AN EXPERIMENTAL STUDY OF HYBRID EXPLOSIVE DUST-GAS-AIR MIXTURES

by

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ABSTRACI

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This thesis reports on an experimental investigation into hybrid dust-gas-air explosions. The objective is to elucidate the major role of admixed methane, when present at different concentrations. λ long horizontal tube constant volume bomb was developed with a novel dust dispersal system for studying explosions in this geometry . Experiments were conducted with fine cornstarch dust, methane and hydrogen gases. The burning rates and maximum explosion pressures for various hybrid compositions are compared to those obtained from single component mixtures. Admixed inflammable gas is found to increase the explosivity of lean mixtures by increasing the total mixture energetics and improving uniform burning throughout the bomb. Increased flame temperature associated with more energetic mixtures increases the chemical kinetic processes which control the burning rate. The chemistry of the admixed gas is found to have an impact on the starch combustion. Excess dust in rich mixtures is shown to act as a thermal sink, similar to inert dusts. Lean explosivity limits were investigated for cornstarch-methane and found to be in line with Le Chatelier's rule. Particle settling can influence propagation in very lean mixtures and those with excess dust.

RESUME

Cette thèse rapporte une recherche expérimentale les explosions hybrides des mélanges poussière-gaz-air. L'objectif de cette thèse est d'élucider le rôle majeur du inflammable, lorsque présent 2 differentes gaz concentrations. Une bombe à volume constant, dont la forme est celle d'une long tube horizontal, a été développée avec un 'nouveau système de dispersion de poussière. Des experiences ont été faites avec de la fine poussière d'amidon, ainsi qu'avec lez gaz méthane et hydrogène. Les taux de combustion et préssions maximales pour differents compositions hybrides sont compares a ceux obtenus pour des mélanges a composition simple. L'addition d'un daz mélange poussière-air a **ffet** vinflammable au poùr d'augmenter l'explosibilité des mélanges pauvres ` en augmentant le pouvoir calorifique du melange et en causant combustion uniform dans la bombe. Une température de flamme augmentée ensemble des mélanges plus énérgetiques accélère les processes cinétiques chimiques qui controllent le faux de combustion. La composition chimique du gaz ajouté affecte la combustion de l'amidon. On démontre qu'un excès de poussière dans un mélange gazeux riche agit comme absorbant thermique, de la même façon qu'une poussière inerte. Des limites d'éxplosivité pour des mélanges maigres . d'amidon et de méthane suivait la règle de Le Chatelier. La précipitation des particules peut influencer la propagation dans les mélanges très maigres et dans les melanges avec un excès de poussière.

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NOMENCLATURE

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A	Area, cross sectional area, [m]
ć	Specific heat capacity, [kJ/kg-K]
Ć	Frequency factor in equation 10, [1/sec]
đ	Diameter, [m or µm]
E	Activation energy, [kcal/mol]
Ġ	Gas concentration, volume fraction
H	Q , heat transfer to particle, [W] abs
h	Enthalpy
h _f **	Enthalpy of formation at 298 K, [kJ/kg]
. ^{Ah} r	Enthalpy of reaction, [kJ/kg]
k .	Conductivity, [W/m-K]
L	Length, [m]
ň	Mass flow rate, [kg/s]
N	M /M, molar ratio of products to reactants
P	Pressure, [bar]
P e	Absolute explosion pressure, [bar]
, p _e	Gauge explosion pressure, [bar]
Pe	p /p , normalized explosion pressure
Pe	(p -p)/p , normalized explosion pressure
, Q .	Rate of energy production, [kW]
Q _{abs}	Rate of heat transfer to particles, [kW]
R	Gas constant, [kJ/kg-K]
Řf	Flame speed relative to stationary observer, [m/s]

S Burning velocity relative to unburned gas, [m/s]
T Temperature, [K]
.V Volume, [m³]
W Dust concentration [g/m³]
x Distance, [m]

Density, [kg/m³]

 α Thermal diffusivity, $[m^2/s]$

and the state of the

τ Ratio of specific heat capacities

 μ Viscosity, $[m^2/s]$

• Equivalence ratio-of combustible mixture

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f Time constant, [s]

5 Thickness, [m]

Subscripts

ad Adiabatic

Al Alumina

b Burnéd gas

C.S. Cornstarch

e Constant volume explosion

Constant pressure flame

Laminar 🗤 🖉

o Initial or normalizing value

p Particles

u Unburned gas

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I. INTRODUCTION

When an explosion occurs in an environment containing. combustible dusts and flammable gases, it is called a Hybrid Explosion. It is now generally recognized that the potential hazard of a hybrid explosion can be greater than that of the individual components. The coal mining industry was the first to recognize this when it was realized that small amounts of methane gas, "known as "firedamp", greatly enhanced the violence of an ensuing coal dust explosion. As the demands for energy continue to increase, coal mining has shifted from shallow mines to deeper ones, with the result that they are increasingly "gassy". Although laws generally prohibit the buildup of flammable gas concentrations beyond fifty percent of the lower flammability limit, gases are still present in small amounts and contribute to the explosion hazard.

Other industrial facilities which encounter the risk of hybrid explosions include large scale refuse incinerators for energy production, in which refuse derived dusts can explode along with vapours from discarded containers in the primary shredder machines. In the plastics industry powdered plastics are often stored near solvents during transportation. Hybrid explosions occur in the grain industry when extraction plants are located too close to grain silos. Typical examples of inflammable mixtures include: hexane with soya bean meal, pentane with styrene and polystyrene, vinyl chloride with polyvinyl chloride (PVC) and cyclopentane with wood.

Industrial facilities are not designed to withstand the pressures developed by even weak dust explosions. Thus these places are equipped with various types of explosion

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mitigation schemes of which the three most common are: relief venting, chemical explosion barriers, and high speed valves to isolate the explosion in the pressure vessel in which it originated. To effectively design an explosion protection scheme based on any of these techniques it is essential to anticipate the potential overpressure and the burning rate as well. It would be impossible to develop an explosion severity database for all possible combinations of hybrid mixtures, hence fundamental knowledge of the mechanisms of turbulent hybrid flame propagation is required to assess potential hazards.

In premixed gaseous flames the laminar flame speed, the lower flammability limit and the quenching diameter are the fundamental parameters which characterize the explosivity of a particular gas, and have been firmly established for many mixtures. Furthermore, the constant volume explosion pressure is directly related to mixture energetics and can be readily calculated. However these parameters are difficult to establish for dust-air mixtures [1,2]. First, dust air mixtures are turbulent by nature; turbulence is required to maintain particles in suspension against the pull of gravi-'ty. Second, local particle concentrations ahead of the flame are generally not known. Third, equilibrium calculations for dust-air and hybrid mixtures are more difficult because complete oxidation of dust particles does not always occur and is generally dependent upon rate processes (diffusion, kinetics etc.). Ballal [3] solved the first problem by way of a free falling flame tube, however particle concentrations are not measured properly. The author does show that smaller particles are more influenced by admixed gas than are large particles, and attributes this to the dominant role of chemical kinetics with small particles. These results agree at least qualitatively with data from flat flame burners [4].

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Explosivity data based on studies in constant volume bombs [5,6,7,8,9], laminar flame burners [4] and flame tubes [3,10,11] have demonstrated that the explosion pressure and burning rate are augmented when small quantities of flammable gas are present in the atmosphere. However the extent of this augmentation is difficult to quantify. Because the explosion characteristics of dust-air mixtures are highly apparatus dependent, the effect of admixed gas must always be studied in a relative context. Widely varying experimental conditions (size of vessel, mixture composition, initial turbulence etc.) amongst investigators make comparisons very difficult. Hence the relative effects of admixture of gas upon total mixture energetics and burning rate are not known.

In an explosion in a long channel, the flame may accelerate rapidly resulting in very high rate of pressure rise. This is the situation in mine shafts and large tubes for pneumatically conveying materials. However, most experimental research is conducted in small scale apparatus with spherical geometry or cylindrical geometry with small aspect ratio. The length of flame travel in a Hartmann bomb [7] is about 15 cm, while in the US Bureau of Mines' 7 liter bomb the flame travel is also about 15 cm. In Bartknecht's 1 m³ sphere [5], the flame travels only 62 cm. These distances are the same order as the turbulent dust flame thicknesses reported by Klemens [11], Slezak [12] and Buksowicz [13]. Hence the flame may travel only one or two flame thicknesses before being extinguished at the wall.

In the present study, hybrid explosions in a long horizontal tube are studied. Generation of a uniform dust cloud in a tube of large aspect ratio also presents difficulty. Slezak [12] attempted to rectify errors due to settling by employing a rotating tube, however this led to large uncertainties in the airborne dust concentration. Klemens ,[11]

and Buksowicz [13] employed a long vertical tube in which dust was dropped from the top by a hopper. However the tube used (#8 cm X 3 cm) is very small with respect to the flame thickness.

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For this study a novel dust dispersal system was developed to generate a uniform turbulent dust cloud prior to ignition. X wide range of hybrid mixtures was studied, including mostly dust and mostly gas mixtures. The flammability characteristics of the vessel are first discussed in relation to homogeneous methane-air explosions in order to determine the effects of heat losses and turbulence generated by the dust dispersal system. The explosivity data for cornstarch-air mixtures are compared with other investigators to establish confidence in the dust dispersal system and the experimental procedure. Furthermore this data serves as a basis for comparison with subsequent hybrid tests. -Various starch-methane-air compositions are tested to determine the maximum explosion pressures and these are compared to values predicted by equilibrium thermodynamics. Measurements of the flame speed and rate of pressure rise are used to assess the effect of gas concentration upon the burning rate. A comparison is made between the effect of combustible •and inert dusts upon rich gas flames. Thus the effect of mixture energetics upon the turbulent burning rate for gasequs, dust-air and hybrid mixtures is established.

Cornstarch-hydrogen-air explosivity is examined to determine the influence of chemistry of the admixed gas. It has previously been concluded that the influence of gases with a high laminar burning velocity are less severe than the influence of methane [5]. However if flame propagation proceeds in volatiles generated ahead of the flame front, the influence of admixed gas should be proportional to its burning velocity.

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Finally, the lean explosibility limits for hybrid mixtures are determined to assess the role of mixture energetics and the applicability of Le Chatelier's rule which was developed for homogeneous gases. Also the effect of dust settling in the long horizontal geometry is discussed.

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II. GENERAL COMMENTS

II.1 Literature Survey

Experimental investigators are generally concerned with the flammability of various hybrid mixtures. This entails lean explosibility limits, burning rate as characterized by the luminar burning velocity or rate of pressure rise in a closed vessel, and the adiabatic flame temperature or maximum explosion pressure.

Lean Flammability Limits

An explosible hybrid mixture can be formed even though the concentration of individual components are themselves below their explosible limit. Several investigators report linear, or almost linear, decrease in the "lower explosible concentration" (LEC) of dust with increasing gas concentrations. This was observed in closed vessels [5,6,7,14,15] as well as horizontal and vertical channels [10,11]. As a result Le Chatelier's rule has been applied to hybrid mixtures:

 $\frac{W}{(LEC)} + \frac{G}{(LEC)} \ge 1$ (1)

If the left hand side, where W and G are the dust and gas concentrations, is greater than unity the mixture is explosible.

Le Chatelier's rule was developed for homogeneous gases and implies a minimum energetics criterion. Measured flame temperatures for near limit coal dust flames were approximately 1600 K [20] which is similar to the characteristic temperature for lean limit hydrocarbon gas flames as proposed by Hertzberg [17] and Burgess [18]. Hertzberg [1] has correlated LEC's for various dusts with their volatile content determined from rapid pyrolysis tests. Experiments with

low and high volatile coals, polyethylene, anthracite, gilsonite and methane indicate that the heating values of the volatiles generated by the lean limit mixtures are approximately 12 kcal/mol. This value is similar to that measured for other hyrocarbons [19] and results in flame temperatures near 1600 K.

Others [15] have shown, in small and large scale experiments, that a minimum flame temperature exists but depends upon whether dust or gas is the dominant fuel. This is supported by Klemens [11], who observed vertically propagating, near limit, hybrid flames. Mixtures containing mostly gas (4.2% CH_4 , 19 g/m³ coal) had smooth laminar flame fronts and those with more dust had irregular, turbulent flame fronts characteristic of dust-air flames.

Uncertainty in these hypotheses is due to variation in reported LEC for various dusts and the lack of definite criteria for determining the LEC of a dust [20].

Explosion Severity

The explosion severity is characterized by the maximum explosion pressure and rate of pressure rise in a closed vessel. These have been studied for a variety of hybrid mixtures. It has been observed [5,6,7,9] that small amounts of admixed gas, below the lean flammability limit, can significantly enhance both the explosion pressure, P and the rate of pressure rise, dp/dt. Direct comparison of various authors' results is not possible because the results are apparatus dependent and different dust-gas combinations are used. For the same reason, theoretical predictions of dp/dt are not possible. Consequently conclusions are based upon observing the effect of altering the mixture composition.

Nagy's experiments in a modified Hartmann bomb, with a broad spectrum of coal dust and methane mixtures [6],

demonstrated that specific hybrid compositions exist whereby
Pe is a maximum and dp/dt is a maximum. These may not occur
at the same dust and gas concentrations. The authors correlated the results with polynomial expressions but these are
of limited value as they are specific to this apparatus and
are not based upon any physical principles.

Feng [7] adopted a similar approach as in [6] to determine the relative flammability of Canadian coals with different volatile contents. The experiments conducted in a Hartmann bomb reveal trends similar to those in [6]. However the magnitude of dp/dt and K_{st} factor (dp/dt.Volume^{1/3}) [5,21,22] are different. It has been established that the burning rate in the Hartmann bomb is generally lower than in larger vessels because of the low turbulence level and low ignition energy.

Bartknecht [5] performed similar tests with PVC dust and propane gas in a 1 m³ sphere. He found that the optimum propage concentration in terms of P_e is close to the lower flammability limit of propane (2% vol) whereas the maximum burning rate occurs with stoichiometric propane-air. Also Bartknecht found that when the propane concentration is increased, the optimum dust concentration, in terms of Ρ_ decreases linearly. From this latter observation, it can be concluded that the explosion pressure is connected to the energy content of the mixture. The effect upon the burning rate depends upon the relative reactivity of the dust and the gas. PVC dust burns slowly because the halogen, chlorine, inhibits chain branching. Therefore, the maximum burning rate occurs where propane itself burns most rapidly. It was also noted that less reactive. dusts are more susceptible to admixed gases than highly reactive dusts.

Peraldi [23] performed thermodynamic calculations to determine the effect of mixture composition upon a hybrid

methane-cornstarch-air detonation. The predicted effects are in good agreement with his observed results. However, no comparison of observed explosion pressures with values calculated from equilibrium thermodynamics has been done to determine if the effect of admixing gas is to alter mixture energetics or to alter the quantity of dust burned by enhancing, reaction rates, diffusion etc.

Flame Speed

Flame speed is closely related to the K_{st} factor (or dp/dt) in that both are indicators of the burning rate. For thin regular flames the flame speed can be extracted from the pressure history of an explosion in a closed vessel [21,24], which is demonstrated in Appendix II. For homogeneous gas flames the laminar burning velocity is a fundamental parameter which can be measured with reasonable accuracy [25], and in some instances it can be calculated for given initial conditions. For dust or hybrid flames the existence of a fundamental characteristic flame speed has not been proven. Several investigators [3,4,8,14,26] have produced flat laminar flames, but the flame speed depends on particle size, shape, chemistry as well as the uniformity of the cloud.

Flame speed is measured in flat flame burners and long flame tubes. Burners produce a stationary flame which simplifies probing; however, they suffer from large heat losses [1]. Open tubes of large diameter are nearly adiabatic, although it is difficult to create laminar flames. Creating a uniform dispersion is still a major stumbling block. To overcome the effects of bouyancy and particle settling Ballal [3] employed a free-falling zero-gravity flame tube in which a flat flame was produced. However this technique limits the size of the apparatus and instrumentation techniques.

The author found that finer particles were affected by admixing methane more than coarse particles. This agrees with Bartknecht's [5] bomb tests with PVC dust and Smoot's [4] flat flame burner data with 10 micron and 33 micron coal dusts. Furthermore, Smoot et al observe that coarser coal dust is more affected when the concentration is excessive $(>500 \text{ g/m}^3)$. From this the authors all conclude that the kinetically dominated combustion of fine particles is more affected by admixed gas than the diffusion controlled combustion of large particles.

Singer et al [10] measured horizontal and vertical flame speeds of several near limit coal dust-methane-air mixtures. The authors observed linearly increasing flame speeds with increasing methane content for mixtures with the same overall equivalence ratio. Mixtures with more methane also seemed to produce steadier flames, with less variation of flame speed in the vertical and horizontal sections of the tube.

Klemens and, Wolanski [11] also measured upward flame propagation for near limit mixtures of lignite-methane-air, and produced photographs of the flame structure. For mixtures in which methane dominated (4.2% CH_A , 19 g/m³ lignite) flames resemble near limit gas flames albeit more luminous. For mixtures containing more lignite $(1.6\% CH_A)$ g/m³ 66 lignite) the flames resemble pure dust flames. They have highly irregular and changing flame fronts, followed by a turbulent region of hot gas with luminous particles. The authors report greater flame speeds for those mixtures than the lean limit methane-air flame. This is attributed to increased flame surface area and mixing due to turbulence.

II.2 <u>Dust Flame Structure</u>

Modelling of hybrid flames requires knowledge about the structure of a dust-air flame. The evidence to be presented supports the hypothesis that volatiles produced in front of the flame provide the mechanism for flame propagation in clouds with fine particle size and high volatile content. This group includes bitumous coals, lignites, vegetable grains, powdered foodstuffs and plastics.

Measurements of laminar "burning velocity" of fine $(d_p \equiv 9 \ \mu m)$ coal dust-air mixtures yield inverted "U" shaped curves of velocity versus concentration typical for premixed hydrocarbon gases. Also the maximum laminar burning velocity is 33 cm/s and two other types of coal tested yielded burning velocities of 30 cm/s and 35 cm/s for identical particle size distributions. Other investigators also report laminar burning velocities for coal dusts between 20 cm/s and 70 cm/s in a variety of apparatus [3,12,13]. These are within the range of many premixed hydrocarbon gases.

Further evidence of coal dust combustion occurring in the volatiles comes from the direct observations in lean methane air burner flames by Seeker et al [27] and McLean et al [28]. Rapid exposure shadowgraphs and schlieren photographs revealed that after 2-3 msec induction period, volatiles evolve rapidly and burn vigorously for 1-2 msec, followed by a longer period during which char particles glow due to heterogeneous oxidation. Also Essenhigh and Howard [29] measured volatile content of char samples collected downstream of a stabilized coal dust burner flame. Volatile content was found to decrease slightly before the visible flame front and rapidly within it. The ratio of volatile matter to fixed carbon decreases to 18% of it original value.

Currently there is conflicting data in the literature concerning dust flame thickness. Values from 5 mm to several cm are reported for similar mixtures. This results from differences in experimental conditions and lack of clear definition of flame thickness. Some investigators refer to the entire luminous region, however, it is more appropriate to refer to the reaction zone which is significantly thinner.

Slezak [12] reports a "bushy" coal dust flame that appears 15 cm thick in his 30 cm diameter flame tube. However, thermocouple (1 mil) traces indicate that the temperature rise occurs within a region of a few millimeters which is consistent with burner flame data [4,26].

Buksowicz [13] and Klemens [11] report, for upward propagating lean lignite-air flame, temperature gradients of 7×10^6 K/s or 1000 K/mm in front of the visible flame; followed by up to 175 msec during which gas temperatures remain elevated. Based on the temperature increase, the lower density exhaust gas exits at 5 times the leading front velocity (40.7 m/s). Thus the visible zone corresponds to (5 X 0.7 m/sec) X 0.175 sec = 0.6 m which is consistent with observations.

However, the thickness of a gas flame is of the order of 0.2 mm, about 10X smaller than the 1 cm reported for dusts [30]. From thermal flame theory the minimum ignition energy, ε , is shown to be proportional to the cube of the flame thickness, δ . If the constant of proportionality is approximately the same for dust and gas, then:

 $\begin{bmatrix} \frac{\epsilon_{dust}}{\epsilon_{gas}} \end{bmatrix} \stackrel{\alpha}{=} \begin{bmatrix} \frac{\delta_{dust}}{\delta_{gas}} \end{bmatrix}^3$

t for many dust-air mixtures has been shown to be of the order of 10^{-3} , to 10^{-2} J as compared to 10^{-4} for premixed

gases. Based on these values $\delta_{dust}/\delta_{gas}$ should be of the order of $10^{1/3}$ or $100^{1/3}$ (2.1 or 4.6). Also from thermal flame theory, the laminar burning velocity, S_L , can be approximated as $S_L = \alpha/\delta$ where α is the thermal diffusivity of the gas if the reactions are assumed to take place at the flame temperature. As S_L has been shown to be of the same order as gas flames (#30-50 cm/s) then one would expect that the effective δ would also be of the same order as gas flames. Thus the actual measure of dust flame thickness might be over-estimating the effective thickness.

These results all indicate that for high volatile content dusts the flame propagates in volatiles generated in front of, or at, the reaction zone. It is therefore reasonable that the behaviour of a dust-air or hybrid flame should be similar to that of a premixed gas flame.

However, it is still uncertain the degree to which admixed gas can increase the explosion pressure and maximum burning rate. Therefore this work is aimed at determining whether admixed gas act solely in a thermal manner, ie. contributing to mixture energetics, or whether it influences the kinetic processes involved in combustion of the dust particles.

III. EXPERIMENTAL CONSIDERATIONS

III.1 Apparatus

The experiments reported in this text were conducted in a constant volume bomb in the form of a long horizontal tube (LHT). The objective was to produce a cloud of nearly uniform density throughout the vessel interior so that a one dimensional flame would be formed by igniting the mixture at one end. To minimize the effect of heat loss to the cold walls, the tube diameter was designed to be large in comparison to the flame thickness as reported by several investigators [3,8,12,13]. The tube was designed to be extended with additional sections, provided initial testing was successful.

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The tube measures 2.18 m (7 ft) long and has an internal diameter of 0.305 m (1 ft) forming an aspect ratio, $L_{/D}=7$. It is constructed of ordinary steel with 12 mm wall thickness and is flanged at both ends. At the ignition end the dust dispersal system is attached as seen in Figures 1 and 2. At the far end the tube is sealed with a blind flange equipped with a 1.9 cm ball valve leading to the exhaust duct. Both flanges are equipped with O-ring seals. There are six threaded ports located along a single longitudinal axis spaced 0.3 m apart, in which diagnostics can be mounted as well as the gas flow inlet. An additional port is located 100 mm from the ignition end, in which the igniter is mounted as

The major design challenge of the apparatus was to generate a uniform dust cloud throughout the entire tube length. An additional criterion was to generate nearly uniform turbulence. This would enhance mixing of the dust, and retain it in suspension for a longer time. The optimized system incorporates a high pressure, low volume air dispersion system. A nominal mass of dust is spread uniformly along a 5 cm X 5 cm V-channel that is 2.0 m long. The V-channel is mounted on supports 4 cm above the tube floor. The dust is dispersed by twenty impulsively started jets emerging from a perforated shock tube which runs the central axis of the LHT. The shock tube is the key to the dispersion system. It allows all twenty jets to be started simultaneously and to be of uniform strength.

The shock tube arrangement is shown in more detail in Figure 3. It consists of a high pressure driver section and a low pressure⁸ driven section mounted on either side of the ignition end pipe flange. The driven section consists of a 38 mm diameter copper tube, with twenty 4 mm holes drilled 100 mm apart. The holes are aligned so that they oppose the V-channel and the jets impinge directly on the dust. At the far end the shock tube is supported by 3 clamps to reduce vibration.

The driver section consists of a square 63 X 63 mm² tube, 0.80 m long (3.18 1) mounted on the external side of the ignition end flange. The tube has four threaded ports in which are mounted the high pressure air inlet, the high pressure fuel inlet, the pressure gauge and a pressure relief valve. The driver section is bolted to the ignition end flange by a 76 mm pipe flange with an O-ring seal and a special crimp which secures a Mylar diaphragm. The diaphragm is ruptured by a pneumatically driven steel plunger running through the driver section.

Procedure for Dispersion:

Prior to dispersion the driver section is pressurized to 10 bars containing the same gas mixture as the test volume. Upon rupturing the diaphragm the shock which is formed pressurizes the driven section and starts the jets. (The shock tube calculations are shown in Appendix I.) The shock Mach number is approximately M=1.86, and the pressure behind the initial shock is p=3.89 bar. It is doubtful that the shock is severely attenuated by the efflux of gas through the perforated tube, behind the shock. The initially unattenuated shock would traverse the tube length in less than 3 msec. The duration of the jets is of the order of 100 msec, and was calculated assuming adiabatic expansion of the high pressure gas into the low pressure shock tube. The flow through the impingement hole is choked, until the pressure in the shock tube decreases below the critical value.

In the first interval, during which the jets are sonic, the pressure in the shocked tube decreases from $p_0=5.94$ bar (equilibrium pressure) to the critical pressure, $p_{cr}=1.89$ bar $\{p_{atm}/p_{cr}=[2/(\tau+1)]^{\tau/(\tau-1)}\}$. In the second interval, during which the jets are subsonic, the pressure decreases from $p_{cr}=1.89$ bar to p=1.02 bar (equilibrium with the test vessel. The calculated duration of the jets is $t_1=61.4$ msec and $t_2=20.4$ msec hence $t_{jet}=81.7$ msec. The figure below shows an oscilloscope trace from the pressure probe mounted in the driver section. The actual duration of the jets is 100 ± 20 msec.



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Righ speed dispersion jets are essential in promoting thorough mixing of dust in air. Since the shock tube is pressurized almost instantaneously, the dispersion jets are uniform along the tube length. It is possible to use this technique with longer tubes as well. The practical tube length will be limited by shock wave attenuation or by settling of dust in the far end before the flame arrives.

Preparing the Gas Mixture:

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The gas mixture in the test section was prepared by a flow through method, displacing five to six times the volume of the vessel to ensure good mixture. The gas mixture was formed by flowing extra dry laboratory air and commercially pure methane (or hydrogen) through a pair of calibrated rotameters (Matheson #603 & #605) into a small mixing chamber then to the vessel. The vessel inlet was located 0.3 m from the ignition end of the tube, and exhausted through the far end of the tube. The mixture in the driver section was prepared by filling methane and air alternately to the appropriate partial pressures, so that the total gauge pressure equalled 9.5 bar.

Instrumentation:

Instrumentation consisted of a single PCB piezoelectric pressure transducer with very high frequency response, located at x=1.22 m where x is the distance from the ignition end. The transducer was calibrated in a shock tube and registered 73.5 mV/bar (5.0 mV/psi). Two ionization probes were located at x=0.91 m and x=1.83 m respectively. Each probe consists of two 76 mm long electrodes spaced 1 mm apart, across which was a 200 VDC potential. As the flame passes the probe, the high conductivity of the reacting gases causes a capacitive discharge and the signal is recorded on an oscilloscope. Permanent photographic records are made of the oscilloscope traces. A single piezoelectric crystal was attached to the exterior wall of the test section. Its function was to generate an electrical impulse upon rupture of the diaphragm which was used to start the timing circuitry.

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Procedure for Test:

 \sim After the dust has been loaded into the vessel and the vessel's gas mixture has been prepared, the driver section is pressurized. The test sequence begins when a remote switch is triggered, causing a solonoid valve to open and drive the pneumatic plunger into the Mylar diaphragm between the high and low pressure sections of the shock tube. This action starts the jets to disperse the dust in the vessel. in the steel, generated by the bursting The stress waves diaphragm, are registered by the piezoelectric crystal attached to the tube wall. The pulse generated by the crystal is delayed electronically, then the delayed pulse is used to trigger the ignition system. The ignition delay time was 85 msec for all experiments except where specifically noted.

After each run the tube was opened to clean out the excess dust and char. Sometimes, after several tests in a short interval the tube wall would become warm, and the inside surface adhesive. This is caused by the deposition of tars and oils during combustion of organic dusts (cornstarch, coal). When this occurred the inside of the tube was scraped down and testing would resume only after the walls had cooled down to room temperature.

III.2 Dust Properties

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In the present experiments <u>cornstarch</u> was selected for use as a combustible dust, because it has many advantageous properties; a) it is readily available in pure form and in large quantities at a reasonable expenditure; b) the particles have a regular shape and a fairly narrow size distribution with an average particle diameter near 15 μ m (microns, 10^{-6} meters); c) its chemical composition is relatively simple, and is representative of many agricultural and carbonaceous dusts, and; d) it is readily dispersable.

Figures 4 and 5 show some photomicrographs of cornstarch particles and the particle size distribution for a random sample. The particles are nearly spherical and do not appear highly porous. The mean particle size based on a frequency average is 14.7 μm and the largest particle is 30 Normally such small particles are cohesive and easily um. agglomerate making dispersion difficult. To facilitate dispersion and reduce agglomeration, the starch was dried overnight at 70 C and mixed with 1% by mass of fumed silica, (a fluidizing agent). This fluidizing agent significantly reduces the weak electrostatic forces which make the particles cohesive, and thus reduces agglomeration. In Figure 4 the cornstarch particles are shown from samples with and without the fumed silica, and in Figure 5 "the particle size distributions are shown for both samples.

Cornstarch has a simple chemical composition. It is basically a polymer of the dextrose molecule shown below. Cornstarch consists of 80% linear chain polymers (amylose), and 20% branched chain polymers (amylopectin). Typically 300 to 400 dextrose molecules form the chain. The basic chemical formula is $(C_6H_{10}O_5)_n$. The molecular weight for the basic dextrose molecule is M=162.1 kg/kmole.



III.3 Ignition System

In all experiments exploding wire ignition sources were used. Initially, the igniter used consisted of a brass wire 0.076 mm in diameter and 25 mm long, connected to a 115 VAC source. For mixtures that were more difficult to ignite, the igniter strength was augmented by wrapping ultra-fine zirconium filaments around the brass wire, to produce a flash bulb effect. The duration of this ignition source was several times longer than the brass wire alone. For all experiments, except where noted otherwise, mixtures were ignited 100 mm from the tube end, and 30 mm from the central axis. This igniter was sufficient for igniting most mixtures except near the lean limit at which point pyrotechnic devices would have been preferable. However, as the ultimate lean explosible limit was not the primary objective of these experiments, it was decided not to radically change the igniter. Although less energetic than high energy capacitive sparks, the present system was found to be preferable. The blast waves generated by short intense capacitive sparks can convect dust away from the ignition zone. If the ignition induction period is long, then energy deposited by the spark may be dissipated before the flame kernel is formed.

The ignition delay period was kept constant at 85 msec. This value leads to the most vigorous combustion of 400 g/m^3 cornstarch-air as shown in Figure 6. The ignition is delayed so that the dust cloud may be properly formed before the mixture is ignited. With excessively long delay times, the turbulence generated by the dispersion process decays, and the dust begins to settle out of suspension.

III.4 Measurement of Burning Rate

Even though there are several ways by which the explosion rate can be measured, none of them are essentially fundamental for dust explosions. For premixed flammable gases the laminar burning velocity is a fundamental property of the mixtures, dependent upon the composition and the initial thermodynamic state of the mixture. However, in most explosible dust-air environments on earth the dust is dispersed by turbulent air motion, rendering it impossible to generate a truly laminar flame as it exists for gaseous fuels. Thus, when one measures the burning rate, flame speed or any other characteristic rate one is doing so for a turbulent flame, for which the turbulence parameters are not generally known. What is measured is not really fundamental and must be considered in a relative context.

The rate of pressure rise in a closed vessel is proportional to the mass rate of consumption of fuel; hence it 18 an important parameter. The relations between dp/dt, the flame speed and burning velocity are derived in Appendix II. It is also readily obtained from the pressure history. However, as the rate of pressure rise (dp/dt) is not constant throughout the explosion, there is some arbitrariness in choosing a particular value. For spherical and nearly spherical geometries, there is a clearly identifiable maximum value of dp/dt. As the flame ball grows, the temperature and pressure of the unburned gases increases, as does the flame surface area. Near the vessel wall, increased heat losses to the wall cause the burning rate to decline. In vessels with large L/D ratios, as in the present case when the mixture is

ignited at one end, the flame kernel initially grows spherically. As it expands, some areas of the flame contact the ressel wall and are extinguished, and the flame propagates in only one direction. The characteristic pressure history reflects these changes as illustrated in Figure 7. In the present study, dp/dt was measured in the region where the flame is unidirectional. This region is also less influenced by the ignition characteristics.

To measure the actual flame speed with respect to laboratory coordinates, the distance between the two ionization probes is divided by the time interval between the signal from these probes. Thus, it is a measure of the average flame speed \dot{R}_f , at a location 1.37 m from ignition. If the flame shape is not planar then the measured value may not be a true indication of the flame speed. However, the flame speed is useful when considered relative to other tests.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

IV.1: Explosivity of Methane-Air Mixtures

(length Most dust bombs have an aspect ratio of the order of unity. However, in the present experiments the L_D ratio is seven, hence it was necessary to assess the flammability characteristics. The first tests conducted in the long horizontal tube involved premixed methane-air. The object was to study the-burning characteristics at different. compositions, the effects of turbulence generated by the impulsive jets of the dust dispersal system and the heat losses associated with the larger surface area to volume ratio of the cylinder. Figure 8 shows comparative pressure histories of 9% methane ($\Phi=0.95$) burning through a guiescent mixture and a turbulent mixture, where the jet strength and the ignition delay time were identical to those used in the later dust experiments. The turbulent burning rate is 4.5 times that of the quiescent mixture as characterized by the burnout time. Comparing the laminar burning velocity to the turbulent burning velocity as calculated from P_ and dp/dt (see Appendix II) the latter is 29 times greater, for both 7% and 9% methane. This results in reduced heat losses to the cold boundary as demonstrated by the peak explosion pressures. The turbulent flame achieves 98% of the adiabatic constant volume pressure, while the slower burning mixture achieves only 73%. All other experiments reported in this text were conducted in a turbulent environment. (

Experiments were done with successively leaner methane-air mixtures, and the resulting maximum overpressures $(P_e^{=}[p_e^{-p}e^]/p_o)$ are shown in Figure 9. The explosion pressures measured in the present experiments compare favourably with those from the 8 1 modified Hartmann bomb [12]. This demonstrates that the correct compositions were obtained in the present tests, and that the thermal

losses are not excessive. For the more energetic mixtures the observed P is close to the adiabatic value but the discrepancy broadens for leaner mixtures. The burnout time, (time from ignition to 95% peak pressure), for different mixtures and the relation between the burnout time and the heat loss can be seen in Figures 10a) and 10b). The burnout time increases in an exponential manner from '0.11 sec to 0.41 sec at 6% methane, where the heat loss is 18%. The observed burnout times are approximately 18 times shorter than the calculated values based upon the laminar burning velocity (Appendix II), however the trends are similar. Thus despite the large surface area to volume ratio, the heat lost to the cold walls by the hot gases is small, except for very lean near limit mixtures which burn slowly. Here, the relative heat losses are much greater.

The observed lean limit in the present apparatus is 6% methane which is slightly higher than the horizontal propagating limit (5.38%) [19], and that measured in the 8 1 bomb. This is probably due to the strong turbulent motion from the dispersion jets quenching the very lean flame kernel.

Figure 11 shows the measured rate of pressure rise (dp/dt) for the present tests. The results are expressed as K_{st} factor, which is defined as the maximum rate of pressure rise multiplied by the vessel Volume^{1/3}. The maximum K_{st} observed here is approximately 115 bar-m/s which corresponds to dp/dt=200 bar/s (Volume^{1/3}=0.571 m). The maximum rate of pressure rise occurs near the end of the tube where precompression of the unburned gases is greatest. Even with constant burning velocity the mass burning rate increases because of the increasing density of the unburned gases ahead of the flame. The observed rate of pressure rise increases with concentration to a maximum near the stoichiometric. For homogeneously premixed gases the burning rate is a function of the flame temperature. According to the thermal flame theory the laminar burning velocity and the flame temperature are related in the following manner:

$$S_{L} = \frac{R T_{f}^{2}}{E \cdot (T_{f} - T_{o})} \sqrt{2C \alpha \exp(-E/RT_{f})}$$
(2)

In the above equation T_f and T_b are the flame and initial gas temperatures, α is the thermal diffusivity of the gas, R is the univeral gas constant, C is a frequency factor and E is some global activation energy. Using a value of E=20 kcal/mol, typical for hydrocarbon gases and C=18 s⁻¹ with α evaluated at a mean temperature, the above equation recovers, within 2%, the accepted values for the laminar burning velocities of methane-air as reported by Bradley et al [25]. The adiabatic flame temperatures were calculated with a general chemical kinetics equilibrium code [31].

The validity of using the laminar burning velocity to relate the effect of flame temperature for highly turbulent explosions can be demonstrated by comparing changes in the calculated laminar burning velocity with the observed changes in dp/dt and \dot{R}_{f} when the mixture composition is altered. In the table below, the burning rates $S_{L'}$ dp/dt and \dot{R}_{f} are normalized against the value for a 9% methane-air flame denoted by the subscript "o". The ratio of the burning velocities is given by:

$$\frac{S_{L}}{S_{Lo}} = \frac{T_{f}^{2}}{T_{f}^{2}} \frac{[T_{fo}^{-}T_{o}]}{[T_{f}^{-}T_{o}]} \sqrt{\exp(\frac{E}{RT_{fo}^{-}} - \frac{E}{RT_{f}^{-}})}$$
(3)

Note that equation (3) is independent of the frequency factor and α in equation (2).

, [METHANE	FLAME TEMP.	SL	(dp/dt)	Ŕ _f
	[* vol]	[Κ]	SLO	(dp/dt)	Řfo
F			• •	ę ,	•
	9	2135	1.0	1.0	1.0
	8	1982	0.75	0.80	0.88
	7	1805	0.51	0.27	0.55
	6	1616	0.31	0.14	0.29

In general the agreement is quite good considering the sensitivity of the burning rate to the turbulence intensity and ignition source both of which can fluctuate, as well as the simplicity of the analysis. Thus the turbulent burning velocity scales approximately with the laminar burning velocity. As seen in Appendix II the turbulent burning rate is approximately 30 times greater than the laminar burning velocity.

These gas flame experiments will form a basis against which further experiments with dust-air and hybrid mixtures can be compared. They also demonstrate the strong dependence of the burning rate upon the mixture composition. Furthermore, the influence of the turbulence generated by the dispersion jets upon the burning rate of a gas flame has been shown.

IV.2 Calculation of Explosion Pressures

Thermodynamic Analysis of Cornstarch-Air Combustion:

The adiabatic flame temperature $T_{f,ad}$ and the adiabatic constant volume explosion pressure, $\overline{P}_e^{=P}e/p_o$, can be calculated from equilibrium thermodynamics. Complete combustion of one mole of cornstarch, $C_6H_{10}O_5$, in air (79% N₂ and 21% O_2) is:

$$c_{6}A_{10}O_{5} + 6O_{2} + 22.57N_{2} ---> 6CO_{2} + 5H_{2}O + 22.57N_{2}$$

The density of air at standard temperature and pressure $(T_0=298 \text{ K}, P_0=0.101 \text{ Mpa})$ is $\rho_0=1.180 \text{ kg/m}^3$. The stoichiometric starch concentration is formed with

$$W_{s} = \rho_{o} \times \frac{M_{C.S.}}{6M_{O2} + 22.57M_{N2}} = 232 \text{ g/m}^{3}$$

where M is the molecular weight. The heat of formation of cornstarch has been measured by Peraldi [23] to be:

 $h_{f,CS}^{\star} = -929 + 40 \text{ kJ/mol.}$

The adiabatic isobaric flame temperature is found by equating the enthalpy of the reactants at atmospheric temperature to the enthalpy of the products at flame temperature:

$$\begin{array}{r} {}^{\star} {}^{\star} {}^{\rm hf}_{\rm f,C.S.} + {}^{\rm 6h} {}^{\star}_{\rm f,02} + 22.57 {}^{\star}_{\rm f,N2} ----> 5 ({}^{\star}_{\rm f,H20} + {}^{\star}_{\rm hH20}) + \\ {}^{\rm 6} {}^{\rm (hf}_{\rm f,C02} + {}^{\rm Ah}_{\rm C02}) + 22.57 ({}^{\star}_{\rm f,N2} + {}^{\rm Ah}_{\rm N2}) \\ \end{array}$$

where $h_{f,}^{\pi}$ is the heat of formation at $T_{O}=298$ K, and Ah is the increase in enthalpy from 298 K to T_{f} . T_{f} is then found iteratively.

The heating value (Δh_r) of cornstarch is therefore:

Δh_{r,C.S.} = 2643 kJ/mol = 16,303 kJ/kg

where:

$$h_r = \Sigma h_{f,products} - \Sigma h_{f,reactants}$$

= $\Sigma h_{products} [T_f - 298 K]$

The maximum calculated flame temperature for cornstarch is T_f =2060 K at stoichiometric, which is very close to the maximum flame temperature for most simple hydrocarbons. The temperature, pressure, and molar ratio for rich starch-air mixtures were calculated assuming products of combustion as determined in reference [23].

The constant volume combustion temperature can be inferred from T_{f} by equating the change in specific enthalpy to the change in specific internal energy. Therefore,

$$\mathbf{T}_{e} = (\mathbf{T}_{f} - \mathbf{T}_{o}) \cdot \mathbf{T}_{b} + \mathbf{T}_{o}$$
 (5)

where τ_b is the ratio of the specific heats of the burnt gases. For the temperature range of interest 1500<T<2600 K, 1.20< τ_b <1.30 and can be approximated within 4% as τ_b =1.464-1.119x10⁻⁴xT[K].

The constant volume explosion pressure is estimated from the constant volume explosion temperature assuming perfect gas behaviour:

(4)

(6)-
where $[M_p/M_r]$ is the ratio of the number of moles of products to reactants (N). For cornstarch-air mixtures N increases from 1.0 to 1.175 for stoichiometric mixtures.

The predicted explosion pressures for different starch-air mixtures are shown in Figure 12, along with the present experimental results and those from other investigators.

Thermodynamic Analysis of Hybrid Combustion:

Equilibrium calculations for adiabatic flame temperature are analogous to those for starch-air mixtures. For the present analysis both fuels are treated identically, except cornstarch is considered as a solid, and its specific volume is negligible compared with the gases. The heating value for methane is:

 $\Delta h_{r,CH4} = 802.7 \text{ kJ/mol} = 50,167 \text{ kJ/kg}$

measured at \mathring{T}_{a} =298 K for the reaction '

 $CH_4 + 20_2 + 7.52N_2 \longrightarrow CO_2 + 2H_2O + 7.52N_2$.

It can be seen that the heating value of starch is approximately 3.3X that of methane on a molar basis and 1/3X that of methane on a mass basis. Therefore the energy released by burning 40 g cornstarch is almost equivalent to 13 g (2% vol) of methane in equal quantities of air.

Adiabatic calculations do not consider heat losses and extinguishing phenomena, hence flame temperatures can be predicted lower than 500 K. However these temperatures are not observed. The minimum flame temperature associated with the lean flammabililty limits for hydrocarbons is approximately 1600 K [1].

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IV.3 Explosivity of Cornstarch-Air Mixtures Comparison with other investigators:

Extensive tests were conducted with cornstarch at various concentrations. The object was to ascertain the explosion characteristics of dust-air mixtures to form a basis for comparison with the hybrid results. It is important that the long horizontal tube yield results that are valid and reproducible. This is done by demonstrating that the present results are compatible with other investigators'.

The maximum explosion pressures $(P_e^{=}(p_e^{-p_o})/p_o)$ for starch-air mixtures, as measured in the present study are shown in Figure 12. Also shown are the explosion pressures observed by Bond [32], Cocks [33] and Nagy [21] in a 333 liter sphere, 20 liter sphere and a 1.2 liter Hartmann bomb respectively. The present results generally agree with these, despite differences in the physical properties of the fuel and configurations of the apparatus. Each investigator employed a unique dust dispersal system. The concentrations quoted are based on the nominal quantity of dust-loaded into the system divided by the volume of the vessel. The most adiabatic vessel in the above comparison is the 333 1 sphere, having the smallest surface area to volume ratio, yet the P from the long horizontal tube are comparable except at very high concentrations. This indicates that the present dust dispersal system is adequate. Bond [32] (333 1 sphere) and Nagy [21] (1.2 l Hartmånn' bomb) report consistent explosions with concentrations between 100-125 g/m³ which were not observed the present tests. Differences in the lean explosible limit arise from differences in the following: (i) ignition sources, (ii) turbulence levels at the time of ignition caused by the different dispersion mechanisms. The results are consistent up to 500 g/m³. Bond reports increasing P_a up to 800 g/m³,

probably as a result of the longer settling time in the 333 1 sphere and different initial turbulence levels from different dispersion systems.

<u>Comparison with predictions:</u>

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Ideally, P_e for an adiabatic explosion is a function of mixture energetics alone. In real explosions however, boundary conditions will be important. Non-uniformity in the cloud density, thermal losses to the boundary, and rate limiting kinetic and/or diffusion processes within the particle will affect the quantity of energy released. From Figure 12 the following may be observed.

a) The predicted pressures are higher than the measured values from any of the investigators.

b) The maximum P_e is predicted to occur with a near stoichiometric mixture (232 g/m^3) whereas it is ob-'served at much higher concentrations, $500 < W < 700^{\circ} g/m^3$. c) The observed value of P_e with 200 g/m^3 starch is 4.5. For concentrations less than this, P_{e} decreases rapidly and successful burns are observed in some tests but are not repeatable. No evidence of ignition was observed for W below 100 g/m^3 . Therefore 200 g/m^3 is the minimum concentration to allow a flame to propagate the entire tube length. Nagy [21] and Bond [32] report lower explosible limits near 100 g/m^3 . This is due to different initial turbulence level and ignitor strength and will be discussed further in a later section. Discusssion on use of the Hartmann bomb for lower explosibility limit tests has been given in ref. [20]. d) Equilibrium, calculations do not predict a lean explosible concentration as it is a function of physical processes. The predicted pressures decrease smoothly from $P_a=3.8$ at W=70 g/m^3 to $P_a=0$ with no fuel.

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e) Equilibrium calculations predict linearly decreasing pressures for concentrations exceeding $300g/m^3$. However observed P_e reaches a plateau at high concentrations and may remain constant beyond $600 g/m^3$.

Theoretical predictions are based on equilibrium c calculations and consider only complete combustion of the reactants. However, for the present experiments for which there was a successful explosion, there remained a lot of slightly charred, even unburned residue. This is especially true at high dust concentrations. The quoted concentrations, though, are based upon the nominal quantity of dust loaded onto the V channel. Particle agglomeration, settling and n adhesion to the cold surfaces reduce[†] the real concentration available to the flame. Non-uniformities in the cloud concentration produce inefficiency in the burning process leaving some mass unburned. Also, it is possible that the burning rate of the large particle, including pyrolysis, devolatilization, and surface reactions, is slow in comparison to the flame speed. That the optimum concentration- is usually much higher than the theoretical stoichiometric, even in burner experiments where the real dust concentration is well known [4], indicates that partial burning is unavoidable and characteristic of dust-air flames.

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The measured P_e is significantly lower than predicted because of increased heat losses resulting from radiation [3] which are not present with gases. Furthermore, as will be discussed later, the burning rate for starch-air flames is significantly slower than for methane-air. Near the observed flammability limit for methane, 6%, the observed pressure was 18% less than predicted. Also, for the very slow burning lean dust-air mixtures, the burnout times are of the order of 0.25 sec by which time particle settling and

dissipation of the original jet-induced turbulence become significant. The lean explosibility limit is further discussed in Section IV.7.

The observed P_e may be lower than predicted also because the calculations assume that all the coxygen in the starch molecule $(C_6H_{10}O_5)$ is available for combustion. For a stoichiometric mixture the oxygen in the starch represents 29.4% of the oxygen in the mixture.

As seen in Figure 12 maximum P_e is predicted to occur with W=300 g/m³. However, investigators observe P_e to be constant beyond 500 g/m³, to 1000 g/m³ or more. This demonstrates the competing effects of (i) the heat absorbed by excess dust and (ii) the effect of devolatilization of dust that does not participate in the combustion process. The mole ratio of gaseous products to reactants for 500 g/m³ is N=1.61. In actual rich dust explosions, increase in the mole ratio may exceed the reduction in the flame temperature caused by the excess dust. As well very rich mixtures burn more slowly, so that much settling of the dust occurs during the explosion, reducing the actual airborne concentration.

Figure 13 shows measured K_{st} for the present tests compared with those of the other authors [32,33,21]. It can be seen that the present K_{st} trends are in good general agreement with the other authors', although slightly lower in value. The maximum K_{st} for the present tests is approximately 35 bar-m/s at W=500 g/m³, compared with 83 bar-m/s as measured by Cocks [33] in a 20 l sphere with W=800 g/m³, and 115 bar-m/s observed with 9% methane in the present set-up. K_{st} increases with concentration and the maximum value occurs with W=500 g/m³, coincidental with the maximum P_e . Similarly, other investigators also observed maximum K_{st} at the same concentation as P_e . The similarity of the trends for the explosion pressure and burning rate implies that the starch-air burning rate depends upon the flame temperature, i.e. it is kinetically controlled. For diffusion limited mixtures, the devolatilization/mixing rate is proportional to the particle surface area and would therefore continue to scale with the concentration, even beyond the maximum P_e .

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IV.4 Explosivity of Hybrid Mixtures

IV.4.1 Explosion Pressure

The explosivity of a variety of hybrid mixtures were examined in the present study. The maximum explosion pressures are shown in Figure 14. Also shown, for comparison, are the results for starch-air mixtures as in Figure 12. From these figures the following observations can be made.

a) P_e is enhanced by the presence of methane for all starch concentrations. The effect is more pronounced with leaner W; with W=600 g/m³ P_e increases only slightly.

b) Admixture of methane (2%-9%) to the optimum starch mixture, W=500 g/m³, results in increased P_e from P_e=6.9 to P_e=8.0. Additional starch, ie. W>500 g/m³ diminishes P_e.

c) For W=100 g/m³ and 200 g/m³ admixture of 2% methane results in greater increase in P_e than subsequent admixture of methane to 4%, 5% etc.

d) W=100 g/m^3 is not ignitable by itself but burns vigorously in the presence of 1% methane. Lean explosibility limits will be discussed in a separate section.

e) Very rich hybrid mixtures can support vigorous combustion. Large amounts of starch (W>200 g/m³) added to 9% methane (Φ =0.95) causes P_e to decrease by acting as a thermal sink.

Addition of methane to lean starch-air mixtures has the effect of increasing the total mixture energetics and so increasing P_e is predicted from the thermodynamic calculations. Comparing W=200 g/m³ and 300 g/m³ mixtures, for the greater starch concentrations the "relative" increase in total mixture energetics decreases for similar

addition of 2% methane. Therefore the relative increase in the observed P_e diminishes. This is also true for subsequent additions of methane to 4% and 6%.

That P_e for hybrid mixtures with very rich starch concentrations increase slightly with addition of methane can be attributed to two factors. (i) Flammable gas which is homogeneously premixed creates more uniform burning in the vessel, therefore more complete combustion. (ii) Addition of flammable gas increases the burning rate (as will be discussed later) so that heat lost to the cold boundary is reduced.

According to equilibrium calculations addition of 2% (13 g/m^3) methane in air contributes $Ah_{r,2\%} = 656.2 \text{ kJ/m}^3$ to the total heating value of the mixture. This is approximately equivalent to the addition of 40.2 g/m³ of cornstarch. The computed and observed explosion pressures for lean cornstarch-air and cornstarch-2% methane-air mixtures are shown in Figure 15. Direct comparison with with experimental values are not possible since it has already been demonstrated that there is a discrepancy between the experimental and calculated P_e for starch only mixtures. In this figure the curves for the computed values of P_e appear parallel within the range of 50-150 g/m³, and the similarity between the effects of 40 g/m³ starch and 2% methane are readily observed.

From the data in Figure 15, similar trends are observed. However, there is a greater difference between the starch-air and the hybrid mixtures than predicted. P_e for the hybrid mixture is predicted to be 1.5 atm greater than the starch only mixture. However in the experimental data, with 200 g/m³, the difference between the hybrid and dust mixtures is 2.1 atm. This suggests that the admixed methane gas assists in more uniform combustion of the starch throughout vessel, we specially at lower concentrations.

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Subsequent additions of methane to W=100 g/m³ result in linear increase in P_e of approximately 0.63 per percent methane. This is very close to the calculated value of 0.75 per percent methane (Figure 16). This difference may be attributed to thermal loss and is within the accuracy of these calculations. These results indicate that the contribution of added methane is primarily to increase total mixture energetics. If it were to assist in the kinetic burning process of the dust particle, then there would be greater effect with more methane. The effect of methane upon very lean dust mixtures (W<150 g/m³) exceeds the predictions. This is attributed to the fact that without methane the flame burns so slowly that particle settling and decay of turbulence are significant.

Fuel rich mixtures:

For methane in air the normal flammability limits are in the range $0.5 < \Phi < 1.5$ where Φ is the equivalence ratio. However even with substantial amounts of starch (W=800 g/m³) added to 9% methane ($\Phi_{total}=4.4$) flame propagation is still possible. Such mixtures result in large quantities of charred and lightly singed cornstarch indicating that much of the starch does not burn. Consequently the excess dust acts as a thermal sink, not participating in the chemical reactions, and combustion occurs primarily with the gaseous fuel. Nagy and Portman [6] measured decreasing P_e with 5% methane and increasing coal dust concentrations (from 500 a/m^3 to 2000 a/m^3).

From the above data it may be concluded that the maximum overpressure strongly depends upon total mixture energetics. Addition of small amounts of methane facilitates flame propagation in very lean mixtures. In rich hybrid mixtures excess starch acts as a thermal sink as well as a source of volatiles. Explosions are possible - in very rich hybrid mixtures containing high concentrations of dust.

IV.4.2 Burning Rate of Hybrid Mixtures

Generally admixture of methane to starch-air mixtures results in significantly increased flame speeds and rates of pressure rise. However, experimental observations of the burning rate are not readily compared with theoretical predictions. This is because: i) true laminar flame speeds, which are characteristic of particular mixtures, have not been established for either dust-air or hybrid mixtures; ii) some fraction of the dust remains unburned; and iii) the structure of the dust-air flame is not well known. Consequently, judgement can be made only on the basis of comparative testing under similar conditions.

The measured rate of pressure rise, dp/dt, for various cornstarch-methane-air mixtures is shown in Figure 17, along with the base line data for starch-air only mixtures. The data is presented as a series of curves for mixtures containing 0%, 2%, 4% and 6% methane. Several observations can be made from this figure.

a) The curves follow the trend of the base line data, exhibiting increasing dp/dt with increasing starch concentration to 600 g/m^3 .

b) For all starch concentrations, mixtures with greater amounts of methane burn more rapidly. The maximum burning rate of the optimum starch-air mixture (72 bar/s at $W = 500 \text{ g/m}^3$) is exceeded by even leaner hybrid mixtures (300 g/m³ starch and 2% methane).

c) With increasing methane content the optimum starch concentration, in terms of dp/dt, decreases.

d) The burning rate increases significantly as the methane concentration approaches the lower flammability limit. The initial 2% methane produces more mild increases in the burning rate.

e) 9% methane-air burns more rapidly (dp/dt=200 bar/s). than any hybrid starch-methane mixture.

f) A mixture containing 100 g/m^3 starch is not explosible by itself but is readily made explosible with as little as 1.5% methane.

The measured values of the flame speed, \dot{R}_{f} , shown in Figure 18 correlate well with the dp/dt data. The trends of the curves are similar as are the magnitudes of the relative increase of \dot{R}_{f} with gas concentration. This substantiates the use of dp/dt as a relative measure of the global burning rate.

These results agree with those of Bartkneckt [5] from his tests in the $1m^3$ sphere with PVC and propane. He found rapid increase of dp/dt when the propane concentration was increased beyond 2% (lean flammability limit) and the maximum burning rate was with 4% propane. Nagy [6] also observed increasing dp/dt with methane content in experiments with coal dust. The maximum dp/dt with 5% methane (and 200oz/ft³ coal) was 40% higher than the maximum dp/dt with 0% methane (and 500 oz/ft³ coal).

As discussed previously, addition of gas to a lean dust air mixture will have a significant effect upon the flame temperature. This will in turn increase the chemical reaction rates. If the mechanism of the dust-air or hybrid flame propagation is such that combustion occurs in the volatiles generated at the flame front, then the characteristic burning rate is proportional to the square root of the net rate of energy production. Thus, admixture of methane gas to a lean-dust mixture, in making the mixture more energetic, should affect the maximum temperature, hence the maximum kinetic rate, similar to that of a premixed gas when made more energetic.

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Ballal [3] developed a simplified model for calculating the burning velocity of dust-air flames. For very fine hydrocarbon particles combustion primarily within the volatiles. The model incorporates simple chemical kinetics in which the burning rate is proportional to the burning rate of CO at the flame temperature. The author assumed that the conversion of CO to CO_2 represented the slowest step in a chain of reactions.

The burning velocity, although strongly influenced by the flame temperature, is not solely dependent upon it. The table below shows dp/dt and \dot{R}_{f} data from Figures 17 and 18 for various hybrid mixtures that yield nearly equivalent explosion pressures. It can be deduced from this table, that for equivalent mixtures, in terms of *mixture* energetics, those containing no methane burn up to .30% slower and those mixtures containing greater amounts of methane burn more rapidly,

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Mixture		Pe	dp/dt	. ^Ř f
₩ (g/m ³)	G (%vol)		(bar/s)	(m/s)
0	7	6.00	55	17
100 .	6	6.10	65	18
200	2	. 6.25	55	14
300	0	5.90	42	11
· 600 j	0	7.00	70	20
600	6	7.00	120	30
300 *	. 4	7.25	88	30 ·

If the laminar burning velocity of the admixed gas is significantly greater than that of the volatiles than the overall reactivity of the volatiles will be increased and this will lead to increased burning rate. In a later section the effect of changing the chemistry of the admixed gas is examined.

Some effect upon the flame speed may be attributed to more uniform burning throughout the flame front cross section. Due to the local variations in dust concentration, there may be some regions incapable of supporting flame propagation, especially in lean overall mixtures. Premixed flammable gas will homogenize these irregularities resulting in more even burning. This smoothing effect was observed by Smoot et al [4] and Cassel [8] in flat flame burners experiments, however augmentation of flame speed due to this alone was not quantified.

is gas concentration itself nearly the When stoichiometric ($\Phi = 0.95$), the inclusion of combustible dust acts to retard the flame as can be seen in Figures 17 and 18. For those mixtures of 9% methane and small amounts of starch (50 g/m³ $\langle W \langle 100 g/m^3 \rangle$) in which P₂ increased from 7.6 to 8.1, the burning rate decreased by 12%. Equilibrium calculations predicted that the starch concentration required to make a stoichiometric mixture with 9% methane is 25 g/m^3 . The trends of dp/dt and the flame speed are almost identical. The burning rate for mixtures with 800 g/m³ starch are 35% of the value for methane alone.

It appears that the rate of energy released by oxidation of the starch in the gaseous reaction zone is insufficient to counter the rate at which heat is conducted to the particles. Subsequent oxidation behind the flame front results in a net increase in explosion pressure for low starch concentrations. With higher starch concentrations, the heat

lost by conduction to the particles is greater than the heat released by oxidation of the starch, and P_e decreases. The slow relative reaction rate of the dust may be due in part to lack of oxygen available for starch combustion. With 9% methane admixed, only 5% of atmospheric oxygen is available for dust combustion, whereas with 6% admixed methane 37% of atmospheric oxygen remains for starch combustion. As well the characteristic time scale of 9% methane-air is 3X shorter than for 6% methane. (The characteristic time scale is given by the flame thickness, $\delta=0.2$ mm, divided by the laminar burning velocity.)

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Comparing these results with tests with 9% methane-air and an inert dust (alumina) indicates that the monotonic decrease in the burning rate with increasing starch. concentration is entirely due to the thermal sink effect of the starch. These results are examined in the proceeding section.

IV.5 Effect of Inert Dust Upon Methane Air Flames

To further verify the thermal effect of dústs upon gaseous flames, experiments were conducted to investigate the influence of aluminum oxide $(Al_2O_3, a.k.a. alumina)$ dust upon 9% methane-air flame. As noted earlier this has been studied by Bradley et al [34] and Mitani et al [35,36]. However these authors' experiments were concerned with very low dust concentrations and laminar burner flames. This study extends the authors' work to highly turbulent and confined flames, with large dust concentrations.

The experimental techniques used were as described previously. Neither the dispersion air blast, nor the ignition delay time were altered. The average particle diameter is $d_p=9$ microns and the density of alumina is 3,970 kg/m³, therefore the average particle mass is approximately 85% that of a cornstarch particle. Hence the particle number density for alumina and cornstarch are similar for a particular mass concentration.

In Figure 21 the experimental values of P_e are shown for concentrations of 50, 100, 300, and 800 g/m³. The solid line represents the the equilibrium adiabatic pressures calculated from equations (5 and 6) and equation (4) modified as:

 $\Sigma h_{f,reactant}^{\star} = \Sigma h_{f,product}^{\star} + \Sigma \Delta h_{products} [T_{f} - T_{o}] + \Delta h_{Alumina} [T_{f} - T_{o}]$ (7)

where:

$$\Delta h_{Al} [T_f - T_o] = W_{Al} C_{Al} \cdot (T_f - T_o)$$
(8)

 W_{Al} and C_{Al} are the concentration and specific heat capacity of alumina calculated at $(T_f + T_o)/2$. For the temperature range encountered, $C_{Al} = 1.25$ kJ/kg-K. The agreement between

the observed values and the estimated values for P_e is very good, especially at lower dust concentrations. It can be seen that P_e is predicted to decrease almost linearly with increasing concentrations, whereas the observed pressures seem to asymptote at higher concentrations. At 800 g/m³ the predicted P_e is 4.75 as compared to the observed value $P_e=5.5$.

, These results indicate that the heat transfer rate to the particles is sufficiently fast so as to occur within the timescale of the explosion. However, even with W=800 g/m³ no quenching is observed; hence alumina is a poor extinguishing agent. Hertzberg et al [16,37] have found that even amounts greater than 2 kg/m^3 could not extinguish a stoichiometric methane air flame in their 8 liter bomb. This was attributed to slow heat transfer to the particles creating a "less than thermal" effect, that is less than equilibrium calculations predict. However, the thermal time constant for these particles is approximately $\Gamma_{th} = 0.35$ msec and probably it is less since the alumina particles are not spherical. (r_{th} $\rho_{\rm p} c_{\rm p} d_{\rm p}^2 / 12 K_{\rm f}$, where $\rho_{\rm p}$, $c_{\rm p}$, $d_{\rm p}$ are the particle density, specific heat and diameter and K_f is the fluid conductivity. This is based on heat transfer to the particle assuming conduction, ie. Nu=hd_D/K_f=2 [38].) Most likely the less than thermal effect results from significant particle settling which occurs with slightly retarded flames and because of agglomeration.

The burning rate for these hybrid mixtures decreases monotonically with increasing alumina concentrations as seen in Figures 19 and 20. Both dp/dt and \mathring{R}_{f} decrease rapidly at first then more slowly with further additions of dust. With $W_{\lambda 1}$ =800 g/m³, dp/dt and \mathring{R}_{f} are 25% the value with zero dust.

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Theoretical predictions

According to Bradley's work [34] for low dust concentrations, the <u>only</u> effect of the dust is to act as a thermal sink, absorbing heat from the flame zone. Thus at a given flame temperature the rate of energy production is given by:

$$Q_{\mathbf{p}}^{n} = Q - H \tag{9}$$

where Q_p and Q are the rates of heat production for a dust laden and dust free flame respectively, and H is the heat transfer rate to the particle. According to classical flame theory, the dust laden flame speed, S_p , will be proportional to the square root under the Q_p versus T_f curve.

$$\frac{\mathbf{s}_{\mathbf{p}}^{\mathsf{i}}}{\mathbf{s}_{\mathbf{o}}} \stackrel{\text{\tiny def}}{=} \sqrt{\frac{\mathbf{Q}_{\mathbf{p}}}{\mathbf{Q}_{\mathbf{o}}}}$$

Consider a dusty gas moving into a stationary flame with a mean velocity S, if the particles are very small, they will closely follow the gas temperature and will reach T_f in the flame zone. The heat absorbed by the particles in reaching T_f is then WC(T_f-T_o) and the rate at which heat is absorbed by the particles is:

$$H = WSA_{f}C(T_{f} - T_{o})$$
(11)

where A_f is the cross sectional area of the flame. The assumption that the particle temperature lags behind the gas temperature only slightly so as to be ignored is quite valid considering the short thermal time constant ($\Gamma_{th}<0.35$ msec). Bradley [34] observed a maximum temperature lag of 15 K for 2.75 micron and 4.3 micron alumina particles.

(10)

The rate of heat release, Q, is expressed as the mass flow rate of fuel (m_f) multiplied by the chemical heat released per unit mass of fuel (Δh_r) .

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$$Q = \dot{m}_{f} \cdot \Delta h_{r} = \rho_{f} GSA_{f} h_{r}$$
(12)

For the particular case of 9% methane-air flame, at atmospheric conditions and considering unit cross sectional area; $\rho_{CH4}=0.654$ kg/m³, G=0.09, S_{L0}=0.45 m/s, $\Delta h_r = 50167$ kJ/kg, and Q= 1328.8 kJ/s.

Bradley assumed for low dust concentrations the chemical reaction rate is not affected by the dust [34]. However for larger dust concentrations, as with the present data and other extinguishment data, the explosion pressure and flame temperature are significantly affected and the chemicalreaction rate is reduced. Small changes in flame temperature have a large effect on the Arhennius dependent chemical feaction rate terms, as was shown by Marx [39] in calculations of hydrogen flame-water droplet interaction.

The effect of adding W=0.1 kg/m³ alumina to the mixture may be determined as follows. The equilibrium flame temperature calculated from equation (7) is T_{f} =1991 K. The burning velocity for the reduced temperature, S', is calculated from equation (3) and this: velocity is in turn used to assess H in equation (11). The new $Q_{\rm p}$ is obtained from equations (9 and 12) and S'_{p} is obtained from equation (10). This new S'D is used to update H in equation (11). Equations (9-12) are re-evaluated, in turn until the solution converges. The results of the calculations for eight dust concentrations are shown in the table below.

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W [g/m ³]	τ _f ∞ _[K]	sp so	sp so	
0 /	2135	1.0	1.0	
100	1991	0.796	0.768	
200	1889	0.665	0.622	
300	1800	0.560	0.510	
400	1716	0.470	0.417	
500	1642	0.398	0.345	
600	1575,	0.338	0.288	
700	1514	0.289	0.241	

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The third column reflects the change in burning velocity due to a decrease in the flame temperature and consequently the chemical reaction rate as calculated from equation (11). The last column shows the combined effect of reduced flame temperature and rate of heat transfer H. It can then be seen from this table that the primary effect of the particles is decreasing the reaction rate within the flame. Also a small fraction of the retardation is due to the rate at which heat is conducted to the particles.

0.247

0.203

Experimental results

800

These results are compared to the observed influence of alumina dust in the present set up. Figure 22 shows the normalized rate of pressure rise and flame speed in comparison to calculated values for S_p'/S_o and S_p/S_o . \dot{R}_{fo} and $(dp/dt)_o$ represent the experimental values observed with no dust present. The agreement between the present theory and experimental results is quite good considering the limitations of the analogy between laminar and turbulent flows. The effects of radiative heat losses have not been considered in

the present analysis; this would have resulted in greater predicted flame inhibition. Although radiative heating of the particle laden mixture ahead of the flame may be a part of the flame propagation mechanism, the increased radiation will result in more thermal losses to the cold boundary. The effect of radiative preheating of the unburned gas was not considered here. It may be concluded then that Bradley's theory has been satisfactorily extended to higher dust concentrations taking into account the primary effect of dust upon the chemical reaction rate.

Furthermore, these results concur with those of Mitani [35,40] using ultra-fine alumina particles dispersed in a mist. The author also found that the influence of some so' called "chemical inhibitors" can be explained solely on the basis of thermal effects.

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IV.6 Effect of Hydrogen Upon Lean Starch-Air Flame

In order to ascertain the role of chemistry of the flammable gas admixed to a dust air mixture some tests were run with cornstarch-hydrogen-air mixtures. The experiments were conducted with 100 g/m^3 cornstarch and various hydrogen concentrations from 0% to 12% by volume. As noted earlier 100 σ/m^3 starch is not by itself ignitable in the present experiment, however it readily ignites and propagates with 3% H_2 . Figure 23 shows calculated and measured explosion pressures for starch-methane-air and starch-hydrogen-air mixtures. The predictions (dashed line) are common to both scales. In these calculations $\Delta h_{r,H2}=121,000 \text{ kJ/kg}$. As with methane, the predicted results overestimate the explosion pressure because of the assumption of complete combustion of the cornstarch and no heat loss. For mixtures with equivalent energy content, those containing hydrogen produce much, greater explosion pressures. This indicates that hydrogen has greater capacity for enhancing combustion of starch than does methane.

The rate of pressure rise data for these mixtures is shown in Figure 24. For $3\% \leq G \leq 9\%$ dp/dt increases mildly from 22 bar/s to 55 bar/s. The trend is similar to equivalent methane-starch mixtures up to 3% methane, but the hydrogen mixtures burn up to 30% faster. However at 12% hydrogen the burning rate increases dramatically to 250 bar/sec, a 4.5X increase from the value with G=9%. No such increase is observed with methane-starch mixtures, and dp/dt=250 bar/s is greater than for any methane-air or methane-starch-air mixture. This sudden change in the burning rate is indicative of a change in the burning mechanism of the mixture.

For H2-air mixtures the horizontal flammability limit is near 6.5% by volume. Thus in mixtures containing 7%, 9% and 12% the gas is capable of sustaining flame propagation without contribution of heat from oxidation of cornstarch. It has been shown by Scholte et al [41,42,43] that the burning velocity of many hydrocarbons increases with the square root of added H₂ gas; $S_{L} = \sqrt{G_{H2}}$. This is qualitatively observed in mixtures containing up to 9% H2. The sudden increase at 12% can be explained from reaction kinetics of hydrogen combustion. Lee et al [44] observed experimentally a sudden increase in the flame speed of H₂-air mixtures at G=13%. This was attributed to a changeover in the competing reactions between H_2+O_2+M ---> HO_2 and $H+O_2$ --> OH+O which occurs around 1300 K in favour of the more rapid OH branching reaction. That the transition was observed in the present case with 9%<G<12% indicates that heat released by combustion of starch is sufficiently rapid to occur within the reaction zone of the gaseous mixture.

A comparison below of 12% H_2 -air, with and without 100 g/m³ cornstarch indicates the severe consequences of the hybrid mixture.

Mi	xture	Pe	Pe P	dp/dt	^T f,ad
G	W	(predicted)			·
[* _{vol}] ° [g/m ³]		•)	[bar/s]	[K]
				¢	
12 H ₂	0	4.3	4.1	45	1250
12 н ₂	100	7.5	7.0	250	2127
4 CH ₄	100	8.0	5.1	45	2269
7 CH4	100	***	7.5	110	

The mixture containing 12% hydrogen and 100 g/m³ starch $(\Phi=0.85, \Lambda_r=2816 \text{ kJ/m}^3)$ burns much more violently than does the more enrgetic methane-starch mixture ($\Phi=0.89, \Lambda_r=3264 \text{ kJ/m}^3$).

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Note that the observed explosion pressures are quite close to those predicted from equilibrium thermodynamic calculations. That the predicted and observed pressures for the 12% H_2 mixture are so close is probably due to lower radiation losses from the hydrogen flame in comparison to methane flames. The equivalence ratio for the two hydrogen mixtures are 0.32 and and 0.94 respectively.

It thus appears that for lean amounts of hydrogen admixed to the dust, acts in a kinetic manner by increasing the flame temperature hence the burning rate as per equation (2). Also the added hydrogen increases the burning rate (or reactivity) of the volatiles-gas mixture. The observed increase in P, and dp/dt per unit volume of admixed hydrogen is less than that per unit volume admixed methane because of low heating value of hydrogen on a molar basis, fuel burned. $h_{r,CH4}/h_{r,H2} = 3.3$ per mole of The stoichiometric concentration of H2 in air is 29.5% as, compared to 9.5% for CH_A . Admixing hydrogen to the cornstarch-air mixture has greater impact upon the explosivity than admixing the equivalent amount (in terms of energy) of methane or additional cornstarch. This is in. agreement with Barktnecht's general observation that highly reactive gases have greater effect upon dusts than do less reactive gases [5].

IV.7 Lower Explosible Limits of Hybrid Mixtures

Explosible limits, are examined to further explain the burning mechanism of hybrid mixtures and to evaluate the significance of the long horizontal geometry. This is not simple as the definition of explosible limit is vague and somewhat arbitrary; hence, the present definition will be explained. A mixture is considered explosible if the explosion pressure is greater than 1.5 bar. It is generally observed in the present experiments that no explosions occurred which generated overpressures between 0 and 1.5 bar. The vessel was inspected after each test to examine the residue. Burned char particles throughout the tube length is indicative of sustained flame propagation and was not present when p, was less than 1.5 bar. Ion probe signals support whether the flame has propagated as far as the probe locations (x=0.91 m, x=1.83 m).

To determine the LEC, (Lower Explosible Concentration), of a hybrid mixture tests were performed for a particular dust concentration with decreasing methane concentrations until the mixture was no longer explosible. The lowest dust concentration tested was 50 g/m³; below this value the dust dispersal system was not reliable. Table VI below presents the results from these tests.

W(LEC) [g/m ³]	сн ₄ [* _{vol}]	CH4 [g/m ³]
125	· 0	× 0
100	· 1	6
50	4	26
0 '	6	38
41		•

The results are shown graphically in Figure 39 and it can be seen that a nearly linear decrease in LEC with increase in methane exists. Also shown are the highest concentrations that were non-explosible. The slope of the explosibility line is approximately -20.8 g starch/ g CH_4 . Previously it was shown that the energy equivalent is 3.07 g starch /g CH_4 . This reflects incomplete burning of the dust particles in very lean mixtures due to non-uniformities in the cloud.

The linear variation of LEC with methane content, an expression of Le Chatelier's rule (equation (1)), indicates similar enthalpy of reaction and flame temperatures for the different mixtures. The lean limit for methane for the present case is 6% and for cornstarch it is 125 g/m^3 . Their calculated enthalpy of reaction and adiabatic flame temperature are shown in the table below. Also shown for comparison are the results of Gaug et al [15] from tests in a 186 l cylindrical vessel. Hertzberg [1] found for a number of higher hydrocarbons, the average heating value for lean limit mixtures is approximately 1990 kJ/m³ (=11.6 kcal/mol mixture). This value is based only on the volatiles extracted from the dusts by rapid pyrolysis methods. Therefore char combustion has no role in determining the lean limit.

onsta.		Starch	Methane	
	Concentration	125 g/m ³	6 %	
Present	۵h _r	2037 kJ/m ³	_1965 kJ/m ³	
	T _f , ad	1520 K	1616 K	
	Concentration	80 g/m ³	5 %	
Gaug et al	Ah _r	1304 kJ/m ³	1640 kJ/m ³	
[15]	Tf,ad	1200 K	1415 K	

For the present results the calculated enthalpies of methane and starch are within 3.5% of each other. In Gaug's results, the lean starch mixture contains 20% less energy than the lean limit methane mixture. This may be a result of non-uniformities in the dust cloud creating slightly richer mixture in the vicinity of the igniter. The lower LEC's reported by Gaug result from use of a more powerful ignition source, (a pyrotechnic device with approximately 1 kJ) and different criterion for explosibility, (1.5 psi explosion pressure).

Gaug's results for hybrid cornstarch-methane-air mixtures also adhere within 10% to Le Chatelier's rule. However his tests with cornstarch-H₂ and Fe-H₂ show marked deviation. These indicate conclusively that hybrid lean explosibility limits are not dependent upon energetics alone; it depends upon the flame propagation mechanism as well. Clearly Fe, which has no volatiles, does not burn as does a gas flame. Thus, Gaug concludes, mixtures which contain fuels with two very different propagation mechanisms, as long as dust is the dominant fuel, require enough gas to maintain the dust lean limit flame temperature. For cornstarch-methane the variation of cornstarch with methane is linear because of similar lean limit flame temperatures.

For the lean dust-air mixture $p_e=1.5$ bar and for the lean methane-air mixture $p_e=4.6$ bar. The lower p_e for the starch mixture reflects the quantity of dust not burned, about 70%. The is due to non-uniformity of the very lean mixture creating regions which cannot support flame propagation. Also a significant amount of dust settles during the explosion because of the slow flame speed. As shown earlier the lean starch mixture propagates at flame speeds near 4 to 5 m/s and have burnout times of the order of 0.4 seconds. In the ignition experiments (Section III.3) the mixtures could not be ignited at all after

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an ignition delay time of 0.4 seconds. This factor will be more significant with lean mixtures containing mainly dust.

Therefore, settling becomes a significant factor contributing to the extinguishment of lean dust-air and hybrid mixtures with low gas concentrations, especially in long tubes. Consequently for these geometries, grain conveyor channels, mine shafts etc., the explosion hazard of a dust-air flame can be less than a gaseous flame because a lean mixture may self extinguish. A CONTRACTOR AND A CONTRACTOR

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1. A long horizontal tube, constant volume bomb, was developed to study hybrid, dust-gas-air explosions. A novel dispersion system generates a uniform dust cloud throughout the tube length, and can be applied to longer tubes. The apparatus yields explosion pressures for cornstarch-air that are consistent with other investigators.

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2. Heat loss to the tube wall varies from 2%, for 9% methane-air (burnout time ≤0.1 sec), to 18% for 6% methaneair (burnout time =0.4 sec).

3. The turbulent burning rate for methane-air flames, as measured by dp/dt and \hat{R}_f , scales with the laminar flame speed of the mixture. The turbulent burning velocity, calculated from the pressure-time history, is approximately 28 times the laminar burning velocity. The maximum burning rate for methane (Φ =1) is greater than for any hybrid starch-methane or starch only mixture.

4. For lean starch-air mixtures, $W \le 200 \text{ g/m}^3$, admixed methane enhances starch combustion. Explosion pressure increases up to 50% more than predicted for the addition of 2% methane to 200 g/m³ starch, ($p_{e,pred}=1.5$ bar, $p_{e,obs}=2.1$ bar).

For $200 \le W \le 500 \text{ g/m}^3$, the increase in explosion pressure from small quantities of admixed gas, (G \le 4%), directly related to mixture energtics, and is proportional to the methane concentration. $p_e = 0.63$ bar/percent methane compared with $p_{e, \text{pred}} = 0.75$ bar/percent methane.

For very rich dust mixtures, W>500 g/m³, the explosion pressure is less affected by admixed methane for $24 \le G \le 94$.

5. Addition of methane, up to 9%, enhances the burning rate of <u>all</u> starch-air mixtures. The burning rate of a lean hybrid mixture can exceed that for the most potent dust-air mixture. This is due, in part, to increased flame temperature with increased mixture energetics affecting the chemical reaction rate of the volatiles-methane-air mixture.

However, the burning rate does not depend only upon flame temperature. For hybrid mixtures yielding similar explosion pressures, those containing more methane burn faster.

6. The explosivity (pressure and rate of pressure rise) increases with increased reactivity of the admixed gas. For mixtures with equivalent energy content the following order is observed with respect to explosivity: cornstarch- H_2 > cornstarch- CH_A > cornstarch.

100 g/m^3 cornstarch added to 12% hydrogen increases the burning rate 5.5 times due to the increased chemical, reaction rate at the higher flame temperature.

7. Starch added to 9% methane-air acts as thermal sink, analogous to an inert dust. The explosion pressure reduces to 6.5 bar with 600 g/m³ starch, from the maximum of 8 bar with 200 g/m³. Also, the turbulent burning rate is reduced to 25% of the value with no dust. Reduction in turbulent flame speed is due to reduced flame temperature, hence chemical reaction rate, and is proportional to the laminar burning velocity. This can be estimated from thermal flame theory.

8. The lower explosible limit of starch decreases linearly with increasing methane concentration, with slope approximately -25 g/m^3 per percent methane. Limit hybrid mixtures, of methane and starch, have equivalent flame temperature and explosion pressure.

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9. In the long horizontal tube with slowly propagating flames, significant settling of the dust occurs because the convection currents generated ahead of the flame by the expanding gas are not strong enough to keep the dust in suspension. This can be an extinguishing mechanism for lean hybrid or dust explosions. It can also prove to be a limitation for explosion mitigation using inert dusts.

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VIII. FIGURES

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Figure 1 - Schematic of apparatus.

Figure 2 - Schematic of ignition end of apparatus and end view of dispersion tube - V-channel arrangement.

Figure 3 - Schematic of driver section.

Figure 4 - Photomicrographs of cornstarch; with and without fluidizing agent.

Figure 5 - Particle size distributions of cornstarch; with and without fluidizing agent.

<u>Figure 6</u> - Effect of ignition delay time on explosion pressure.

<u>Figure 7</u> - Pressure-time history of 9% methane-air explosion.

Figure 8 - Comparison of turbulent and quiescent burning of 9% methane-air in Long horizontal Tube.

Figure 9 - Maximum explosion pressure for methane-air mixture; predicted and observed.

Figure 10 - Burnout time and heat loss for methane-air explosions.

Figure 11 - Burning rate for methane-air mixtures.

Figure 12 - Maximum explosion pressure for cornstarch-air.

Figure 13 - K_{st} factor for cornstarch-air.

Figure 14 - Observed explosion pressures for hybrid mixtures.

Figure 15 - Explosion pressure for starch-air and starch-2% methane-air; predicted and observed.

<u>Figure 16</u> - Explosion pressure for methane-air-100 g/m^3 starch.

Figure 17 - Rate of pressure rise for hybrid mixtures.

Figure 18 - Flame speed for hybrid mixtures.

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Figure 19 - Rate of pressure rise for different alumina concentrations with 9% methane	starch and
Figure 20 - Flamé speed for different starch and concentrations with 9% methane.	l alumina
<u>Figure 21</u> - Maximum explosion pressure for 9% methane-air-alumina mixtures.	· · · · · · · · · · · · · · · · · · ·

Figure 22 - Comparison of normalized burning velocities for 9% methane-air-alumina mixtures; observed and predicted.

<u>Figure 23</u> - Maximum explosion pressure for 100 g/m^3 starch with different hydrogen content.

Figure 24 - Rate of pressure rise for 100 g/m^3 starch with different hydrogen content.

Figure 25 - Lower Explosible Concentration (LEC) in atmospheres containing methane.

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Samples 1) and 2) do not contain powder fluidizing agent while samples 3) and 4) do contain powder fluidizing agent. Note that the bars at the lower right corner of each micrograph represent $5x10^{-6}$ m.

Figure 4 - Photomic rographs of cornstarch



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Particle size determined by Image Analysis.

Particle Size Distribution of Cornstarch

Frequency Percent for Particle Size Interval (Microns)

lot	<u>0-1</u>	<u>1-2</u>	2-3 3-4	<u>4-5</u>	<u>5-6 6</u>	<u>-7 7-8</u>	8-9	<u>9-10</u>	<u>10-11</u>	<u>11-12</u>	<u>12-13</u>	13-14 .
Cornstarch #1 Cornstarch #2	0.0 0.0	0.1 0.1	0.9 <u>2.0</u> 0.7 1.7	1.2 1.0	1.3 1 1.2 1	.7 4.8 .0 3.3	5.6 2.8	9.2 5.6	9.4 6.9	9.2 5.7	9.6 7.3	7.6 6.8
	<u>14-15</u>	15-16	<u>16-17</u>	<u>17-18</u>	<u>18-19</u>	<u>19-20</u>	<u>20-21</u>	21-22	<u>22-23</u>	23-24	<u>24-25</u>	25-26
Cornstarch #1 Cornstarch #2	6.8 6.4	10.7 13.3	4.7* 5.3	3.8 5.4	2.7 5.0	2.2 4.9	1.6 4.5	1.1 2.5	0,8 2.0	0.7 2.9	0.2 0.5	0.2 0.5
<u>ب</u>	<u>26-27</u>	27-28	28-29	<u>29-30</u>	"Hean	Dev.	<u>Min.</u>	Hax.			Ĩ.	*
Cornstarch #1 Cornstarch #2	0.0 0.5	0.2 0.3	0.1 0.2	0.0 0.2	12.7 14.7	4.3 5.1	1.8	31.9 42.5				v

st dard deviation 141 aisim a particle size

maximum particle size

ple #2 contains 1% funed silica fluidizing adjent.

Figure 5



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<u>Figure 6</u> - Effect of ignition delay time on explosion pressure with $W=400 \text{ g/m}^3$ cornstarch.





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C. S. Marine Starting









Real Children & Knows



Figure 15 - Explosion pressure for starch-air and starch-2% methane-air; predicted and observed.

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APPENDIX I

1. Shock Tube Relations and Impulsive Jet Duration

To calculate the pressure driving the dispersion jets a shock tube analysis was performed for the dispersion system. The analysis is based on standard shock tube analysis as outlined in reference [1]. Also it demonstrates that the jets emerging from the driven section are of equal strength.

A schematic of the shock tube is shown in the figure below; consisting of the low pressure driven section, 1, and the high pressure driver section, 4.

4 1 L.P. "Driven" H.P. "Driver"

(1)(\$) (2) (4 C,

Upon rupturing the diaphragm an expansion wave begins to travel to the right at the speed of sound for gas condition 4, a_4 , and a shock travels to the right with velocity c_s . The shocked gas, to the left of the contact surface, is at condition 2 and the expanded gas, to the right of the contact surface is at condition 3. Across the contact surface the following conditions hold:

- $\mathbf{p}_3 = \mathbf{p}_2$ (1)
 - (2)

Also considering isentropic compression and expansion of the gases the following relations for u_2 , u_3 , p_2 , and p_3 can be derived:

$$u_{2} = a_{1} \left[\frac{p_{2}}{p_{1}}^{-1} \right] \sqrt{\frac{2/\tau_{1}}{(\tau_{1}+1)(p_{2}/p_{1}) + (\tau_{1}-1)}}$$
(3)
$$u_{3} = \frac{2a_{4}}{(\tau_{4}-1)} \left[\frac{1 - p_{3}}{p_{4}}^{(\tau_{4}-1)/2\tau_{4}} \right]$$
(4)

Substituting equations 3 and 4 into equation 2 one arrives at the following:

$$\frac{\mathbf{p}_{4}}{\mathbf{p}_{1}} = \frac{\mathbf{p}_{2}}{\mathbf{p}_{1}} \begin{bmatrix} 1 - \frac{(\tau_{4} - 1)(a_{1}/a_{4})(\mathfrak{p}_{2}/\mathfrak{p}_{1} - 1)}{\sqrt{(2\tau_{1})}\sqrt{(2\tau_{1} + 1)(\mathfrak{p}_{2}/\mathfrak{p}_{1} - 1)}} \end{bmatrix} \frac{-2\tau_{4}}{(\tau_{4} - 1)}$$
(5)

Note that the pressures can be related as follows using equation 1:

$$\frac{\mathbf{p}_3}{\mathbf{p}_4} = \frac{\mathbf{p}_3}{\mathbf{p}_1} \frac{\mathbf{p}_1}{\mathbf{p}_4} = \frac{(\mathbf{p}_2/\mathbf{p}_1)}{(\mathbf{p}_4/\mathbf{p}_1)}$$
(6)

Hence by rearranging equation 6, we get an implicit equation for p_2 as a function of the initial conditions.

$$\frac{p_4}{p_2} = \begin{bmatrix} 1 - \frac{(\tau_4^{-1})(a_1/a_4)(p_2/p_1)}{\sqrt{(2\tau_1)}\sqrt{(2\tau_1^{+}(\tau_1^{+1})(p_2/p_1^{-1}))}} \end{bmatrix}^{\frac{-2\tau_4}{(\tau_4^{-1})}} (7)$$

For the present case two simplifying assumptions can be made. Since the high and low pressure gas are of the same mixture, and τ does not vary significantly with pressure, one can assume: Also, because the initial temperature of the driver and driven sections are the same, $T_1=T_4=T$,

 $a_A = a_1 = a$

Thus equation 7 can be expressed more simply as:

$$\frac{p_4}{p_2} = \frac{1}{\sqrt{(2\tau)}} \left[\frac{(\tau-1)(p_2/p_1-1)}{\sqrt{(2\tau+(\tau+1)(p_2/p_1-1))}} \right]^{-2\tau/(\tau-1)}$$
(8)

For the mixtures encountered in the present study, which are mostly air (>90%), the initial conditions are:

R=0.287 kJ/kg-K, τ =1.4, a= 344 m/s at T= 295 K, ³p₄=10.52 bar, p₁=1.01 bar

where R is the gas constant. By solving equation 8 iteratively, one obtains the result:

$$p_{A}/p_{2}=2.70.$$

Consulting the gas tables one obtains the shock Mach number,

$$M_{a} = c_{a} / a = 1.865.$$

Thus the shock traverses the driven section at a speed of 642 m/s. As the driven section of the shock tube, the perforated copper tube, is 2 m long the time required for one traverse is 3.1 msec. As will be shown this is considerably shorter than the time required to vent the shock tube through the perforated jets.

2. Efflux from the Perforated Tube

To estimate the duration of the dispersion jets the flow rates are calculated assuming the pressure in the shock tube has reached quasi-equilibrium. Because the shock traverses the tube in a relatively short time the equilibrium pressure at the start of the process, p_0 , is assumed to be produced by adiabatic expansion of the high pressure gas into the driven section of the shock tube:

$$P_0 = \frac{p_4 V_4^{T}}{(V_4 + A V)^{T}}$$
 ((9)

In the above expression V_4 is the volume of the driver section and V is the additional volume occupied by the high pressure gas after it has expanded, such that:

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$$AV = \frac{(AV_1 - V_4)}{(1 + A)}$$
(10)

where V_1 is the volume of the driven section and A is expressed as:

 $\mathbf{A} = \begin{bmatrix} \mathbf{p}_4 \\ \mathbf{p}_1 \end{bmatrix}^{1/\mathsf{T}} \mathbf{V}_4 \\ \mathbf{V}_1$

 $T_{3} = \frac{p(V_{4} + AV)}{p_{4}V_{4}} T$ (12) $T_{2} = \frac{p(V_{1} - AV)}{p_{1}V_{1}} T$ (13)

Hence the mass average temperature in the tube is given by:

$$o = \frac{(V_4 + \Delta V)T_3 + (V_1 - \Delta V)T_2}{V_{\text{Total}}}$$

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(11)

(14)

For the present experimental conditions described above in which

 $V_A=3.25$ liters and $V_1=2.28$ liters,

we get:

 $T_0 = 278 \text{ K}, \text{ p} = 5.94 \text{ bar}.$

The time required to vent the shocked gas through the dispersion holes is calculated as adiabatic efflux from a closed vessel to the atmosphere. This is not a bad assumption, because the shock tube is very small compared to the volume of the test vessel, (\equiv 3%). This is described in detail in reference [2].

Let the subscript "o" denote the initial gas condition and "1" the condition of the discharging gas. The conservation of mechanical energy yields:

$$\frac{\tau}{(\tau-1)} \frac{p_1}{\rho_1} + \frac{u_1^2}{2} = \frac{\tau}{(\tau-1)} \frac{p_0}{\rho_0}$$
(15)

where u₁ is the average speed of the discharging fluid and 1 is the density. Therefore the mass flux, Q, through the vessel is:

 $Q = F \rho_1 u_1$

where F is the total orifice area. Simultaneous solution of equations 15 and 16, assuming adiabatic expansion of the gas, allows u_1 to be expressed in terms of the pressure in the vessel.

 $u_{1} = \sqrt{\frac{2\tau}{(\tau-1)}} \frac{p_{0}}{\rho_{0}} [1-x^{(\tau-1/\tau)}]$

(17)

. (16)

In the above expression X is the non-dimensional pressure, p_1/p_a , where p_a is atmospheric pressure. For sonic flow through the orifice X=X_{cr} where:

$$X_{cr} = \frac{2}{\tau+1}$$
 (18)

Hence the maximum flowrate, when $X \leq X_{cr}$, is given by combining equations 16 and 17.

$$Q_{\text{max}} = F \rho_0 \left[\frac{2}{\tau+1} \right]^{1/(\tau-1)} \left[\frac{2\tau}{\tau+1} \right] \frac{p_0}{\rho_0}$$
(19)

When $X > X_{cr}$, Q is given by equations 16 and 17. The discharge time is calculated by considering the discharge in two parts:

for
$$p_a \le X \le X_{cr}$$

 $\overline{p_o}$

for $X_{cr} < X \leq 1$.

During the efflux cess the pressure, density and temperature inside the shock tube vary and these are accounted for by considering equation 15 and adiabatic expansion. the resulting equations for t_1 and t_2 are formed by integrating the discharge rates over the respective intervals.

$$t_{1} \frac{\tau(\tau-1)F}{2} \sqrt{\frac{2\tau}{(\tau-1)RT}} = \frac{-1 + \left(\frac{P_{a}}{P_{a}X_{c}}\right)^{(\tau-1)/2\tau}}{C_{q} \left(\frac{2}{\tau+1}\right)^{1/(\tau-1)} \sqrt{\frac{\tau-1}{\tau+1}}}$$
(20)



The two equations were solved numerically assuming a discharge coefficient, $C_q=0.95$ which is probably high considering the flow is actually passing through many small holes and F is the total orifice area. For the initial conditions previously calculated the discharge times are:

 $t_1=61.3$ msec, $t_2=20.4$ msec therefore $t_{total}=81.7$ msec.

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2. Ginzburg, I.P., "Applied Fluid Dynamics", U.S. Department of Commerce, Washington D.C., (1963), NASA TT F-94, pp. 206-209.

Program to Calculate Efflux From a Vessel



8.7

L FUNCTION FUNCT(X) COMMON GAMA,GAMAM,PP A=-(3.WGAMA-1:)/2./GAMA B = GAMAM/GAMA C = PPHNB FUNCT, = (XHMA)/SQRT(1.-CM(XHM(-B))) RETURN END L

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T1	0.61282-01	SECONDS
TZ	Q.2041E-01	SECONDS
Π	0, 8169E-01	SECONDS
	PO = 0.5940E	+01 ₁

APPENDIX II

Calculation of Flame Speed and Burning Velocity from Pressure History

This analysis is based upon theory for gas explosion in a spherical bomb [1]. The flame is assumed to be thin with respect to the dimension of the vessel. A schematic of a long horizontal tube, with a flame propagating from right to left, is shown below. The length of the tube is L, the cross sectional area is \hat{A} , and the position of the flat flame is.

x_b. ХP S, Re NIRNET UNBURNT

In reference [1] it is shown than the initial volume of the burnt gas at time t, occupied a volume given by:

$$\frac{x_{o}}{L} = \frac{p - p_{o}}{p_{e} - p_{o}} = \frac{m_{b}}{m_{o}} = n$$
 (1)

where p is the pressure at time t, p_0 is the initial pressure in the tube, and p_e is the maximum explosion pressure. m_b and m_0 are the burned gas mass and the mass of the mixture respectively. This, can also be stated as: the overpressure at time t is proportional to the fraction of ' gas burned.

The volume occupied by the burned gas, λx_b , can be found by subtracting the volume of the unburned gas from the total volume of the vessel.

$$Ax_{b} = AL - m_{o}(1-n)(RT_{u}/p)$$

2)
R'is the gas constant for the unburned gas, and T_u is the temperature of the unburned gas. T_u can be determined assuming isentropic compression of the gas ahead of the flame:

$$T_{u} = T_{o} \left[\frac{p}{p_{o}} \right]^{(\tau-1)/\tau}$$
(3)

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where T is the ratio of the specific heats for the unburned gas, and T_o is the initial gas temperature. Substituting -equations (3) and (1) into equation (2) one has:--

$$Ax_{b} = AL - m_{o} \frac{(p_{e}-p)}{(p_{e}-p_{o})} \left[\frac{RT_{o}}{p_{o}} \right] \left[\frac{p}{p_{o}} \right]^{-1/T}$$
(4)

Differentiating equation (4) with respect to time yields an expression for $dx_b/dt=R_f$.

$$\frac{dx_{b}}{dt} = R_{f} = \frac{1}{A} \left[\frac{m_{o}}{p_{e} - p_{d}} \right] \frac{1}{p_{o}} \left[\frac{p}{p_{d}} \right]^{1/\tau} \frac{dp}{dt} \left[\frac{1 + p_{e} - p}{\tau p} \right]$$
(5)

The initial mass of the tube can be expressed as:

$$m_{o} = \rho_{o} L A \qquad (6)$$

and substituting equation (6) into equation (5) yields:

$$\dot{\mathbf{R}}_{f} = \frac{d\mathbf{p}}{dt} \frac{\mathbf{L}}{(\mathbf{p}_{e} - \mathbf{p}_{o})} \left(\frac{\mathbf{p}}{\mathbf{p}_{o}}\right)^{T} \left\{ \frac{1 + 1}{\tau} \left[\frac{\mathbf{p}_{e}}{\mathbf{p}_{o}} - 1 \right] \right\}$$
(7)

The burning velocity can be extracted from equation (7) by considering that:

$$\mathcal{F}_{f} = S_{t} (1 + \rho_{u}/\rho_{b}), \qquad (8)$$

and

$$\frac{\rho_{\rm u}}{\rho_{\rm b}} = \frac{1}{\tau} \left[\frac{p_{\rm e}}{p} - 1 \right] \tag{9}$$

Calculation of Burnout Time for Laminar Methane-Air

Knowing that the mass burning rate is given by

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$$dm_b/dt = S_L \rho_{ij} A \qquad (10)$$

and ρ_u increases isentropically with increasing P_u , and assuming that the laminar burning velocity is constant with respect to temperature and pressure of the unburned gases, the following is obtained:

$$\frac{dm_{b}}{\left[\left(\frac{m_{b}}{m_{o}}\right)\left(\frac{p_{e}-p_{o}}{p_{o}}\right)^{+1}\right]^{1/\tau}} = \lambda \cdot S_{L} \rho_{o} \cdot dt \qquad (11)$$

Equation (10) can be integrated and the time for $m_b/m_0^{=1}$ found. The results are summarized below for various methane-air mixtures.

G∘ [% _{vol}]	Pe,ad	S _L [m/s]	,b [s]	۲ ⁰ /۱ ^۶
5	5.10	0.12	8.43	0.25
6	5.83	0.16	5.98	0.35
7	6.53	0.22	4.14	0.50
8	7.15	0.31	2.83	0.73
9	7.63	0.42	2.07	1.00
10	7.92	0,45	1.86	1.11
1	-			

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Experimental Results

The calculations is shown in the tables below illustrate the following pattern of flame development.

1. Rapid burning because of i) increasing surface area of the flame as it initially grows spherically and in which regime the calculations are not applicable, and ii) free expansion of unburned gases.

2. Steady burning at rate S, however R_f decreases because pressure in the tube increases. More work is required to compress the gas ahead of the flame.

3. Decreasing S and \hat{R}_{f} to the point near the wall where $\hat{R}_{f}^{\pm}S$. This is due to reduction in turbulence associated with lower convective speed of the gases. Near the wall the flame does not propagate by convection, rather by diffusion only.

REFERENCE

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<u>7% Methane-Air:</u> $p_e=6.85$ bar $S_L=0.22$ m/s

p	dp/dt	S [m/s]	R _f [m/s]
[bar]	[bar/s]		
1.82	81.3	19.0	56.6
2.50	74.8	14.0	31.3
. 3.18	40.3	6.3	11.6
3.86	51.2	7.0	10.9
4.54	53.4	6.5	9>- 0
5.22	47.1	5.2 '	6.4
6.03	49.1	. 4.9	5.4
6.44	51.2	• 4.9	5.1

<u>9% Methane-Air:</u> p_e=8.69 bar

S_L=0.42 m/s

	p [bar]	dp/dt [bar/s]	S _T [m/s]	R _f [m/s]
	1.54	126	25.3	109.0
	3.04	79	9.7	22.5
	4.26	122	11.8	20.6
	5.35	151	12.4	18.0
	7.26	174	11.5	13.2
ŗ	8.48	126	7.5	7.6

A¥.

p_e=6.85 bar

p [bar]	dp/dt [bar/s]	. S _T [m/s]	R _f [m/s]
1.82	51.7	12.1	36.0
2.36	67.3	13.1	30.9
3.18	21.2	3.3	6.1
3.85	32.4	° 4.4	6.9
4.53	43.5	5.3	7.3
5.76	47.1	4.8	5.5
ه ، 58 ک	32.4	3.0	3.1

3% Methane+ 200 g/m³ Starch: p_e=7.80 bar / ₽ ; dp/dt $\mathbf{s_T}$ P ^Rf [bar/s] [bar] [m/s] [m/s] 1.68 67.3 14.4 51.7 2.49 89.0 14.3 36.1 3.05 47.1 6.6 13.9 3.85 61.1 7.2 12.5 4.54 70.9 7.4 11.2 5.22 , 75.0 7.1 9.6 5.90 83.6 7.3 9.0 7.26 49.1 3.7 3.9 7.73 5.8 0.4 0.4 1