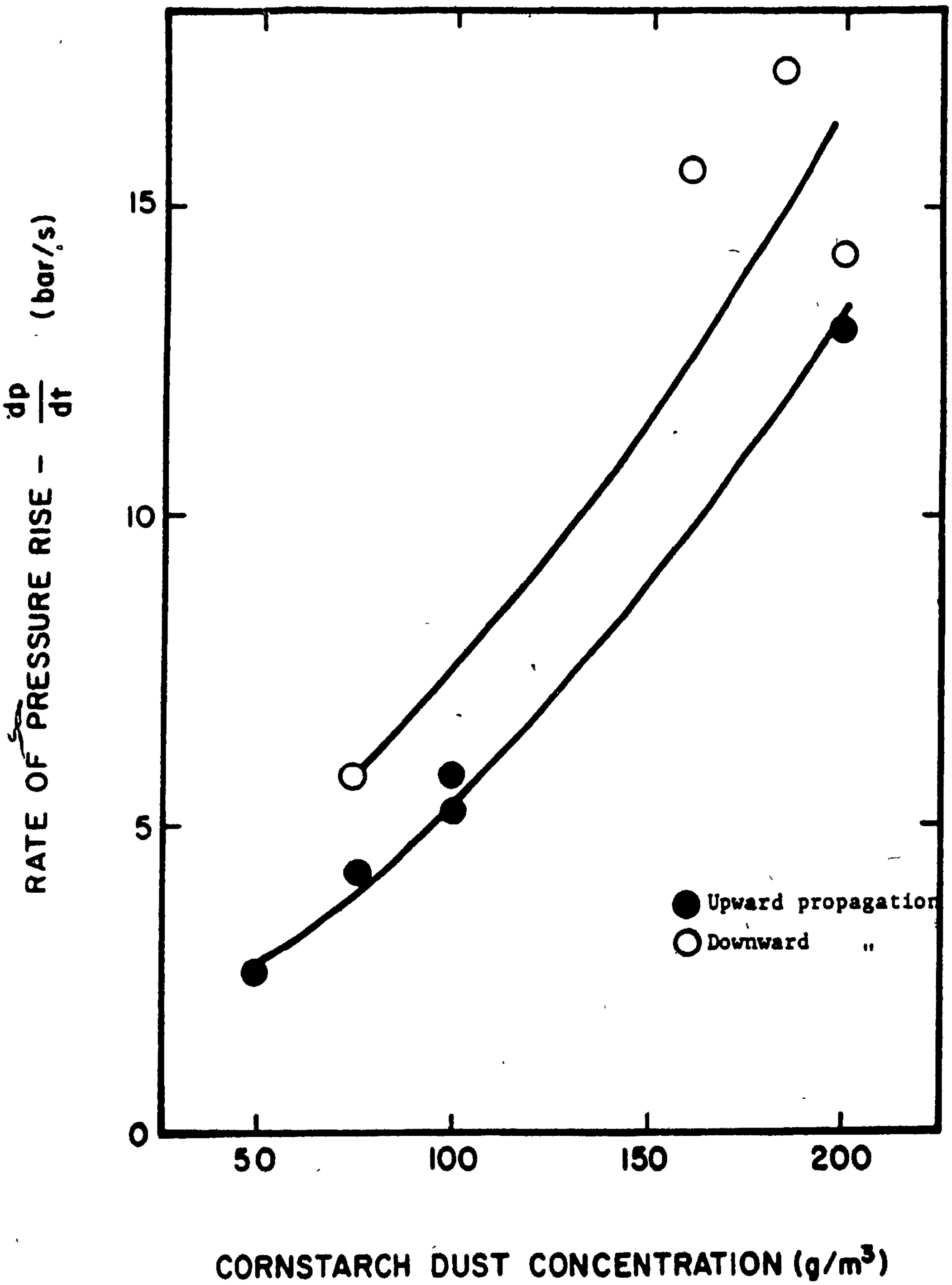


Fig. 33. The variation in rate of pressure rise as a function of cornstarch dust concentration in the vertical tube for upward and downward flame propagation directions.

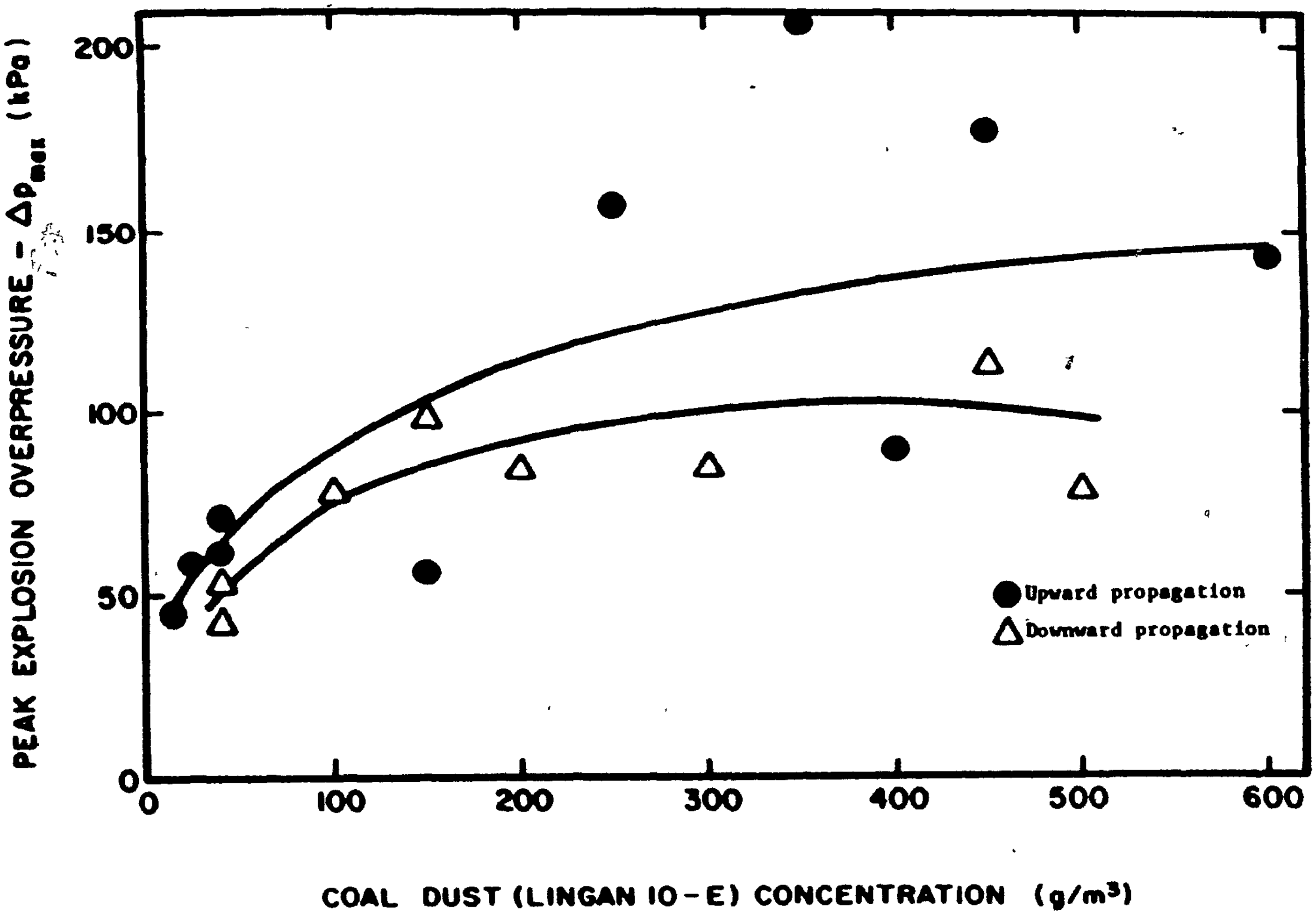


Fig. 34. The variation in peak explosion overpressure as a function of Lingan 10-E coal dust concentration in the vertical tube for upward and downward flame propagation directions.

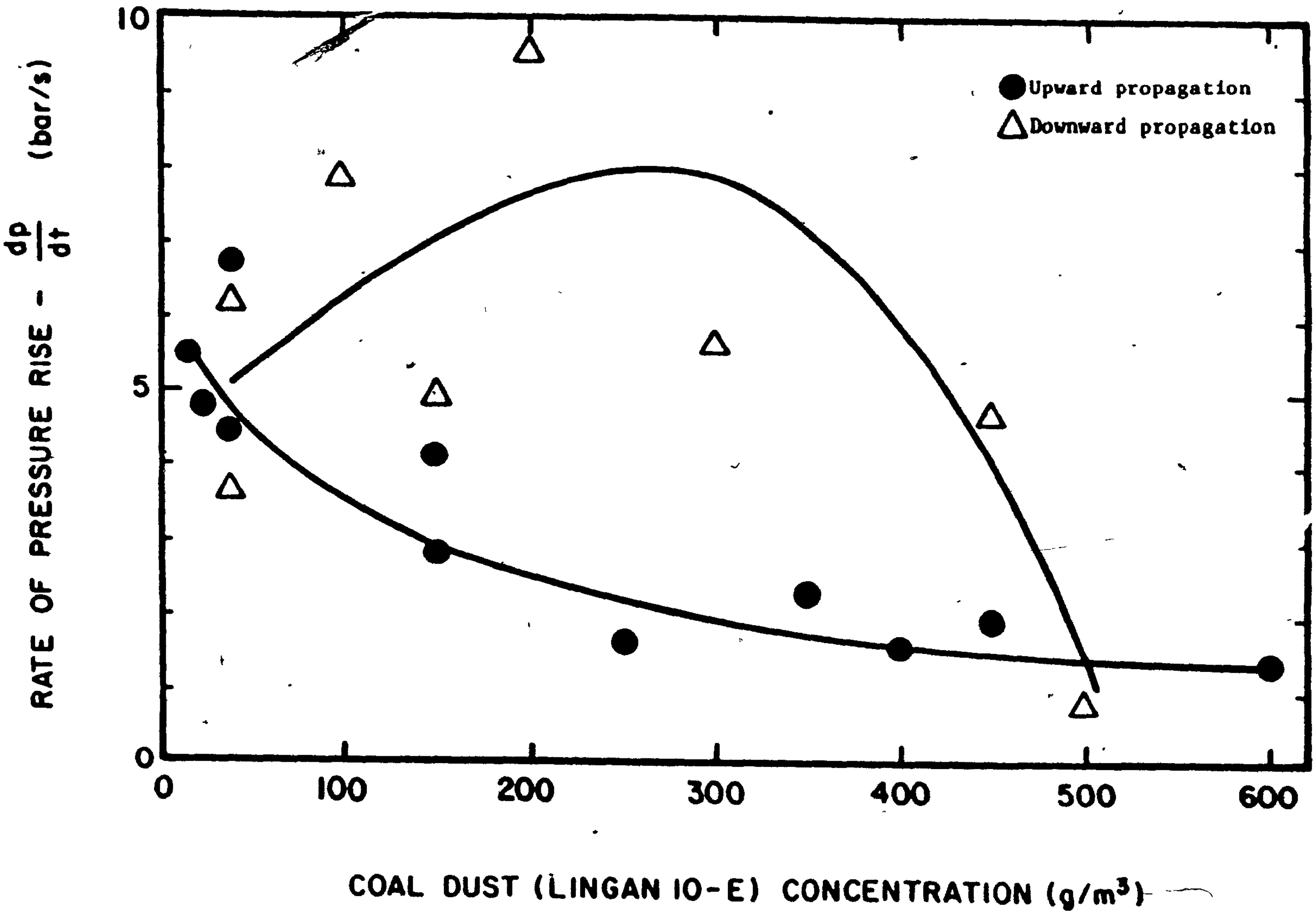


Fig. 35. The variation in rate of pressure rise as a function of Devco Lingan 10-E coal dust concentration in the vertical tube for upward and downward flame propagation directions.

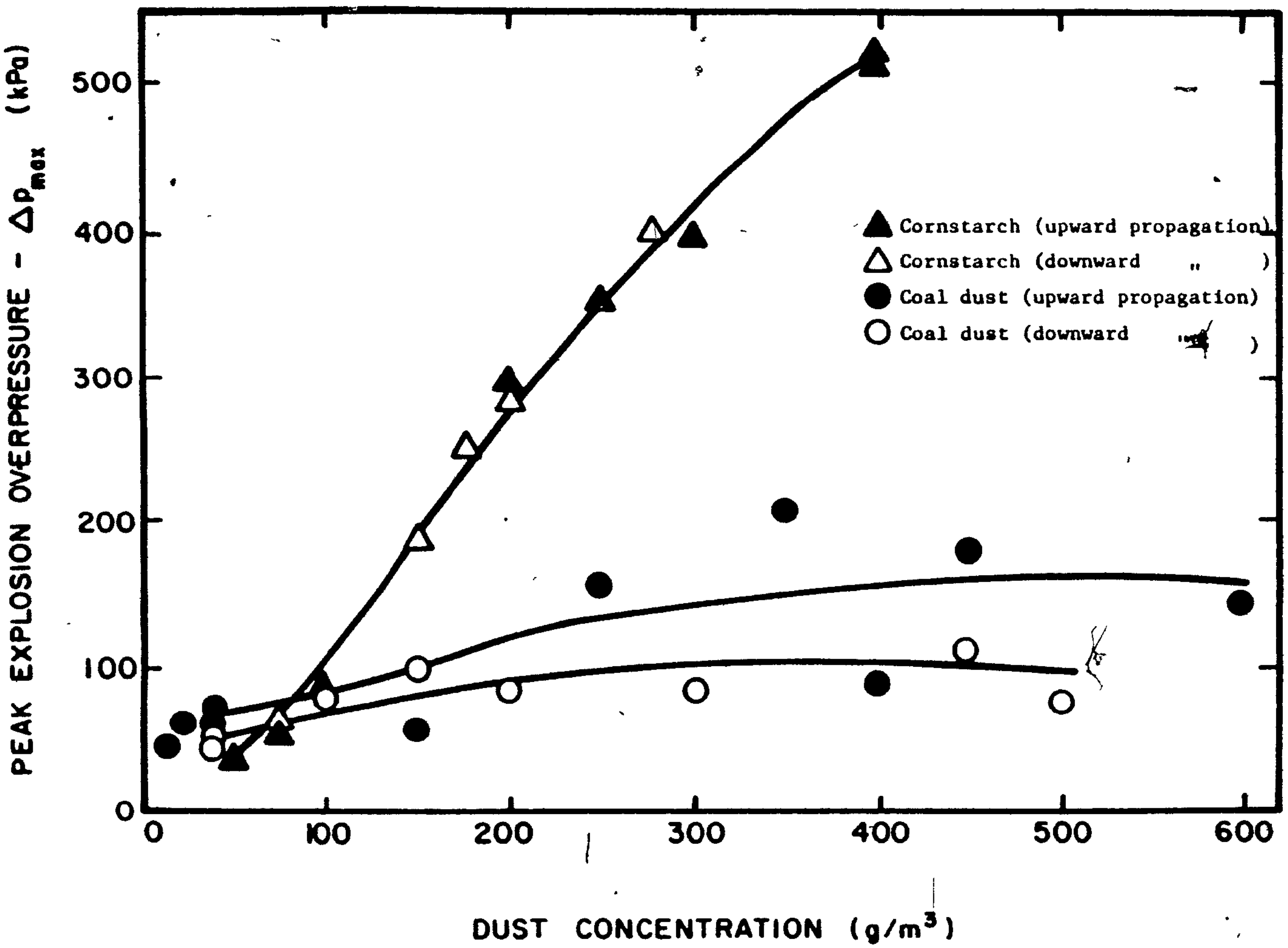


Fig. 36. The variation in peak explosion overpressure as a function of cornstarch and Devco Lingan 10-E coal dust concentrations in the vertical tube.

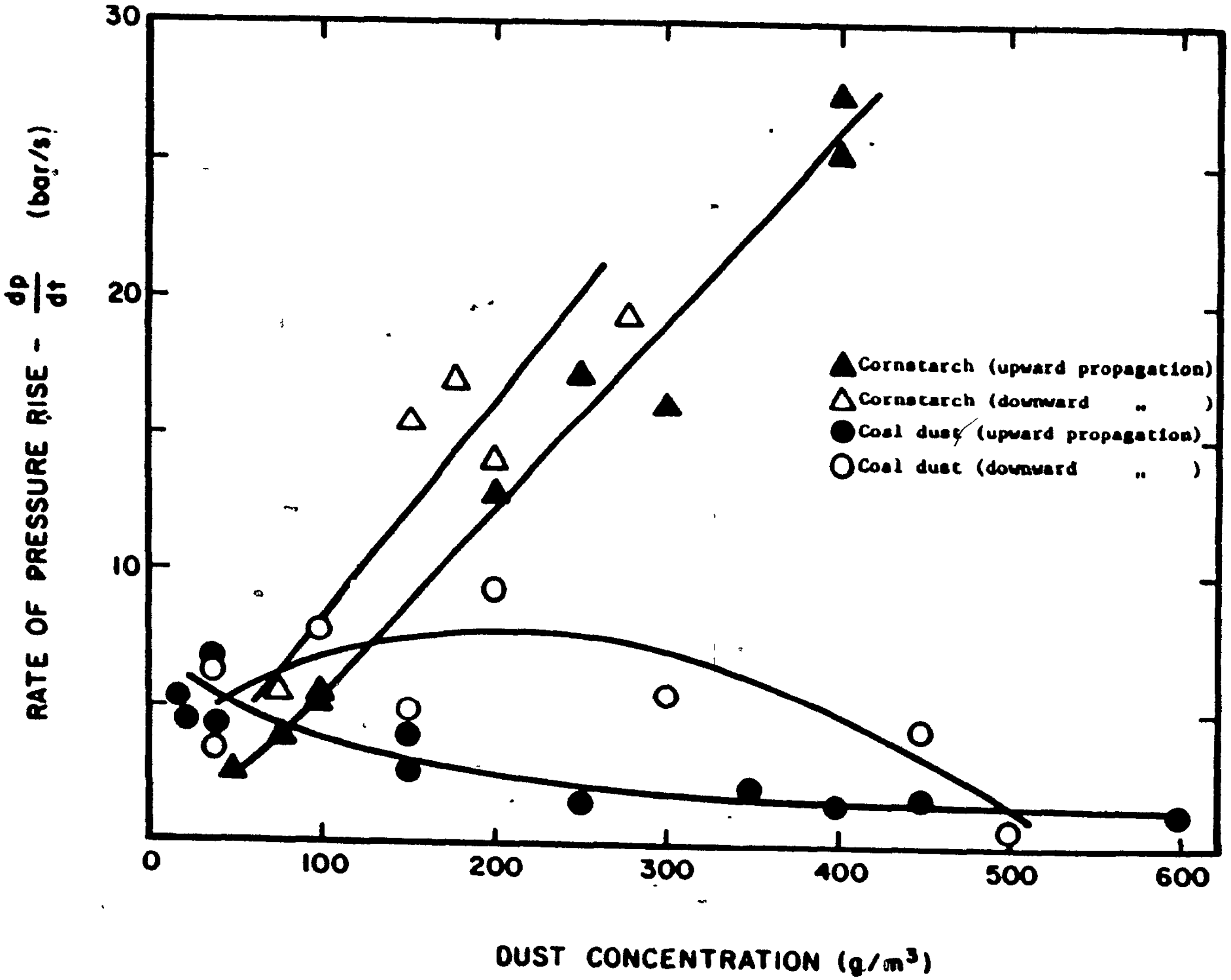


Fig. 37. The variation in rate of pressure rise as a function of cornstarch and Devco Lingan 10-E coal dust concentrations in the vertical tube.

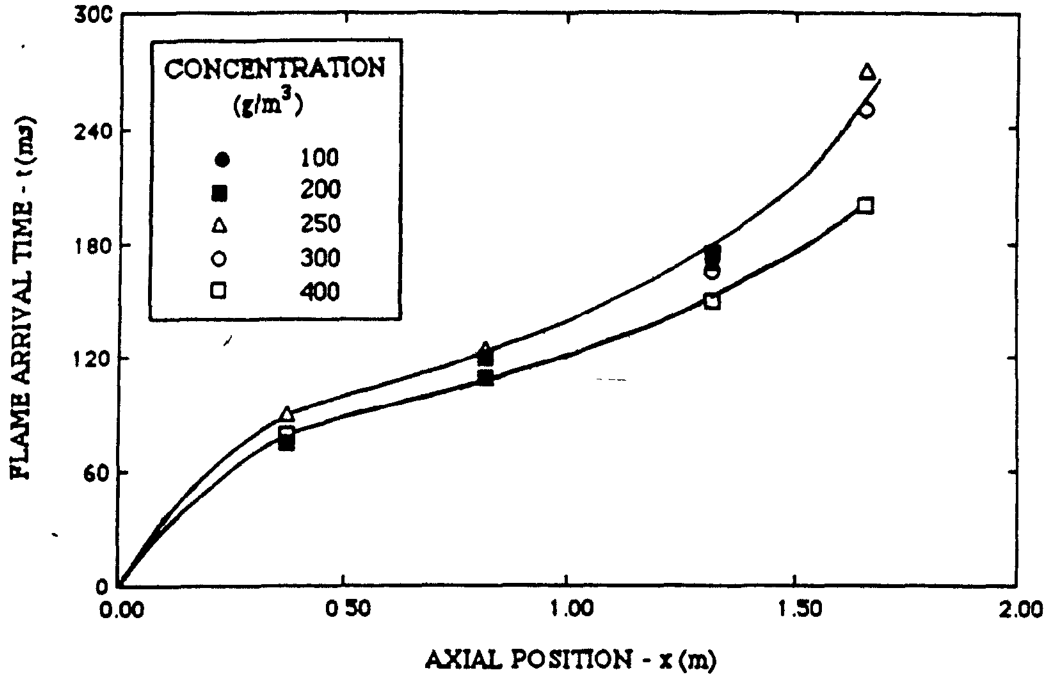


Fig. 38a. Flame arrival time as a function of distance travelled in the closed vertical tube for upward propagating cornstarch dust-air flames.

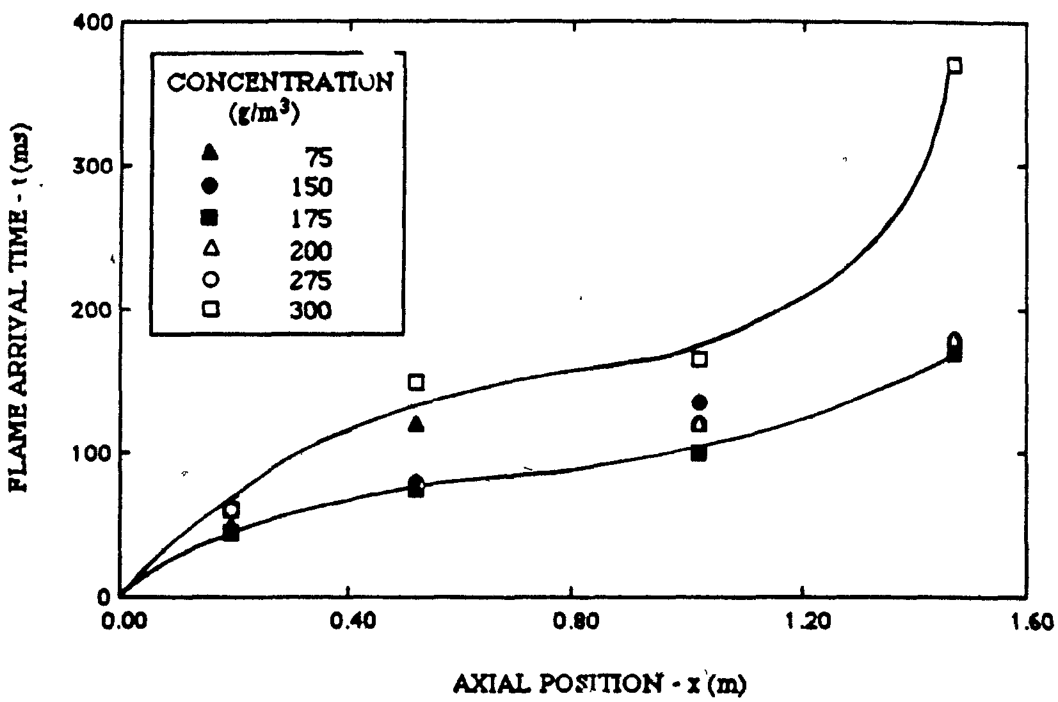


Fig. 38b. Flame arrival time as a function of distance travelled in the closed vertical tube for downward propagating cornstarch dust-air flames.

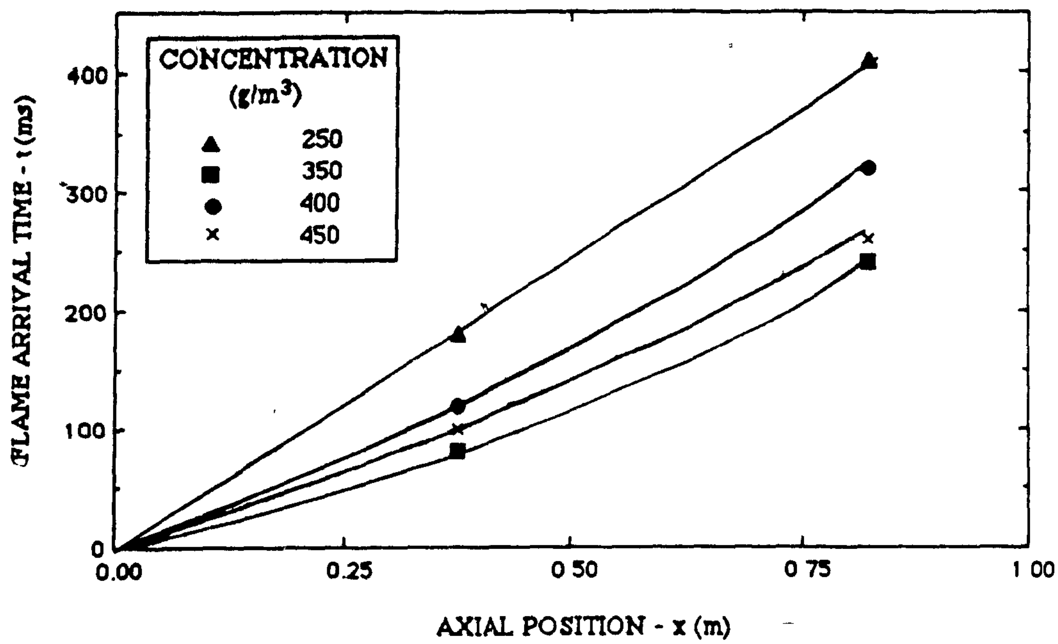


Fig. 39a. Flame arrival time as a function of distance travelled in the closed vertical tube for upward propagating Lingan 10-E coal dust-air flames.

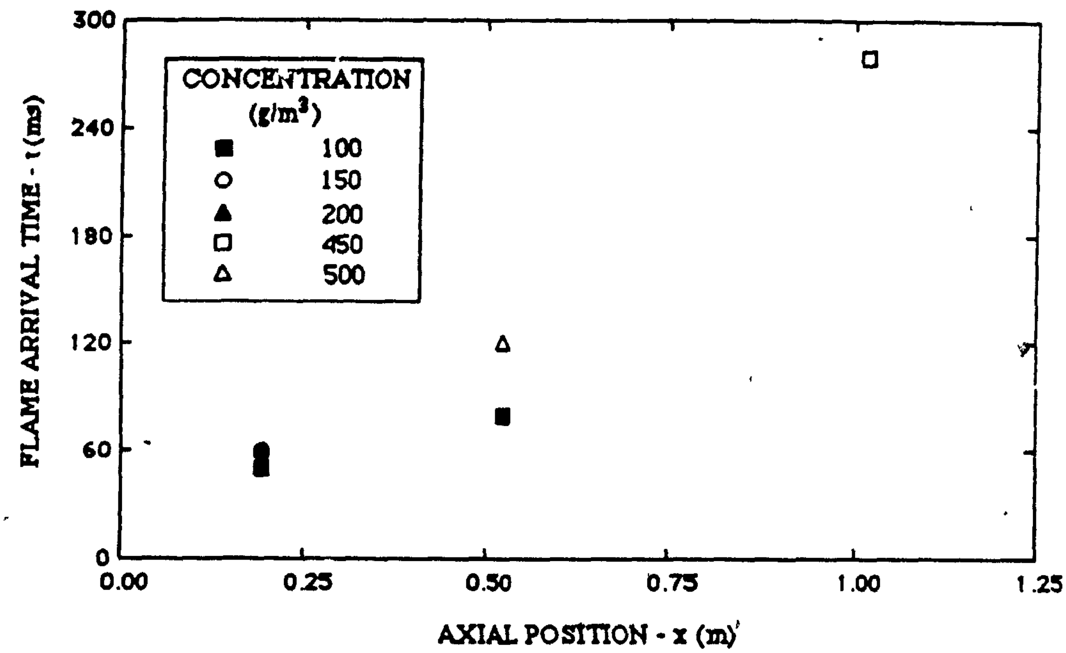


Fig. 39b. Flame arrival time as a function of distance travelled in the closed vertical tube for downward propagating Lingan 10-E coal dust-air flames.

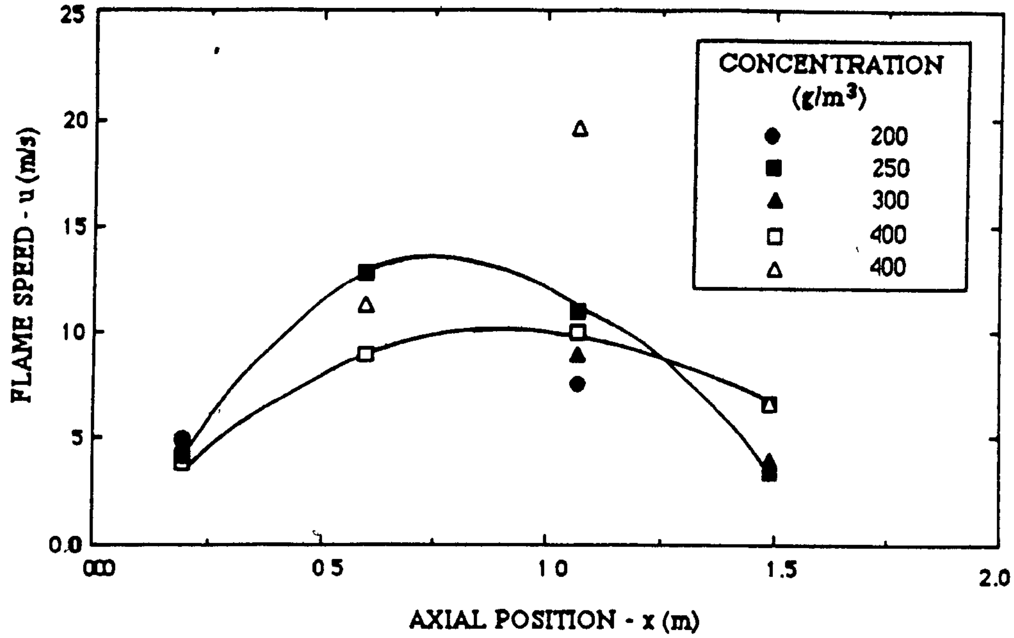


Fig. 40a. Flame speed as a function of distance travelled in the closed vertical tube for upward propagating cornstarch dust-air flames.

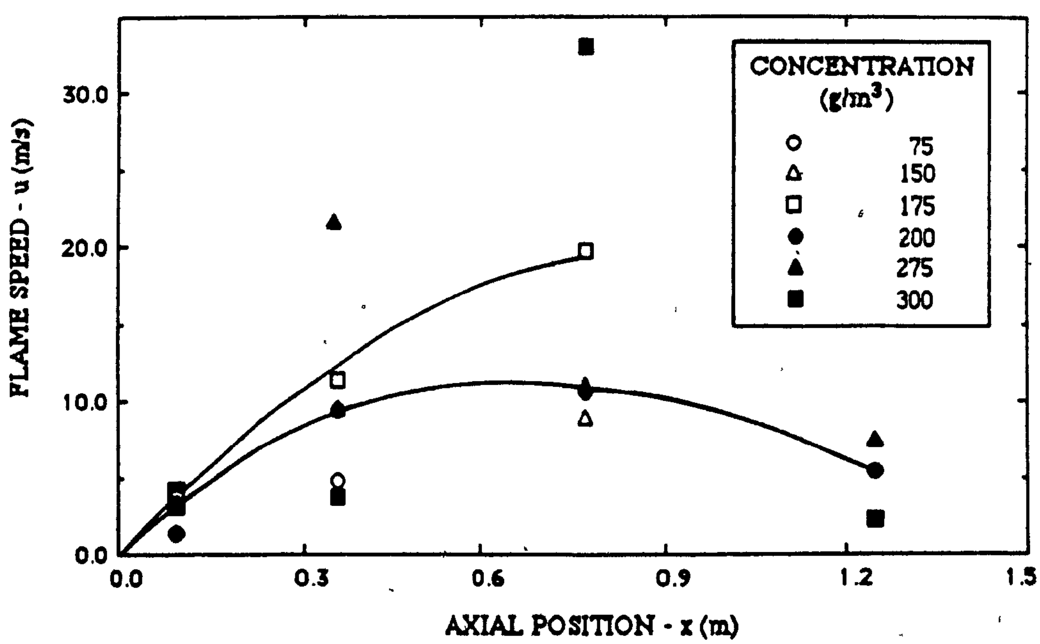


Fig. 40b. Flame speed as a function of distance travelled in the closed vertical tube for downward propagating cornstarch dust-air flames.

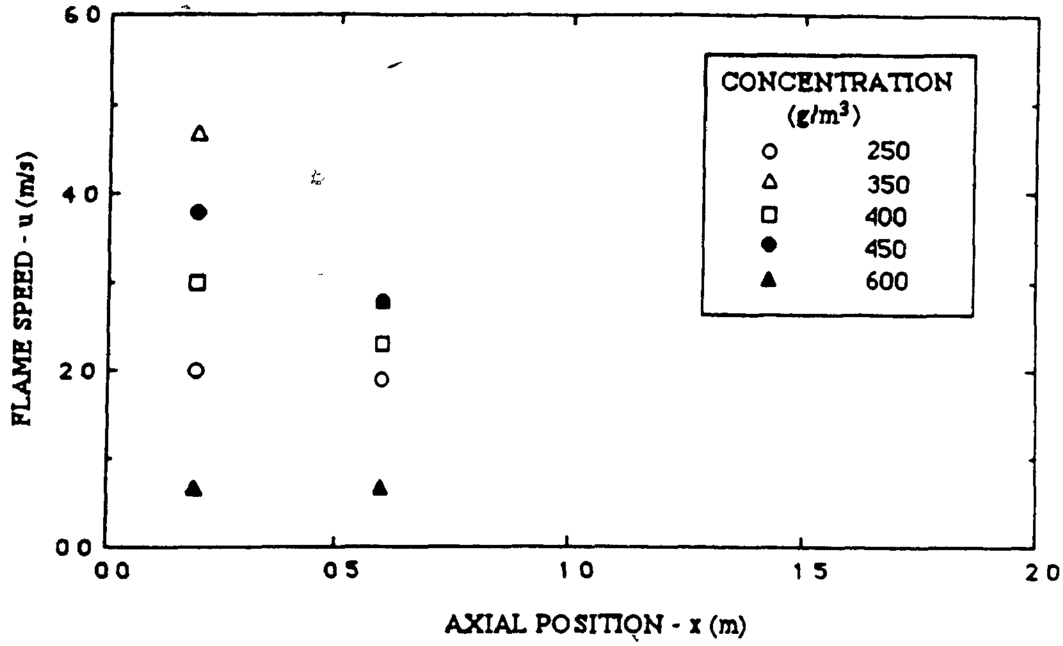


Fig. 41a. Flame speed as a function of distance travelled in the closed vertical tube for upward propagating Lingan 10-E coal dust-air flames.

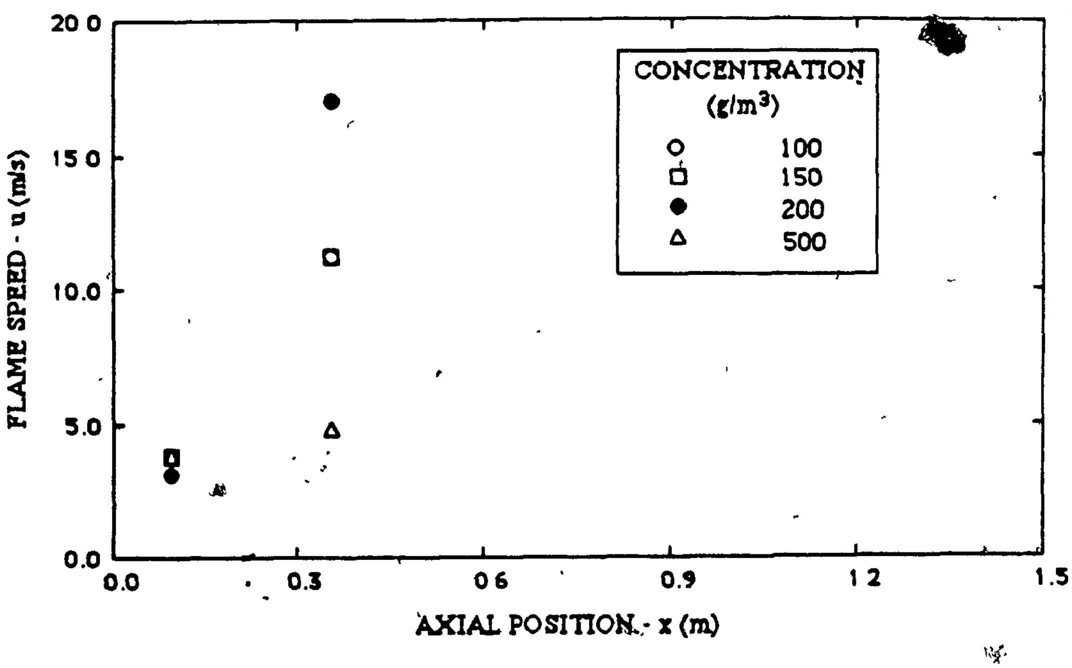


Fig. 41b. Flame speed as a function of distance travelled in the closed vertical tube for downward propagating Lingan 10-E coal dust-air flames.

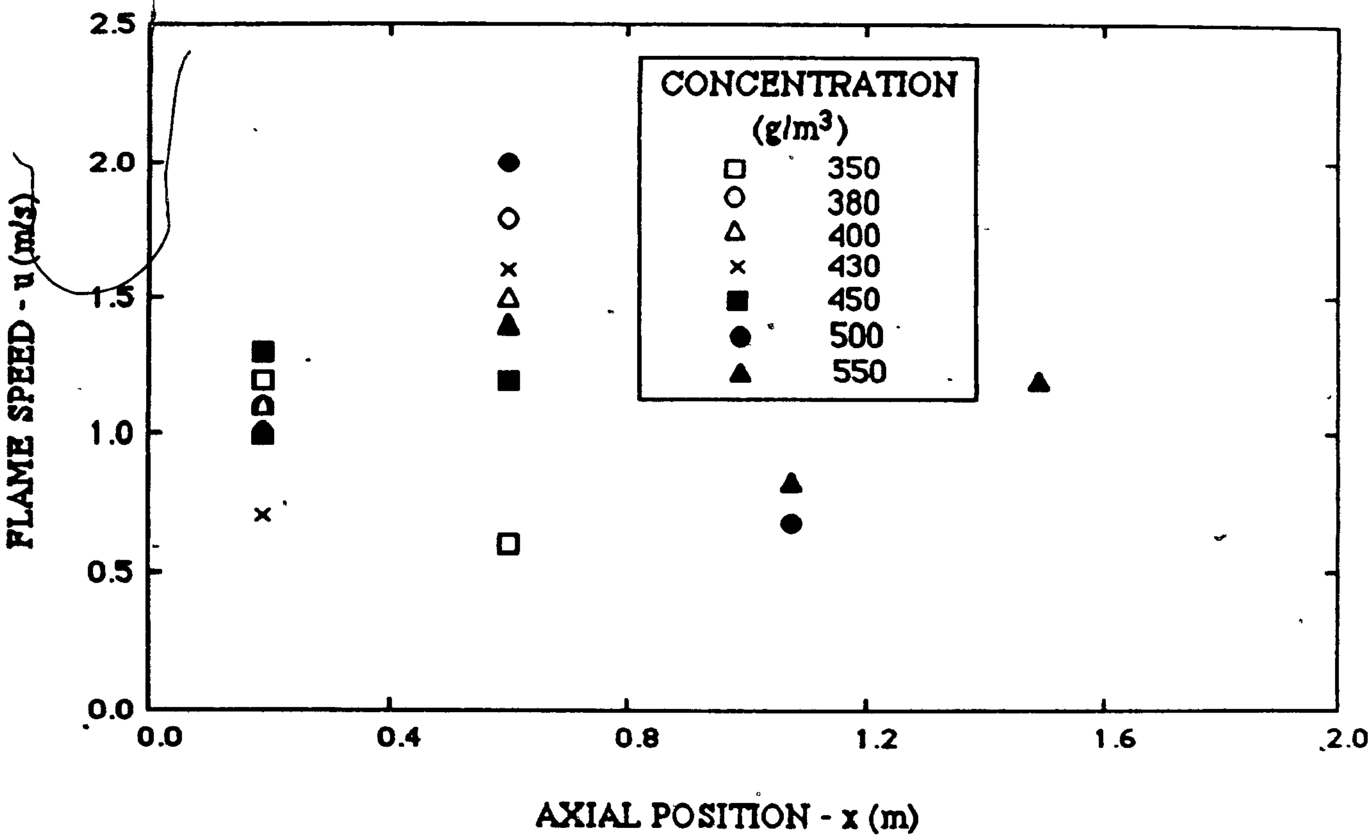


Fig. 42. Flame speed as a function of distance travelled in the open vertical tube for upward propagating cornstarch dust-air flames.

TABLE 1

Relative position of ionization probes with direction of flame propagation

	Distance between probes (cm)			
	ignitor to 1st probe	1st to 2nd probe	2nd to 3rd probe	3rd to 4th probe
UPWARD DIRECTION	37.5	45.0	49.5	33.5
DOWNWARD DIRECTION	19.0	33.5	49.5	45.0

TABLE 2

Properties of cornstarch dust

Chemical formula	$(C_6H_{10}O_5)_n$
Mole weight of monomer	162
Density	1.5×10^3 kg/ m^3
Particle size	14.7 μm average (5.1 μm standard dev.)
Volatile content	90% or above
Theoretical stoichiometric concentration	253.7 kg/m
Heat of combustion	2.64×10^3 kJ/mole
Heat of formation	928 kJ/mole
Higher heating value	2.84×10^6 kJ/mole
Ignition temperature	650 - 750 ^{0}K

TABLE 3

Optimum ignition delay time for each dust fuel tested in the 180 L cylinder

Dust fuel	Optimum t_D (ms)
cornstarch dust	200
Devco Lingan 10-E coal dust	100
Devco No. 26 coal dust	300

TABLE 4

Constant volume lean flammability limits of cornstarch dust and Lingan 10-E coal dust for different ignition delay times

Ignition delay time (ms)	Cornstarch dust-air lean limit (g/m^3)	Lingan 10-E coal dust-air lean limit (g/m^3)
100	–	40
200	75	50
300	80	60
400	80	60
500	80	70
600	95	90

TABLE 5A)

Lean cornstarch dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 200 ms)

Concentration (g/m^3)	Δp_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
70	10.7	96
75	18.8	179
75	33.8	146
75	57.9	106
75	9.6	73
80	47.5	101
80	>67.5	257
80	14.5	118
90	>67.2	403

TABLE 5B)

Lean cornstarch dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 300 ms)

Concentration (g/m^3)	ΔP_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
70	16.1	149
75	14.5	112
80	22.0	134
80	>27.0	224
80	18.7	179
80	>37.6	112
80	17.5	134
85	25.5	158
90	24.2	149
90	11.4	81
90	16.1	154
90	18.6	121
95	>48	246
100	>48	336

TABLE 5C)

Lean cornstarch dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 400 ms)

Concentration (g/m^3)	ΔP_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
60	14.5	189
65	12.4	134
70	17.0	269
80	22.7	134
80	13.1	137
90	15.2	96
95	20.7	269
100	>43.0	149

TABLE 5D)

Lean cornstarch dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 500 ms)

Concentration (g/m^3)	ΔP_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
80	28.0	298
80	49.0	336
80	14.7	168
85	25.7	298
85	15.2	168
90	28.3	224
90	21.5	192
95	49.7	269

TABLE 5E)

Lean cornstarch dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 600 ms)

Concentration (g/m^3)	ΔP_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
80	14.8	101
90	13.4	101
95	56.4	101
95	17.5	76
100	39.3	112

TABLE 6A)

Lean Lingan 10-E dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 100 ms)

Concentration (g/m^3)	ΔP_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
30	12.1	134
30	18.8	272
40	24.2	217
40	22.7	348
50	52.4	361

TABLE 6B)

Lean Lingan 10-E dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 200 ms)

Concentration (g/m^3)	Δp_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
40	14.8	137
45	14.8	156
50	30.3	192
50	36.5	242
55	53.1	228
60	21.5	201

TABLE 6C)

Lean Lingan 10-E dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 300 ms)

Concentration (g/m^3)	Δp_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
50	16.1	122
50	17.9	168
60	25.5	235
60	17.2	154
60	24.2	242

TABLE 6D)

Lean Lingan 10-E dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 400 ms)

Concentration (g/m^3)	ΔP_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
55	18.9	112
60	22.7	118
70	34.5	142
120	>83.0	285

TABLE 6E)

Lean Lingan 10-E dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 500 ms)

Concentration (g/m^3)	ΔP_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
50	14.8	101
60	16.5	78
70	21.5	168
70	13.1	78
70	21.5	90

TABLE 6F)

Lean Lingan 10-E dust-air results in the 180 L cylinder at different ignition delays (ignition delay : 600 ms)

Concentration (g/m^3)	ΔP_{max} (kPa)	$(dp/dt)_{max}$ (kPa/s)
70	16.1	192
70	20.1	192
80	18.8	269
90	20.7	299
90	16.1	189
90	18.8	224

TABLE 7

Lean flammability limits in cornstarch dust-air mixture under constant volume

Source	Lean flammability limit (g/m^3)
Present 180 L	75-80
Gaug et al. 500 L [36]	70
Jacobson et al. 1.2 L [3]	40
Theoretical [7] (based on estimated heating value)	103

TABLE 8

Select properties and lean flammability limit data of different coal dust samples

Coal dust sample	Nominal particle size (μm)	Proximate analysis (%)				Heating value (MJ/kg)	Measured lean limit (g/m³)	Theoretical lean limit (g/m³)
		Moisture	Volatiles matter	Fixed carbon	Ash			
Devco Lingan (pesent 180 L)	44 *	0.84	32.73	52.99	13.44	30.7	40	59
Devco No. 26 (present 180 L)	70 *	0.70	32.09	62.74	4.47	26.5	40	68
Devco No. 26 (1.2 L [40)	70 *	0.70	32.09	62.74	4.47	26.5	67	68
Pittsburgh (7.8 L [19])	7-9	1.4	33.6	55.8	9.2	30.6	130	59
Pittsburgh (20 L [24])	7-9	1.4	33.6	55.8	9.2	30.6	90	59
Gilsonite (7.8 L [19])	22-26	0.5	85.4	14.0	0.2	41.3	65	44
Pocahantas (7.8 L [19])	20-40	1.2	16.2	75.4	7.2	33.4	230	54
Reading (7.8 L [19])	3-5	0.9	6.6	83.3	9.2	30.7	450	59

* largest particle size

TABLE 9

Constant pressure upward propagation in a cornstarch dust-air mixture (400 g/m^3) at different ignition delays

Time delay between dispersion & ignition (ms)	Flame speed between probes (m/s)			
	ignitor to 1st probe	1st to 2nd probe	2nd to 3rd probe	3rd to 4th probe
60	1.3	1.5	0.4	–
100	1.2	0.5	1.2	–
100	0.7	1.3	0.8	–
150	0.8	2.2	0.8	–
200	1.1	1.6	–	–

TABLE 10

Constant volume upward propagation results in the vertical tube for cornstarch dust-air mixture

concentration (g/m³)	Δp_{max} (kPa)	(dp/dt) (kPa/s)	Flame speed between probes (m/s)			
			ignitor to 1st probe	1st to 2nd probe	2nd to 3rd probe	3rd to 4th probe
50	36	262	–	–	–	–
75	54	420	6.0	–	–	–
100	>48	517	4.7	–	–	–
100	85	572	3.4	–	–	–
200	299	1316	5.0	12.8	7.6	–
250	356	1743	4.2	12.8	11.0	3.4
300	399	1640	5.0	12.8	9.0	4.0
400	526	2564	3.8	9.0	10.0	6.6
400	513	2756	4.7	11.3	19.5	6.6

TABLE 11

Constant volume downward propagation results in the vertical tube for cornstarch dust-air mixture

concentration (g/m^3)	Δp_{max} (kPa)	(dp/dt) (kPa/s)	Flame speed between probes (m/s)			
			ignitor to 1st probe	1st to 2nd probe	2nd to 3rd probe	3rd to 4th probe
75	59	572	3.8	4.8	–	–
150	188	1564	4.2	9.6	9.0	–
175	252	1723	4.2	11.3	19.8	–
200	284	1413	3.8	11.3	12.4	7.5
275	406	1978	3.2	22.5	11.0	7.5
300	>324	–	3.2	3.8	33.0	2.2

TABLE 12

Constant volume upward propagation results in the vertical tube for Lingan 10-E coal dust-air mixture

concentration (g/m^3)	Δp_{max} (kPa)	(dp/dt) (kPa/s)	Flame speed between probes (m/s)			
			ignitor to 1st probe	1st to 2nd probe	2nd to 3rd probe	3rd to 4th probe
15	45	55	–	–	–	–
25	59	482	–	–	–	–
40	61	448	1.9	–	–	–
40	71	682	5.0	–	–	–
150	57	283	5.4	–	–	–
150	57	407	4.7	–	–	–
250	158	165	2.0	1.9	–	–
350	207	234	4.7	2.8	–	–
400	90	152	3.0	2.3	–	–
450	179	193	3.8	2.8	–	–
600	143	131	0.67	0.67	–	–

TABLE 13

Constant volume downward propagation results in the vertical tube for Lingan 10-E coal dust-air mixture

concentration (g/m^3)	Δp_{max} (kPa)	(dp/dt) (kPa/s)	Flame speed between probes (m/s)			
			ignitor to 1st probe	1st to 2nd probe	2nd to 3rd probe	3rd to 4th probe
40	44	365	3.8	–	–	–
40	54	620	3.8	–	–	–
100	79	792	3.8	11.2	–	–
150	100	496	3.8	11.2	–	–
200	86	951	3.1	17.0	–	–
300	85	565	3.8	–	–	–
450	114	469	3.8	–	–	–
500	79	83	3.8	4.8	–	–