Ignition and propagation of dust explosions
Ignition and propagation of dust explosions

PROEFSCHRIFT

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Summary

This thesis presents an overall model of the mechanism of dust explosions. The ignition process of a dust explosion in general is defined by the balance of the rate of heat production and the rate of heat loss to the surroundings. Ignition parameters such as the Minimum Ignition Energy, the Minimum Ignition Temperature and the Maximum Experimental Safe Gap can be derived by using this balance. However, very small ignition volumes, smaller than the critical ignition kernel, need extra energy to ignite. Burning dust clouds with volumes smaller than this critical ignition kernel can not initiate a dust explosion. A unique laser ignition method has been applied to determine the kinetic data of the ignition reaction and to study the phenomenon of the critical ignition kernel.

A step-by-step approach was chosen in studying the propagation of a dust explosion. First the laminar burning velocity was investigated, then the role of turbulence in dust explosion propagation and finally the rate of pressure rise in a closed vessel due to a propagating dust explosion.

The laminar propagation velocity of dust explosions appears to be determined mainly by thermal conduction. Burner experiments and closed vessel experiments were used to approach the laminar burning velocity. The agreement with theoretical models is strongly dependent on the choice of the dynamic ignition temperature, a parameter which is difficult to model or to measure. This dynamic ignition temperature is different from the Minimum Ignition Temperature, as the latter is determined using a much longer heating time scale.

The effect of turbulence in closed explosion vessels can be incorporated by adding the turbulent and the molecular diffusion components. The large thickness of a typical dust flame usually exceeds the dimensions of the eddies of the turbulent flow. The wrinkled flame theory from gas explosion fundamentals has therefore been replaced by a mixed flame theory. This mixed flame theory is based on an increased transport of heat in the flame front by small eddies. The effect of turbulence on dust explosion propagation is determined by the intensity and the scale of the turbulence. Experiments show a good agreement with this theory for a number of powders.

In order to accurately simulate the development of explosion pressure in a closed spherical vessel, it is necessary to incorporate the thickness of the flame front into the conventional model. Especially dust explosions appear to develop thick flame fronts. Relatively large vessels should therefore be used in dust explosion testing to allow application of the cubic law. This cubic law assumes an infinitely thin flame front propagating in a closed spherical vessel. It is nevertheless possible to apply small vessels for dust explosion testing by adjusting the level of turbulence inside the vessel.

To better test the correctness of the dust explosion propagation theory, a high pressure, high temperature explosion bomb has been built. This apparatus allows study of the propagation of dust explosion at high temperatures, high pressures, high levels of turbulence and extreme stoichiometric conditions.
Samenvatting

Dit proefschrift geeft een algemene beschrijving van het mechanisme van stofexplosies. Het proces van ontsteking van stofexplosies wordt bekeken aan de hand van een balans van de warmteproductie door de verbranding en de afvoer van warmte naar de omgeving. Bekende ontstekingsparameters zoals de minimale ontsteekelementemperatuur, de minimale ontsteekeenergie en de 'maximum experimental safe gap' kunnen verkregen worden met behulp van deze balans. Een uitzondering wordt gemaakt voor ontsteekvolumina kleiner dan het kritische ontsteekvolume. Deze volumina hebben een extra hoeveelheid energie nodig om te expanderen tot het kritische volume. Dit kritische volume is het kleinste volume van een brandende stofwolk dat nog een vlamvoortplanting kan veroorzaken. Een unieke laser ontsteekmethode is toegepast om deze verschijnselen te onderzoeken.

Voor het bestuderen van de voortplanting van stofexplosies is gekozen voor een stapsgewijze aanpak. Achtereenvolgens zijn de laminaire brandsnelheid, de invloed van turbulentie op deze brandsnelheid en de methoden voor het omrekenen van een verbrandingsnelheid naar een drukstijging in een gesloten vat bestudeerd.

Uit dit proefschrift blijkt dat de laminaire brandsnelheid van stofwolken vooral bepaald wordt door het warmtetransport door geleiding. Tevens blijkt uit vergelijking van experimentele resultaten en modelberekeningen dat de dynamische ontsteektemperatuur in het vlamfront een belangrijke parameter is. Gebrek aan kennis van deze parameter maakt het modelleren van de laminaire verbrandingsnelheid nog moeilijk.

De grote dikte van het vlamfront maakt het onwaarschijnlijk dat vergroting van het vlamfrontoppervlak door de wervels in de stroming de brandsnelheid van het poedermengsel vergroot. Het effect van turbulentie op de verbrandingsnelheid komt dan ook vooral tot uiting in een verhoogde thermische geleidbaarheid van het mengsel. Zowel de schaal als de intensiteit van de turbulentie spelen daarbij een rol. Experimenteel blijkt deze theorie voor een groot aantal poeders op te gaan.

Om uit de verbrandingsnelheid van een poedermengsel de drukstijging in een gesloten vat te berekenen is het noodzakelijk de dikte van het vlamfront in de berekening mee te nemen, stofexplosies blijken zich namelijk over het algemeen met relatief dikke vlamfronten voort te planten. Dit heeft ook consequenties voor het gebruik van de bekende kubische wet. Deze wet kan alleen gebruikt worden voor grotere vatens of er moet een correctie voor de vlamfrontdikte toegepast worden.

Om in de toekomst het inzicht in het mechanisme stofexplosies verder te verdiepen is een speciale 20 liter explosiebol ontworpen. Deze bol is geschikt voor proeven bij verhoogde druk, verhoogde temperatuur en hoge turbulentieniveaus. Tevens is de bol bestand tegen puur zuurstof zodat ook de chemische reaktiesnelheid effektief beïnvloed kan worden.
## Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>constant</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>surface area</td>
<td>m²</td>
</tr>
<tr>
<td>AIT</td>
<td>auto ignition temperature</td>
<td>K</td>
</tr>
<tr>
<td>b</td>
<td>constant</td>
<td></td>
</tr>
<tr>
<td>Cₚ</td>
<td>specific heat</td>
<td>J kg⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Cₛ</td>
<td>solid concentration</td>
<td>kg/m³</td>
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<tr>
<td>C</td>
<td>concentration</td>
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<tr>
<td>D</td>
<td>diffusion coefficient</td>
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<td>D</td>
<td>diameter</td>
<td>m</td>
</tr>
<tr>
<td>d, d₅₀, dₚ</td>
<td>average particle diameter</td>
<td>m</td>
</tr>
<tr>
<td>E</td>
<td>energy</td>
<td>J</td>
</tr>
<tr>
<td>Eₐ</td>
<td>activation energy</td>
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</tr>
<tr>
<td>h</td>
<td>heat transfer coefficient</td>
<td>W m⁻² K⁻¹</td>
</tr>
<tr>
<td>I</td>
<td>turbulence intensity</td>
<td>-</td>
</tr>
<tr>
<td>k</td>
<td>reaction rate constant</td>
<td></td>
</tr>
<tr>
<td>Kₐ</td>
<td>absorption factor</td>
<td>-</td>
</tr>
<tr>
<td>Kₛ, Kₛₘ</td>
<td>normalised rate of pressure rise</td>
<td>bar m/s</td>
</tr>
<tr>
<td>L</td>
<td>inter-particle distance</td>
<td>m</td>
</tr>
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<td>mass</td>
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</tr>
<tr>
<td>Mₐ</td>
<td>solid molecular mass</td>
<td>g/mol</td>
</tr>
<tr>
<td>MESG</td>
<td>maximum experimental safe gap</td>
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</tr>
<tr>
<td>MIE</td>
<td>minimum ignition energy</td>
<td>J</td>
</tr>
<tr>
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<td>pressure</td>
<td>bar, Pa</td>
</tr>
<tr>
<td>Pₘₐₓ</td>
<td>maximum explosion pressure</td>
<td>bar, Pa</td>
</tr>
<tr>
<td>Qₗₒₛₙ/pₐₒₑₙ</td>
<td>volumetric rate of energy</td>
<td>J m⁻³ s⁻¹</td>
</tr>
<tr>
<td>Q</td>
<td>heat of combustion</td>
<td>J/kg</td>
</tr>
<tr>
<td>QD</td>
<td>quenching distance or diameter</td>
<td>m</td>
</tr>
<tr>
<td>R, r</td>
<td>radius</td>
<td>m</td>
</tr>
<tr>
<td>R</td>
<td>universal gas constant</td>
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</tr>
<tr>
<td>R(τ)</td>
<td>correlation function</td>
<td>-</td>
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<tr>
<td>Sₛₒₐₛ</td>
<td>solid surface area</td>
<td>m²/m³</td>
</tr>
<tr>
<td>Sₜ</td>
<td>burning velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
<td>s</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
<td>K</td>
</tr>
<tr>
<td>uₖₒₜₜ</td>
<td>flow velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>u'</td>
<td>rms value of the velocity</td>
<td></td>
</tr>
<tr>
<td>v</td>
<td>velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>V</td>
<td>volume</td>
<td>m³</td>
</tr>
<tr>
<td>x</td>
<td>position</td>
<td>m</td>
</tr>
</tbody>
</table>
\( \alpha \) emission efficiency of particle cloud
\( \gamma \) ratio of specific heats
\( \delta_{ash} \) thickness of ash layer
\( \delta_p \delta_r \) thickness of the reaction zone
\( \epsilon \) emission factor
\( \eta \) viscosity
\( \lambda \) thermal conductivity
\( \mu \) viscosity
\( \nu \) kinematic viscosity
\( \rho \) density
\( \sigma \) Stefan Boltzmann constant
\( \tau \) time scale
\( \phi \) fraction of unreacted solid
Chapter 1

Introduction

1.1 Description of the subject

For more than two centuries dust explosions have been known to occur. The first recorded incident is the famous flour dust explosion in Turin in 1785 [Bartknecht, Field]. At that time it was thought that gases produced by the organic dust caused the explosion and the subsequent fire. In the next decades dust explosions were reported in processes involving starch, aluminium, chocolate, paper, and rubbers. Especially elevators, mills and silos have been subjected to explosion damage during these years. In the 20th century a better understanding of the dust explosion phenomenon led to the recognition of the risk

![Diagram showing the basic conditions for a dust explosion]

*Figure 1.1 Basic conditions for a dust explosion.*
of dust explosions in a wide range of industries. Typical industries at risk are those handling agricultural products, foodstuffs, pharmaceuticals, chemicals, polymers and rubbers, metals, wood, and coal [Field].

In general, dust explosions can occur whenever a combustible dust, sufficiently dispersed in air, contacts an ignition source. Figure 1.1 summarizes the three most important conditions for a dust explosion: a combustible dust, a dispersive air flow, and an ignition source. A fourth condition is a certain degree of containment of the dust cloud, but in practice dust explosions can occur without fulfilling this condition.

A wide variety of powders are proven to be explosive under specified conditions. As for the dispersion, a simple draught of air is usually sufficient to disperse some accumulated dust, and in many industrial processes dust/air mixtures are already present in explosive ratios. The ignition source necessary to initiate the explosion is also easy to obtain: mechanical sparks from tools or machinery, smouldering particles in dust heaps, static electricity, hot surfaces or fires are some of the most common causes of dust explosions. However, the ignition source of industrial dust explosions is still unknown in 25% of the cases [Bartknecht].

When dust explosions are compared with gas explosions, both differences and similarities appear. The most important difference is the heterogeneous character of dust explosions. This contrasts with the homogenous nature of gas explosions, in which the reactants are mixed on a molecular level. A dust/air mixture always consists of solid particles surrounded by gaseous oxygen. The combustion of the dust is always limited by the transfer of heat or mass to or from the available solid surface or by the rate of chemical reaction at the solid surface.

Another aspect of dust clouds is the need for a dispersive air flow to prevent the particles from depositing. This contrasts with quiescent gas mixtures, which remain stable indefinitely. These two deviating aspects of dust explosions explain the enormous difference in the level of understanding of gas and dust explosions. Combined with the much lower frequency of dust explosion accidents, the result is a poor theoretical understanding of the various aspects of dust explosions.

In spite of these differences, however, many similarities exist between gas and dust explosions. In both cases the same distinction can be made in propagation mechanism: deflagrations or combustion waves and detonations.

An explosion is classified as a deflagration when the flame front propagates due to the transport of heat and mass in front of the flame front. The mechanism of heat transfer can be either radiation, conduction or convection, while mass transport is by diffusion or convection. In unconfined, quiescent gas clouds, a typical propagation speed of 0.1 - 10 m/s can be attained. Turbulence or confining walls can increase this speed up to several hundreds of meters per second. Due to their heterogeneous nature, dust explosions propagate with speeds an order of magnitude slower. The exchange of mass and heat at
the solid surface takes considerably more time than the molecular reactions of gas explosions.

A suitable fuel/air mixture can detonate spherically when it is ignited by a charge of high explosive. Detonations can also develop in tube-shaped systems by the coalescence of flame-generated pressure pulses into shock waves. A detonation itself is generally defined as a shock wave sustained by the energy of the chemical reaction initiated by the temperature and pressure of the detonation wave. Typical detonation wave velocities in gaseous systems are 1000-3500 m/s [Lewis and Von Elbe]. Although detonations seldom occur in dust/air mixtures, they are very well possible. With the aid of strong flame jet or shock wave detonation drivers, it has proven to be possible to achieve detonations in dust clouds of small and reactive particles [Lee, Wolanski]. Dust detonation waves can also travel with speeds well over 1000 m/s.

Another important resemblance between gas and dust explosions is the damage they cause in industrial accidents. Both kinds of explosion can produce destructive air blasts and initiate fires through their hot combustion products. Therefore practical methods of prevention or suppression of dust explosions have also been developed. Despite the lack of theoretical understanding, it has been possible by means of expensive, full scale dust explosion tests to develop all kinds of explosion proof constructions, explosion vents, extinguishing equipment or preventive measures, like inverting of the explosive mixture and the guarding against ignition sources.

In the last decade, however, the introduction of computer simulation of gas explosions in industrial environments has shown the need for reliable fundamental knowledge of the mechanisms of dust explosions. A better understanding of the nature of dust explosions will almost certainly be more efficient in developing more effective measures of dust explosion prevention or suppression than the purely empirical approaches employed so far.

1.2 Aims and structure of the research programme

In the first place it is important to gain more insight into the nature of dust explosions. Therefore, a thorough understanding of the parameters which can influence a dust explosion is necessary.
In addition to studying the dust explosion parameters, this thesis also looks into the ignition process and the role of turbulence in the propagation of dust explosions. Furthermore, an effort is made to develop a qualitative and quantitative overall description of the propagation.

A step-by-step approach was chosen in this dust explosion programme. An inventory of the important chemical and physical properties of the powder suspension and knowledge of the combustion mechanism and heat and mass transfer relationships form the basis
Figure 1.2  
Structure of the research programme on dust explosion indices and description of the propagation mechanism. Dashed lines represent the intermediate steps necessary for the calculations of the desired properties.
of an ignition model of a dust cloud as well as a mathematical model of the laminar burning velocity. Experiments to test this theory are performed, and it is shown that the experimental results support the theory developed. Empirical relationships between the burning velocity and turbulence characteristics of the dust cloud are necessary in order to translate the imaginary laminar burning velocity into a realistic turbulent burning velocity. This turbulent burning velocity can then be used to calculate the desired explosion indices, such as explosion pressure and rate of pressure rise in closed vessels. In Figure 1.2 the structure of the research programme is summarized. In this figure the two starting points of the programme are defined: the dust and the apparatus. To obtain the ignition properties of a dust cloud in a certain environment, the kinetic data of the dust together with the heat transfer data of the environment are supposed to be the key parameters (Chapter 3). Furthermore the dust properties are supposed to determine the laminar burning velocity of the dust cloud (Chapter 4). Combined with the properties of the flow inside the apparatus, this laminar burning velocity can be translated into a turbulent burning velocity of the specific dust in this apparatus (Chapter 5). Finally knowledge of the dimensions and the shape of the apparatus will make it possible to calculate the rate of pressure rise inside the apparatus due to an explosion of the specific dust (Chapter 6).

This approach was chosen in order to gain a more fundamental understanding of dust explosion phenomena. The numerical gas dynamic methods used to simulate gas explosions give little or no insight into the mechanism of dust explosions. They only predict the effects of the explosion as a whole, based on the assumption of simple particle combustion mechanisms and the neglect of the different regions of particle-fluid interactions. In this thesis, however, the complex dust explosion mechanism is separated into independent steps. At every separate step, the theoretical view is compared with experiments. In the end, it should be possible to construct a more or less complete description of the mechanism of dust explosions (Chapter 7).

Finally, this work is certainly not complete. It is more in the nature of an orientation on methods of dust explosion investigation. Hopefully, it will serve as the foundation of an explosion group at Delft University of Technology, working in close cooperation with the group Explosion Protection and Prevention of PML-TNO in Rijswijk, the Netherlands.

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Chapter 2

Introduction to dust explosion testing

Modern dust explosion literature can be divided into two major areas: one focused on direct industrial applications of the test methods on dust explosions and another, more theoretical, attempting to gain a better insight into the nature of dust explosions. This chapter reviews the current knowledge on dust explosion testing as well as the physical and chemical parameters which are known to influence the course of dust explosions. The more fundamental studies of the nature of dust explosions are treated extensively in the next chapters concerning the different aspects of the mechanism of propagation of a dust explosion.

2.1 Dust explosion testing

When dusts are to be tested three major questions arise: is the dust explosive, what is the maximum severity of the resulting dust explosion and what is the ignition sensitivity of the dust?

2.1.1 Explosibility

An explosion can be defined as "a propagation of a flame in a pre-mixture of combustible gases, suspended dust(s), combustible vapour(s), mist(s), or mixtures thereof, in a gaseous oxidant such as air, in a closed, or substantially closed, vessel" [ISO]. A shorter definition is "an explosion is a rapid combustion with a marked and measurable pressure increase" [VDI guideline]. When a dust is tested on explosibility a sufficiently strong ignition source should be used, and the dust concentration must be within the explosion limits. The explosion limits are the fuel concentrations between which an explosion is possible.

2.1.2 Explosion severity

The explosion severity is usually expressed in terms of the explosion indices $P_{\text{max}}$ and $K_{\text{St}}$. And $P_{\text{max}}$ is the maximum overpressure attained during an explosion relative to the pressure in the vessel at the time of ignition. The term $P_{\text{max}}$ is sometimes reserved for the maximum value of the overpressure determined over a wide range of dust concentrations [ISO]. The explosion index $K_{\text{St}}$ is defined as the maximum rate of pressure rise with time $(dP/dt)_{\text{max}}$ of an explosion in a closed volume $V$, according to
the so-called cubic relationship [ISO]:

\[ K_{st} = \left( \frac{dP}{dt} \right)_{max} \frac{1}{V^{3/2}} \]

Again, the symbol \( K_{st} \) is sometimes reserved for the maximum value of \( K_{st} \) determined over a wide range of dust concentrations. Figure 2.1 shows a schematic drawing of a pressure-time plot during a dust explosion in a closed volume. In this figure the important parameters are explained.

\[ \text{Figure 2.1} \quad \text{Recording of the pressure, } P, \text{ against the time, } t, \text{ during an explosion. The explosion is initiated at time } t_0. \text{ The maximum explosion pressure is called } P_{\text{max}} \text{ and the maximum rate of pressure rise is } \left( \frac{dP}{dt} \right)_{\text{max}} \]

2.1.3 Sensitivity of dust suspensions to ignition sources

The quantification of the sensitivity of dust suspensions is necessary to determine the level of preventive measures against possible ignition sources. Although a large number of different ignition sources exists, the ignition sensitivity is usually defined by two
parameters: the minimum ignition energy (MIE) and the minimum ignition temperature (MIT).

The minimum ignition energy is defined as the lowest electrical energy stored in a capacitor which, once discharged over a spark gap, barely ignites the most optimal dust concentration in air [Bartknecht]. This MIE is therefore a measure of the sensitivity of powder to explosions initiated by (static) electricity or mechanical sparks produced by grinding or friction.

The minimum ignition temperature is the lowest temperature of a surface which will just ignite the most readily ignitable dust mixture in air [Bartknecht]. The value of MIT can be seen as a measure of the ignitability of dust clouds by hot surfaces or high temperatures arising as during welding, friction, fires and to some extent mechanical sparks.

2.2 Dust explosion test equipment

Many types of apparatus have been developed to measure the above mentioned parameters. This chapter will only summarize the equipment which was used during the measurements described in this thesis. These instruments are accepted in Europe to be the standard equipment for dust explosion testing. Field gives an extensive overview of the equipment and procedures in use in other countries. These are usually not essentially different from the methods described here, except for differences in the volume of some vessels, energies of ignition sources, or methods of dust dispersion.

2.2.1 The 1 m³ vessel

This explosion vessel is the only really standard piece of equipment [ISO]. In Figure 2.2 the most important parts of this vessel are drawn. It consists of a cylindrical explosion vessel with a volume of 1 m³ and an aspect ratio of about 1. A 5.4 litre container is used as a dust storage container. Before the explosion, this container is pressurized up to a pressure of 20 bar. The dust container is connected to the explosion vessel with a quick acting valve of 3/4 inch diameter. When an explosion is performed, the valve is opened and the dust is dispersed into the explosion vessel by pressurized air passing through a semicircular spray pipe with 44 holes of 5 mm diameter. After a delay time of 600 ms, the igniter in the centre of the explosion vessel is activated, and the explosion is monitored by a pressure transducer and a recorder.

Before opening the vessel after an explosion it is purged with air to remove toxic or dusty material. To prevent interaction of the different experiments, careful cleaning of the vessel is always necessary.

The ignition source used in the 1 m³ vessel is a pyrotechnic igniter with a total energy of 10 kJ. The igniter contains 2.4 gram of a mixture of 40% zirconium powder, 30% barium nitrate and 30% barium peroxide. An electric fuse head activates the chemical
reaction of these components.

**Figure 2.2**  Schematic drawing of the 1 m³ explosion vessel, equipped with a dust container, quick acting valve, spray pipe, igniter and pressure transducer. A connection is made to purge the vessel with air. From Bartknecht.

The 1 m³ vessel can be used to measure several explosion indices: explosibility, explosion limits, $P_{\text{max}}$ and $K_{\text{St}}$. If the vessel is equipped with an electric spark circuit instead of the pyrotechnic ignition source, it is also possible to determine the value of the minimum ignition energy.

2.2.2 The 20 litre sphere

For the testing of expensive powders, an explosion vessel with a volume of 20 litre has been developed. According to ISO norm 6184/1, explosion vessels with volumes other than 1 m³ can be accepted. These vessels must give equal results (within 20%) for the explosion indices, for at least five dusts, in each of the following ranges:

- $K_{\text{St}} < 200$ bar.m/s
- $200 < K_{\text{St}} < 300$ bar.m/s
- $K_{\text{St}} > 300$ bar.m/s

Siwek [1977] found, after extensive experimental testing of different sized vessels, that 20 litre is the smallest vessel which still satisfies the demands in this ISO norm. An
important detail is the fact that he used 10 kJ igniters in all the vessels during the experiments.

![Diagram](image)

**Figure 2.3**  *The 20 litre sphere as developed by Siwek.*

The equipment consists of a 20 litre spherical vessel with a water jacket and a 0.6 litre dust storage container. The procedure is somewhat different from the procedure in the 1 m³ vessel: the explosion vessel is evacuated down a pressure of 0.4 bar in order to produce an initial pressure of 1 bar after injection of the dust. The dust storage vessel is filled with the powder to be tested and is pressurized with air up to a pressure of 20 bar. The powder is dispersed into the explosion sphere by opening of the quick acting valve between the dust container and the spray pipe. This spray pipe is equipped with 112 holes of 3 mm internal diameter. After a delay time of 60 ms, the 10 kJ ignition source is activated. The explosion pressure in the 20 litre sphere is recorded by two independent transducers. Figure 2.3 shows the 20 litre sphere developed by Siwek. This vessel is now in use in many countries because it is much easier and cheaper to operate than the large standardized vessel, and it requires considerably less powder. The conformity in results between the 20 litre sphere and the 1 m³ vessel is illustrated in Figure 2.4, which compares the $K_S$ values of a variety of dusts determined in both vessels.

In the 20 litre sphere the same explosion indices can be measured as in the standardized 1 m³ vessel. It is also possible to equip the sphere with an electric spark device to determine the minimum ignition energy.
Figure 2.4  Comparison of $K_{St}$ values of various dusts in both the 20 litre sphere as developed by Siwek and the standardized 1 m³ vessel [ISO]. Figure reproduced from Bartknecht [1989].

2.2.3 The Hartmann Cell

The Hartmann Cell consists of an 1.2 litre glass or metal explosion cylinder, a valve and a storage bottle for compressed air. The powder sample to be tested is placed on the bottom of the cylinder. After opening the valve, the air disperses the powder into the explosion cylinder via a mushroom-shaped distributor. An electric spark ignites the dust cloud after a fixed delay time. In the closed metal Hartmann Cell the pressure is measured during the explosion. Figure 2.5 shows a drawing of a glass Hartmann Cell. The apparatus was originally developed as a testing method for all explosion indices [Field]. In the course of time, however, the values of $K_{St}$ and $P_{max}$ measured in the Hartmann cell were shown to disagree with the values obtained in the standardized cubic vessel. The explosive concentration range measured in the cell is also much smaller than the real explosion limits. The wall effects in the cylindrical cell are such that a dust explosion cannot occur adiabatically.

Nowadays the Hartmann Cell is used mainly to determine the minimum ignition energy and to demonstrate the phenomenon of dust explosions qualitatively. In these cases the explosion is performed at optimal dust concentrations, and no exact values of the explosion indices $K_{St}$ and $P_{max}$ are necessary.
Figure 2.5 Drawing of the Hartmann Cell [Field].
The cell consists of a glass tube, a valve, a compressed air container and ignition electrodes. A paper membrane closes the cylinder during the dispersion of powder.

2.2.4 The Godbert-Greenwald oven and the BAM oven

The Godbert-Greenwald oven and the BAM (from: Bundesanstalt für Materialprüfung, Berlin) oven are pieces of equipment exclusively designed to measure the minimum ignition temperature of dust clouds. They are based on the same principal of operation: a heated wall igniting a dispersed powder.

The Godbert-Greenwald oven is an evenly heated vertical pipe in which the powder is dispersed with a downward directed air flow. The explosion behaviour in the pipe is observed with the help of a mirror on the bottom of the oven. The experiments start at high temperatures and the minimum ignition temperature is determined by a successive decrease of the temperature in the apparatus. Figure 2.6 illustrates this apparatus, which is mainly in use in Great Britain and the USA.

The BAM oven (Figure 2.7) is a German apparatus designed to measure substantially lower values of the minimum ignition temperature than the Godbert-Greenwald oven. A deflector inside the horizontally placed oven causes an increased residence time of the dust cloud inside the apparatus. In practice, the ignition temperature of dust particles is dependent on the residence time of the powder in the equipment.
2.3 Parameters influencing dust explosions

To understand the propagation mechanism of dust explosions, it is necessary to be familiar with the parameters which can influence the propagation of a dust explosion. Many of these parameters are already well-known and their effects quantified. A good overview of these parameters was made by Field. This paragraph, containing new material together with some literature data, is intended as a basis for understanding the nature of dust explosions.

2.3.1 Chemical composition of the dust

The chemical composition of the dispersed dust is perhaps the most important dust property. It determines whether a dust suspension can explode or not. An exploisible dust requires a chemical composition which can react exothermically with the oxygen in the air. In practice, most organic dusts, metals and polymers fulfil this condition. The chemical composition also dictates the kind of explosion mechanism. This mechanism depends on the physical properties of the dust under reaction conditions and on the properties of the reaction products: solid, liquid or gas. In general, three different reaction schemes can be distinguished in the propagation of a dust explosion:
Type 1. A reaction on the solid or liquid surface, forming gaseous products. This type of reaction is characterised by complete combustion of the particle in an excess of oxygen. The reaction rate is proportional to the total particle surface area. In the case of lean mixtures, the reaction rate is limited by the diffusion of oxygen towards the surface, or by diffusion of the products away from the surface. Carbon is a dust which react according to this Type 1 reaction.

![Graph showing relationship between dust concentration and K-St](image)

**Figure 2.8** Relationship between dust concentration and $P_{max}$ for a Type 1 and a Type 2 dust. The average particle size of the carbon is 4.8 μm and the average particle size of silicon is 3.3 μm [Van der Wel et al., 1991]. The vertical lines represent the stoichiometric ratios of the dust concentrations.
Type 2.
A reaction on the solid or liquid surface, forming solid or liquid products
Type 2 dusts can only react partially with oxygen, since the products form a layer on the surface of the particles. This layer, solid or liquid, hinders the transport of oxygen towards the reactive surface. Because only a limited portion of the particle mass can react, the maximum explosion severity is reached at dust concentrations much higher than the stoichiometric ratio. This phenomenon is illustrated by Figure 2.8. Here the dependence of the $P_{\text{max}}$ value on dust concentration is given for two dusts, carbon and silicon. Silicon is a Type 2 dust having the maximum explosion severity at concentrations far above stoichiometric. A Type 1 dust like carbon reaches the maximum value closer to the stoichiometric concentration. Most metals exhibit a Type 2 reaction.

Type 3.
A reaction in the gas phase, forming solid, liquid or gaseous products
Type 3 powders are highly volatile. Before the chemical reaction takes place, Type 3 dusts evaporate because of the heat supplied by the approaching flame front. The subsequent combustion occurs completely in the vapour phase. Dependent on the relative rate of combustion and evaporation, the explosion behaviour is determined by the particle surface area or by the chemical kinetics. Most polymers exhibit a Type 3 reaction.

There is also a large variety of powders which react according to combinations of these mechanisms. They are usually powders containing volatile matter. The gaseous components react in the first part of the flame front, and the residual solid portion of the particle reacts with the residual oxygen. Dependent on the percentage and reactivity of the volatile matter and the particle size and concentration, it is usually justified to group these dusts under one of the three basic reaction mechanisms. Powders with a high percentage of volatile matter and high dust concentrations, for example bituminous coal react in the same way as particles composed of purely volatile matter. Most dusts of organic origin and coal have a combined reaction scheme.

2.3.2 Dust concentration and homogeneity of dispersion

The concentration of the dust particles has a direct influence on the behaviour of dust explosions. In Figure 2.9 the dust explosion indices of carbon are given as a function of concentration. In these figures three regions can be observed: at lean concentrations the indices are proportional to the concentration, as an excess of oxygen exists. Around the stoichiometric ratio of the reactants a maximum is reached in explosion severity and explosion pressure. A further increase in concentration results in a decrease in both $K_{\text{St}}$ and $P_{\text{max}}$. This decrease is due to the extra mass of dust present during the propagation of the explosion. This powder excess serves as a heat sink for the energy released during combustion and thus lowers the propagation velocity and the explosion pressure.
Figure 2.9  Explosion indices of activated carbon as a function of dust concentration [Van der Wel et.al., 1991]. The average particle size is 20 μm.

Figure 2.10  Results of chromatographic analyses after dust explosions of activated carbon at different powder concentrations, the average particle size is 20 μm [Van der Wel et.al., 1991].
Figure 2.9 also shows the existence of a lower and upper explosion limit. The lowest explosible dust concentration is determined by the maximum particle-to-particle distance at which a dust cloud can still sustain a flame propagation. The maximum concentration is reached when the excess powder absorbs sufficient heat to prevent the dust cloud from reaching the minimum ignition temperature.

The data in Figure 2.9 were obtained with a powder well dispersed in air. In practical situations the powder will be inhomogeneously dispersed, with locally very high and very low concentrations. The test methods, however, are focused on determining the maximum explosion indices at optimum dust concentrations. In this way they will predict the most severe explosion possible. Therefore, much effort must be devoted to obtaining a uniform dispersion of the powder in the explosion test vessel.

To demonstrate the complicated effect of dust concentration on dust explosion behaviour, Figure 2.10 gives the gas composition after explosion of activated carbon at different powder concentrations. In region 1 an excess of oxygen is present, allowing for complete conversion of the carbon to carbon dioxide. At concentrations around the maximum values of the explosion indices (region 2), both carbon monoxide and carbon dioxide are formed. At higher concentrations the expected increase in carbon monoxide is found. An exception occurs at high dust loadings (region 4), at which the heat sink effect lowers the reaction temperature to temperatures below 1200 °C. At these low temperatures the reaction mechanism changes, and a preference for forming carbon dioxide occurs, as reported by Caram and Amundson [1977].

2.3.3 Particle size distribution and particle porosity

Together with the chemical composition, the particle size distribution of a powder determines whether an explosion can be sustained or not. Usually an average particle diameter of 0.50 mm is regarded as the maximum size of particle still able to burn explosively. In addition to the explosibility, the particle size distribution also determines the severity of the explosion. Large particles, having a relatively small specific surface area, explode only moderately. Small particles, with high specific areas, exhibit higher values of the explosion index $K_{SI}$. Figure 2.11 shows the explosion indices for different particle size distributions of activated carbon.

At lean concentrations and around stoichiometric ratios there is a strong effect of particle size on the value of $K_{SI}$ because smaller particles react faster than larger particles. Although the explosion rate does not affect the total mass burned, a minor effect is observed in the values of $P_{\text{max}}$. This is caused by the cooling of the wall of the test vessel. Fast explosions have less time to lose energy at the wall and they therefore produce a slightly higher explosion temperature and pressure.

At higher concentrations the particle size effect becomes less pronounced. Indeed, small particles can react faster than larger particles, but they also have a larger surface area which absorbs heat.
Figure 2.11  Explosion indices of activated carbon samples with different particle size distributions at various concentrations, the dashed lines represent the stoichiometric combustion ratios [Van der Wel et al., 1991].

The effect of particle surface on the reaction rate is illustrated by Figure 2.12. Here, the $K_{St}$ value of activated carbon samples is plotted versus the total exterior surface area. This figure shows an initially linear relationship between explosion index and surface area. At higher concentrations the heat sink effect becomes dominant, and the explosion index is determined by the total mass of carbon instead of the total surface area.

Figure 2.12  Explosion indices of different activated carbon samples as a function of the outer surface area [Van der Wel et al., 1991].
The influence of particle porosity is illustrated by Figure 2.13, in which samples of activated carbon and graphite with similar particle size distributions are compared. Activated carbon, which is porous, has a specific surface area 20-30 times larger than graphite, and explodes considerably more violently than graphite. Another effect is the decreased density of the particle, which causes the number of particles in the dust cloud to increase and thus the reacting surface area. It must be mentioned that the effect of particle size and of porosity becomes less important when the combustion rate is no longer limited by the particle surface area. A combustion rate limitation by kinetics of a gas phase reaction will result in an explosion behaviour more or less independent of particle size.

![Graph of K-st vs. conc. (g/m³)](image)

**Figure 2.13** Comparison of explosion index measurements of porous activated carbon (solid line, d = 8.4 μm) and graphite (dashed line, d = 7.9 μm) [Van der Wel et al., 1991].

2.3.4 Oxygen concentration

A practical application of the influence of the oxygen concentration is preventing dust explosions. Decreasing this oxygen concentration in the atmosphere sustaining the dust cloud is one practical method of preventing dust explosions. Bartknecht gives an example of the dependence of dust explosion behaviour on oxygen concentration, see Figure 2.14. The oxygen concentration at which an explosion is no longer possible is often referred to as the maximum allowable oxygen concentration.
2.3.5 The presence of a solid inert material

To obtain a less severe explosion, or even to prevent a dust suspension from exploding, it is possible to admix inert solid material into the powder. The effect of this inert material is essentially the same as the presence of high concentrations of combustible powder. The extra mass absorbs the heat released by the explosion. The exact concentration of inert material necessary to prevent explosions depends on the properties of the dust suspension and must be determined by experiment in the laboratory.

![Graph showing the influence of oxygen content on explosion indices](image)

*Figure 2.14*
*The influence of the oxygen content upon the explosion indices of an insecticide, from Bartknecht.*

2.3.6 Moisture

The influence of moisture on the course of a dust explosion is difficult to predict quantitatively. Moisture can influence an explosion in three different ways. If a powder is sufficiently moist, it is difficult to disperse in air and thus less able to explode. For this reason, moisture is often used as a preventive measure against dust explosions. Moisture also has an effect on the particle size in the dust cloud. Small particles adhere to one another quite easily in moist air, forming larger and less explosive agglomerates.

The third effect of moisture on a dust explosion is found in the reaction mechanism. For
example, the presence of small amounts of water can enhance the reaction between coal and oxygen.

2.3.7 Temperature and pressure of the dust dispersion

Dust explosions occurring at elevated initial temperatures tend to exhibit lower maximum explosion pressures than those occurring at ambient temperatures. Bartknecht gives a linear relationship between the reciprocal temperature and the $P_{\text{max}}$. That the $P_{\text{max}}$ tends to decrease with increasing initial temperature is simple to explain. By approximation,

$$\frac{P_{\text{max}} - T_{\text{max}}}{P_{\text{initial}} - T_{\text{initial}}}$$

where $T$ is the absolute temperature. Furthermore, increasing initial temperature will usually not strongly increase the adiabatic flame temperature. The behaviour found in practice is therefore seen to be in accordance with theory.

The relationship of initial temperature and rate of pressure rise is less clear. Proportional as well as inverse proportional relationships between temperature and $K_{\text{St}}$ are reported in the literature. Higher temperatures affect dust explosion propagation in a number of contrasting ways. The particles are more easily ignited because they need less energy to reach the ignition conditions; propagation is thus facilitated. At constant pressure, increased temperature results in lower partial oxygen pressures, lowering the rate of reaction and decreasing the amount of dust which can burn. Through the Arrhenius effect, increased temperature results in a somewhat higher initial combustion rate. The net effect of temperature on dust explosion indices is therefore produced by a combination of contrasting effects.

Pressure and dust explosion indices are unambiguously related. Both $P_{\text{max}}$ and $K_{\text{St}}$ are proportional to the initial pressure of the dust cloud. Bartknecht tested dusts over a pressure range of 0.25 - 2 bar.

2.3.8 Flow properties

The flow of the air is intrinsically coupled to dust explosions. Some turbulence in the air suspension is necessary to prevent the dust particles from depositing. In addition to its role in the support of the dust cloud, turbulence also has an important effect on the propagation velocity. The delay time between introduction of the powder into the test vessel and the moment of ignition determines the degree of turbulence in the dust cloud when the explosion takes place. Longer delay times result in a lower degree of turbulence. Figure 2.15 shows how this delay time effects the $K_{\text{St}}$ value. In Chapter 5 a detailed study of the role of turbulence on dust explosion propagation is given.
Figure 2.15  The relationship between the ignition delay time and the $K_{St}$ of a 500 g/m$^3$ suspension of Lycopodium [Van der Wel et al., 1992].

2.3.9 Geometry of the enclosure

The ultimate result of a dust explosion largely depends on the geometry of the enclosed space. Obstacles in the flame front are known to generate extra turbulence, thus increasing the propagation velocity. Generation of turbulence is also induced by dust explosions in long, tube-like systems. It is even possible that detonative explosions are initiated. In spherically symmetric containers little or no turbulence is created by the expansion of the gases, while the level of turbulence in open-ended tubes can increase enormously.

2.3.10 Ignition source

The lower explosibility limit is especially influenced by the energy of the igniter. Table 2.1 shows the effect of igniter size on the apparent explosibility limits of several activated carbon samples. The lower explosibility limit is defined as the dust concentration at which the heat generated is just able to maintain the minimum ignition temperature of
the dust suspension. Additional energy in the form of a larger igniter effectively lowers this concentration. The resulting concentration also depends on the volume of the explosion vessel, the duration of the ignition, the combustion mechanism and the particle size distribution.

Table 2.1 The lower explosibility limit [g/m³] of activated carbon samples as a function of the energy of the igniter, measured in the 20 litre sphere [Van der Wel et al., 1990].

<table>
<thead>
<tr>
<th>d_p [µm]</th>
<th>E = 10 kJ</th>
<th>E = 2 kJ</th>
<th>E = 0.3 kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>10</td>
<td>55</td>
<td>-</td>
</tr>
<tr>
<td>19.7</td>
<td>20</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>79.0</td>
<td>25</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>raw material</td>
<td>20</td>
<td>90</td>
<td>125</td>
</tr>
</tbody>
</table>

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Chapter 3

Dust explosion sensitivity: The concept of ignition

3.1 Introduction

For a dust explosion to occur it is necessary for a combustible dust/air mixture to come into contact with an ignition source. This ignition source will initiate the explosion by supplying enough energy to start the chemical reaction between the dust and the oxygen in the air. The amount of energy necessary to activate this reaction depends on the physical nature of the ignition source as well as the chemical and physical properties of the dust. A wide variety of ignition sources exist which are capable of initiating dust explosions: flames, hot surfaces, electric and electrostatic sparks, mechanical sparks. It is also possible to initiate a dust explosion by heating the dust/air suspension. Knowledge of the different kinds of ignition sources and of the properties of the dust is essential in order to apply effective measures against explosion risks.

To assess the possible risk of ignition sources several practical criteria have been developed [Bartknecht, 1989]:

**The Minimum Ignition Temperature (MIT)**
This is the minimum temperature of the wall enclosing a dust cloud at which the chemical reaction between the dust and oxygen develops spontaneously into an explosion. At this temperature the production of heat by the chemical reaction just exceeds the loss of heat to the surrounding wall.
The MIT is a useful tool to judge flames, hot surfaces and friction sparks for their capability to ignite dust clouds.

**The Minimum Ignition Energy (MIE)**
Literally this is the minimum amount of energy which can initiate an explosion in a dust/air mixture. In practice this is taken to be the energy content of a capacitive, electric spark. The MIE of a dust cloud provides information about its sensitivity to ignition by electric, electrostatic and mechanical sparks.

**The Maximum Experimental Safe Gap (MESG)**
This is defined as the maximum distance of two parallel plates at which a combustion wave in a dust/air mixture between those plates is quenched. The MESG is used to design slits in electrical parts, rotary air locks and flame arresters.
All these criteria are very well suited to assess the sensitivity to ignition of a dust cloud and the risk of different ignition sources, but they are not absolute parameters. It is also impossible to relate the different parameters to each other. Furthermore, it appears that little is known concerning the exact ignition mechanism of dust clouds in these test methods. This lack of understanding makes it difficult to predict the ignition behaviour of dust clouds under circumstances different from those in the test equipment.

This chapter does not pretend to give an exact description of the ignition process or relationships between ignition energies, ignition temperatures and quenching distances. Even in the relatively simple case of gas explosions it still is impossible to give such relationships [Glassman]. In the next paragraphs, however, a speculative description of the different aspects of the ignition processes in dust clouds will be given. This description is based on information from the literature as well as experiments, and it is primarily intended to create a general picture of the ignition process. Next an attempt is made to interrelate the different concepts of dust cloud ignition by use of a new ignition source: an IR laser.

The basic assumption in this chapter is the concept of a volume of a dust cloud, which has a given temperature. In this dust cloud energy will be produced by a chemical reaction and in the mean time it loses energy by heat transfer towards the surroundings. Successful ignition is achieved whenever enough energy is supplied to the dust cloud to rise its temperature up to a level at which the heat production in the dust clouds exceeds the heat loss rate.

3.2 The Minimum Ignition Temperature

To understand the process of the Minimum Ignition Temperature measurement it is best to look first at the theoretical Auto-Ignition Temperature [Glassman].

The auto-ignition phenomenon is best described by the classical theories of Semenov and Frank-Kamenetzki. Semenov's theory defined the Auto Ignition Temperature (AIT) by the energy balance between the production of heat by the chemical reaction and the loss of heat to the surrounding system.

Semenov assumed a homogeneous distribution of the temperature in the dust cloud and he proposed the following equations.

The equation for the production of heat in a dust cloud is somewhat complicated. A distinction can be made between the different rate governing processes: mass transfer through the film layer surrounding the particle, mass transfer through the ash layer covering the solid particle, or chemical reaction either on the solid surface or in the gas phase. In practice, however, it is possible to exclude the mass transfer rate controlling processes. If these processes control the reaction rate they will hardly give explosive reaction accelerations. The temperature dependence of the mass transfer constants or diffusion constants is more or less linear, which is comparable to the temperature dependence of the rate of heat loss. It should further be noted that the ignition processes of dust explosions are usually the initial stages of reactions. There is then enough oxygen
to presume chemically restricted reaction rather than mass transfer controlled reaction. The rate of volumetric heat production in the case of a chemically restricted reaction rate is:

\[ Q_{\text{production}} = a \cdot Q \cdot S_{\text{solid}} [O_2] \cdot k \]  

(1)

Here \( a \) is constant, \( Q \) is the heat of reaction, \( S_{\text{solid}} \) the solid surface area concentration of the dust cloud, \([O_2]\) the bulk concentration of oxygen and \( k \) is the rate constant for the surface reaction. In the case of a reaction in the gas phase it is still the solid surface area which determines the gas phase concentration. In the initial stage of the explosion the fuel evaporates from the solid surface before the combustion starts.

The rate constant, \( k \), is exponentially dependent on the temperature, and this can cause an explosive reaction acceleration. Usually the well-known Arrhenius relation is used to express the temperature dependence of the reaction rate constant:

\[ k = k_0 \cdot \exp\left(-\frac{E_A}{RT}\right) \]  

(2)

Here \( k_0 \) is the frequency factor, \( E_A \) the activation energy of the chemical reaction and \( R \) is the universal gas constant.

The solid surface area concentration of the dust cloud, \( S_{\text{solid}} \), can be estimated from the particle density, \( \rho_{\text{solid}} \), the solid concentration, \( C_{\text{solid}} \), and the average particle size, \( d_p \): In the case of spherical particles:

\[ S_{\text{solid}} = 6 \cdot C_{\text{solid}} / (\rho_{\text{solid}} d_p) \]  

(3)

The equation for the volumetric heat loss to the wall becomes:

\[ Q_{\text{loss}} = h \cdot \frac{A}{V} (T - T_w) \]  

(4)

Here \( h \) is the heat exchange coefficient of the film of air near the wall, \( A/V \) the specific wall surface area i.e. the total surface area of the heated wall divided by the container volume, \( T \) the actual temperature of the dust cloud and \( T_w \) is the wall temperature. This temperature is different from \( T_0 \), the temperature of the surroundings. This equation was improved by Frank-Kamenetzki by incorporating the inhomogeneous temperature distribution in the dust cloud during the ignition process. However, for a basic understanding of the auto-ignition process the Semenov approach is satisfactory.

The temperature, \( T \), in the dust cloud reaches the theoretical AIT when the next two conditions are satisfied [Essenhigh, Misra and Shaw, 1989], the Van 't Hoff condition:

\[ Q_{\text{loss}} = Q_{\text{production}} \]  

(5)
and the Taffanel and Le Floch condition:

\[ \frac{dQ_{\text{loss}}}{dT} = \frac{dQ_{\text{production}}}{dT} \] (6)

The theory of Semenov is illustrated in Figure 3.1. Figure 3.1 (a) shows the case in which no explosion will take place, the mixture rises in temperature up to point \( a \), because, until point \( a \), the production of heat exceeds the heat losses. Above point \( a \), however, the rate of heat loss becomes larger than the production rate and the temperature remains at the level of point \( a \). Only large disturbances of the temperature past point \( b \) can cause an explosive run away reaction. The production of heat then becomes larger than the heat loss rate.

Deviations in temperature smaller than point \( b \) (for example \( T = AIT \)) are damped because of the unbalance in heat production.

At point \( c \) in Figure 3.1 (b) the conditions in Eq. 5 and Eq. 6 are just satisfied. In this diagram the temperature rises spontaneously until point \( c \), where the production and loss of heat are balanced. The temperature at point \( c \) is defined as the Auto Ignition Temperature. Even a small positive deviation of the temperature causes the rate of production to exceed the rate of loss of heat, resulting in an accelerated reaction. In Figure 3.1 (c) the situation is shown in which the sample temperature directly accelerates from the initial temperature towards an explosive value, without having a stable point.

Application of the Van't Hoff condition and the Taffanel and Le Floch condition onto equations 1 and 2, including equation 2, results in Eq. 7 and Eq. 8, respectively.

\[ h \cdot \frac{A}{V} (T - T_w) = a \cdot Q \cdot S_{\text{solid}} [O_2] \cdot k_0 \cdot \exp\left(-\frac{E_A}{RT}\right) \] (7)

\[ h \cdot \frac{A}{V} - a \cdot Q \cdot S_{\text{solid}} [O_2] \cdot k_0 \cdot \exp\left(-\frac{E_A}{RT}\right) \cdot \frac{E_A}{RT^2} \] (8)

Division of these two equations results in equation 9. From this relationship Glassman approximates the AIT of the dust cloud in the container by equation 10.

\[ T - T_w = \frac{RT^2}{E_A} \] (9)

\[ AIT - T_w = \frac{RT_w^2}{E_A} \] (10)
Figure 3.1  Different orders of heat loss rates at a constant heat production rate of a hypothetical reaction.
Combination of equations 7, 9 and 10 yields a relationship for the theoretical wall temperature necessary for auto ignition of a contained dust cloud:

$$\frac{h \cdot A \cdot \frac{R \cdot T_w^2}{V}}{E_A} = e \cdot a \cdot Q \cdot S_{\text{solid}} [O_2] \cdot k_0 \cdot \exp\left(-E_A/(R \cdot T_w)\right)$$

(11)

From this relationship two groups of variables can be distinguished:

- group 1 = \((h \cdot A/V)\)
- group 2 = \(E_A\) and \((a \cdot Q \cdot S_{\text{solid}} [O_2] \cdot k_0)\)

Group 2 variables depend only on the powder dispersion to be tested, while the group 1 variables depend on the apparatus in which the AIT is determined. They are material variables and equipment variables.

The experimental techniques determining the AIT of a sample are based on a successive shift of the heat loss line by variation of the wall temperature. Measurement of the temperature of the sample at a range of wall temperatures gives an indication of the AIT. Exact values are almost impossible to obtain, the excess of heat produced near to the AIT becomes infinitely small and, therefore, the rise in temperature towards the AIT occurs very slowly. The accuracy of the measurements is limited by the duration of the experiments. In the case of experiments with gases, this effect is of a minor importance, and good approximations of the AIT can be obtained. However, when dust samples are tested, the duration of the test is limited by the time the sample remains airborne. This time is much too short to allow an accurate measurement to be made.

In practice, the AIT of powder-air dispersions is approximated by the so-called Minimum Ignition Temperature (MIT). In this case the entire wall of the vessel or a part of it is heated up to a temperature around the AIT. The powder-air dispersion is blown into this vessel, and the occurrence of an explosion is observed. By successive decrements of this wall temperature, the MIT is determined as the wall temperature at which the dispersion just fails to ignite.

In addition to the difference in AIT and MIT already defined by Eq. 10, a number of practical aspects cause the MIT (the experimentally determined wall temperature) to deviate from the theoretical wall temperature, \(T_w\):

- In the case of the experimental determination of the MIT, the temperature distribution is far from homogeneous, while the AIT is based on a constant temperature in the dust cloud. For this reason, the MIT is higher than the theoretical value of \(T_w\).

- Due to a restricted residence time of the dust cloud in the MIT test vessel it is obvious that the value of the MIT must be higher than \(T_w\); the dispersion has only a limited time period to elevate the temperature up to the wall temperature,
$T_w$ before it deposits. This restricted residence time causes the MIT to be higher than the $T_w$.

- The heating of the dust particles in the dispersion occurs slower than that of the gas. The relatively cold particles serve, therefore, as a heat sink for the reaction energy produced by the combustion. This effect causes the MIT to be higher than $T_w$.

- In the case of partially volatile material, the heat of evaporation also lowers the particle temperature and thus the whole dust cloud temperature. This effect causes the MIT to be higher than $T_w$.

Although all these phenomena cause the MIT to be higher than the theoretical $T_w$, it will be difficult to quantify this difference. The difference will strongly depend on the powder dispersion characteristics, for example chemical composition, particle size, and concentration. Nevertheless, it is still possible to use Eq. 11 to assess the relative influence of the different parameters on the wall temperature necessary to ignite the dust cloud. In particular the group 1 variables are useful to understand the effect of different container geometries, volumes or injection methods. Knowledge of the group 2 parameters can be used to calculate other ignition parameters, such as the MIE or the MESG.

3.3 The Minimum Ignition Energy

The concept of the minimum ignition energy contains actually a twofold problem: what is the absolute minimum ignition energy of a dust cloud and what is the best way to approach this value with the use of an electric spark. In practice the electric spark is used to determine the minimum ignition energy of dust clouds. Much effort has been devoted to finding ways to obtain the absolute minimum spark ignition energy [Bartknecht (1989), Eckhoff (1976), Lewis and Von Elbe (1987)]. Different spark circuit designs, electrode spacings and pre-ionisation are used to minimise the energy necessary to ignite a dust cloud. All these investigations are based on trial and error without serious attempts to explain the results or to give a quantitative, or even a qualititative, description of the ignition process. Such a description could be very useful for predicting the effect of the physical properties of the electrical spark and, even more important, could also be used to understand the ignition behaviour of other types of sparks, such as electrostatic discharges and mechanical sparks.

In this paragraph, therefore, the theoretical absolute minimum ignition energy as well as the physical nature of electric sparks are treated. Together they should result in a description of the mechanism of ignition of dust clouds by sparks.
3.3.1 The theoretical minimum ignition energy of gases

The best way to study the theoretical minimum ignition energy of gases is to simulate the different processes which occur during the ignition. There are no 'clean' experimental data available, because ignition experiments are always performed using electric sparks. Detailed calculations were made by Frendi and Sibulkin [1990] and Sibulkin and Siskind [1987]. They simulated the ignition process of stoichiometric methane-air mixtures. Their calculations presume a certain volume ($V$) of the mixture heated for an ignition time ($t_{\text{ign}}$). Incorporated are the effect of expansion, diffusion of heat, chemical reaction and the possible formation of a shock wave. They simulated the ignition process both with and without the formation of a shock wave. Their results are shown in Figures 3.2, 3.3 and 3.4. Figure 3.2 illustrates the effect of the formation of a shock wave by sudden thermal expansion at short ignition times. At ignition times shorter than 2 $\mu$s a shock wave causes the ignition energy to become larger because the wave absorbs energy thus lowering the amount available for ignition.

Figure 3.3 shows the effect of the ignition volume on the ignition energy of the methane-air mixture. Down to a size of 0.1 mm there is a tendency to lower ignition energies at smaller ignition volumes. Below this specified volume the ignition energy attains a constant value. This phenomenon is better explained by Figure 3.4. Here the

![Graph showing comparison of minimum ignition energies obtained by simulation, with and without the occurrence of a shock wave. Stoichiometric methane-air mixtures. From Frendi and Sibulkin [1990].](image_url)
Figure 3.3  Variation of minimum ignition energy with kernel radius for different ignition times. Stoichiometric methane-air mixtures. From Frendi and Sibulkin [1990].

volumetric ignition energy density is plotted against the diameter of the ignition volume. Again a change in tendency is observed around an ignition volume diameter of 0.1 mm. Above 0.1 mm the energy density is more or less constant, which means that the temperature of the ignited volume is more or less constant in this region. At volumes smaller than 0.1 mm, however, extra energy seems to be necessary to ignite the gas-air mixture. This value of 0.1 mm is a characteristic volume often named the 'critical ignition kernel'.

Volumes larger than the critical value behave in accordance with the Semenov theory. The ignition temperature in the heated volume is dictated by the balance between the volumetric heat loss (Eq. 12), either by convection or conduction, and the heat production by the chemical reaction (Eqs. 1 and 2).

\[
Q_{\text{loss}} = h \frac{6}{D} \left( \frac{T_0}{T} \right)^{1/3} (T-T_0)
\]  (12)

This equation is similar to the equation used in the MIT theory (Eq. 4) except for the heat transfer coefficient, \( h \), which now accounts for the heat transfer by diffusional transport processes to the surrounding air, and secondly the use of the temperature of the surrounding air, \( T_0 \), instead of a wall temperature. The term \( A/V \) in Eq. 4 is replaced by \( 6/D \) in Eq. 12, where \( D \) is the original diameter of the ignited volume of the fuel dispersion. A spherical ignition volume is assumed. A correction \( (T_0/T)^{1/3} \) is made for the expansion of the ignition volume due to the increased temperature. This
expansion effectively decreases the specific area available for heat transfer.
In the case of a successful ignition the rate of heat production exceeds the rate of heat loss, according to the Van 't Hoff condition, Eq. 5. The ignition temperature obtained with these relationships can be translated into an ignition energy by using Eq. 13. Here \( \rho \) is the average density of the dispersion and \( C_p \) the average specific heat of the dispersion. \( D \) is again the original diameter of the ignition volume, before expansion.

\[
\text{ignition energy} = \rho C_p \frac{\pi}{6} D^3(T-T_0)
\]  

(13)

This implies that, in the region where the ignition volumes are larger than the critical value, the ignition process is described by the following mechanism. First the ignition volume is heated up to the auto ignition temperature appropriate to this volume. It expands and the chemical reaction starts. The resulting flame acts as a stable ignition source for the rest of the gas mixture. Volumes smaller than the critical ignition kernel will not initiate propagation of a flame, unless they are supplied with extra energy. The hypothesis is that the total ignition energy supplied should be enough to expand the critical ignition kernel to the dimension of the quenching distance (see paragraph 3.4) and to heat this volume up to its ignition temperature. The resulting flame will then be
able to initiate a stable flame propagation. In theory less energy is necessary to expand a much smaller volume to the critical size and heat it up to the flame temperature because of its lower density. In this case, however, the resulting flame has a smaller rate of heat production (Eqs. 1 and 2), and a larger volume will therefore be needed to meet the Van 't Hoff ignition condition. From Eqs. 1, 2 and 12 a relationship for the diameter of the critical ignition kernel can be derived.

$$\frac{T_0}{T}^{-\frac{1}{3}}(T-T_0)$$

3.3.2 The minimum electric spark ignition energy of dust clouds

In order to compare the theoretical minimum ignition energy of gases, as treated in paragraph 3.3.1, with the experimental minimum spark ignition energy of a dust cloud it is useful to distinguish different effects. These effects are caused by the electric nature of the spark, the presence of dust particles, the shape of the ignition volume and the flow properties of the gas because it is necessary to have some flow to disperse the particles in air.

The effect of these phenomena is difficult to quantify, but Glassman [1977] mentions that the ignition efficiencies of electric sparks for gases can vary from 2-16%. In the case of dust dispersions this efficiency is even lower because of the effects described below.

The effect of the electric nature of the spark

An electric discharge can influence the theoretical minimum ignition energy in several ways:

- To produce a capacitive spark it is necessary to have electrodes, these usually have a spacing of several millimetres (3-6 mm). Because the spacing is relatively small in comparison to the ignition kernel, it will lose energy to the electrodes by convective transport of heat. Another possibility to loose energy to the electrodes is the absorption of the kinetic energy of the electrons and ions accelerated by the electric field and their collision with the electrodes.

- Due to the high temperatures inside a spark discharge, of the order of 60000 K, it is very well possible that the ignition efficiency is decreased by the radiative transport of energy to the surroundings.

- Sparks with a short duration produce a shock wave by the sudden expansion of the ignition volume caused by the high heating rate. The formation of a shock wave extracts energy from the spark. This effect is demonstrated in Figure 3.2, where it is shown that the ignition energy is increased when shock waves are taken into account. Eckhoff [1976, 1991] proved that shock waves produced by short sparks can move a paper pendulum, which means that shock waves possibly possess kinetic energy.
A less well known effect of a spark discharge on the ignition process is the appearance of an ion wind caused by the moving positive ions. As the negative electrons are much smaller they are less capable of inducing a 'wind'. An ion wind can disturb the formation of an ignition kernel and can thus quench the early flame, but it can also increase the ignition efficiency by improving the transport of heat in the kernel. Some researchers [Borghese et. al. (1991) and Pitt et. al. (1991)] observed toroidal structures in the initial flame developing from an electric spark. Due to the ion wind the real ignition volume is different from the assumed spherical shape.

The effect of flow

The interaction between an igniting spark and a flowing reactive mixture is explained relatively simply by comparison of the velocity of the flow and the dimensions and duration of the spark. These parameters can be combined in a dimensionless number:

\[
\text{dim. number} = \frac{\text{spark diameter}}{\text{spark duration} \times \text{flow velocity}}
\]

Large dimensionless numbers indicate a negligible effect of the flow on the spark development. During the spark discharge the reactive mixture is moved only slightly in comparison with the spark dimensions. Small numbers, however, show that the flow influences the discharge by diffusion of the dissipated electric energy. The ignition volume is thus enlarged. In extreme cases the ignition can be quenched by the flow when the diffusion of energy is too strong. Table 3.1 summarises some typical values of the dimensionless number under various conditions.

To assess the influence of turbulent flow on electric sparks it is possible to replace the flow velocity by the RMS value of the fluctuating turbulent velocity (see Chapter 5).

<table>
<thead>
<tr>
<th>Spark duration [(\mu\text{s})]</th>
<th>Flow velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 3.1 Typical values of the dimensionless number for various flow conditions and several spark characteristics (the spark diameter is estimated to be 50 \(\mu\text{m}\)).
The effect of the heterogenous character of the dust dispersion

The difference between the ignition mechanism of a reactive dust-air dispersion and a gaseous mixture is caused by a combination of three effects: the inertia of the solid dust particles, the inter-particle distance and the heterogenous combustion mechanism of the particles.

Eckhoff [1991] gave some calculations on the position of dust particles after a short discharge. Due to the inertia of the particles a dust-free zone is developed. Such a dust-free zone hinders the ignition of the dust-air mixture.

Some typical inter-particle distances in a dust dispersion with spherical particles of a density of 2000 kg/m³ are given in Table 3.2. The calculations are made using equation 15.

\[
\text{inter-particle distance} = \left(\frac{\rho \pi d^3}{6C_s}\right)^{\frac{1}{3}}
\] (15)

\(\rho\) is the density of the solid particle, \(d\) the average particle diameter and \(C_s\) the solid concentration.

**Table 3.2** Average inter-particle distances of a hypothetical dust dispersion with spherically shaped particles having a density of 2000 kg/m³.

<table>
<thead>
<tr>
<th>inter-particle distance [mm]</th>
<th>dust concentration [g/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>average particle size [μm]</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.047</td>
</tr>
<tr>
<td>10</td>
<td>0.47</td>
</tr>
<tr>
<td>100</td>
<td>4.7</td>
</tr>
<tr>
<td>1000</td>
<td>47</td>
</tr>
</tbody>
</table>

The results of the calculations given in Table 3.2 indicate that it is hardly permissible to treat the dust dispersion as a homogeneous, reactive mixture. A typical spark diameter is 0.050 mm, which is much smaller than the average inter-particle distance. This fact, combined with the effect of inertia, indicates that combustion of the particles hardly plays a role in the initial stage of spark development. Only after the ignition kernel is sufficiently expanded will the first particles start to react.
The effect of the shape of the ignition volume

The shape of the electrical spark used for ignition of a dust explosion implies a cylindrical ignition volume with a diameter d and a length l. In the case of small electrical energies, the ratio of the diameter to length can be very small. In this case it is mainly the diameter of the ignition volume which determines the probability of ignition. The extra length only absorbs energy without increasing the probability. In the case of small sparks, it is better to minimise the length of the spark. However, too short a length causes the electrodes to absorb energy. An optimal length can be found empirically.

3.4 The Maximum Experimental Safe Gap

The Maximum Experimental Safe Gap (MESG) is a strictly experimental parameter used to design explosion proof slits in equipment and flame arresters. For example Bartknecht [1989] studied the MESG to obtain design rules for rotary valves. He determined this parameter in a 20 litre sphere mounted in a 1 m³ vessel. The 20 litre sphere was split into two halves to form a gap. A dust explosion was initiated inside the 20 litre sphere, and it was observed whether the explosion propagated through the gap into the larger vessel in which dust was also dispersed. Variation of the slit was used to measure the maximum safe gap. Due to the high velocities inside the gap this type of test results in small values for the quenching parameter. Another method to investigate the quenching behaviour of dust explosions is the so-called Quenching Distance or Quenching Diameter [Ballal, (1980, 1983)]. The quenching distance (QD) is a relatively rare parameter in dust explosion testing. Recent publications of Lee [1992], however, point out the importance of this parameter as a fundamental property of the dust dispersion. The quenching distance is proportional to the flame thickness, and measurement of the quenching distance can, therefore, give a better understanding of the combustion mechanism of the particles. Since there must be a connection between the Quenching Distance and the Critical Ignition kernel diameter, it must be important in understanding the ignition mechanism.

The Quenching Diameter is more or less equivalent to the Quenching Distance, except for the fact that it is measured in a tube-shaped gap instead of a slit.

The major problem of the QD of a dust explosion is to measure them experimentally. Gravity causes particles to deposit, which leads to an inhomogeneous particle distribution. The turbulent flow necessary to disperse the particles strongly interferes with the quenching distance since it enhances the flame front velocity. The heterogenous character of the dust cloud manifests itself in the inter-particle distance; to have a stochastically acceptable measurement it is obvious that the gap width must be several times larger than the inter-particle distance. The measurement must be repeated many times to yield the desired reproducibility. Quenching distances smaller than the inter-particle distance are almost impossible, since there are no dust particles to propagate a flame. Table 3.2 gives some typical values of the inter-particle distance.
To overcome all these uncertainties the MESG as defined by Bartknecht [1989] and Vogl and Bartknecht [1992] has been investigated. This parameter has the advantage of being smaller than the QD, and so leads to operation on the safe side. Due to the high velocities it is not necessary to consider deposition. The flame front is simply pushed through the gap by the explosion pressure, resulting in a critical flow velocity \( v \).

Figure 3.5 shows a schematic drawing of the situation in the gap.

\[
\begin{align*}
T_f & \\
\text{dx} & \\
\downarrow & \\
\text{v} & T_0 \\
\uparrow & \\
T & \\
\downarrow & \\
T_0 & \\
\hline
\end{align*}
\]

\[\text{MESG}\]

\text{Figure 3.5  Ignition of a dust cloud by a flame front travelling through a gap.}

The flame front enters the gap at the flame temperature and is cooled in the gap by the cold walls. The temperature of the jet leaving the gap is determined by the gap diameter and the gap length. For a cylindrical gap with diameter \( d \) and length \( l \) the temperature decrease can be estimated by Eq. 16.

\[
\frac{T - \text{flame temperature}}{\frac{\text{heat. loss rate}}{\text{volume}}} = \frac{\text{residence time}}{\text{volum. spec. heat}}
\]

\[
-T_f - \frac{2h}{d} \frac{(T_f - T_0)}{C_{p,mix} \rho_{mix} v} \frac{1}{\text{v}}
\]  

(16)
In a manner analogous manner to the MIT and the MIE, it is possible to model the MESG using a balance between the heat loss and heat production in the jet leaving the gap with a temperature $T_{\text{gap}}$ defined by Eq. 16. The equations are similar to the ignition energy equations, except for the fact that the diameter need not be corrected for expansion, since the mixture has already expanded when it leaves the gap.

3.5 Laser ignition of dust clouds

3.5.1 Introduction

In the former paragraphs models have been given for the different conventional ignition properties. In all cases the approach of Semenov was applied. This approach assumes a balance between heat production and heat loss at the point of ignition. Although more sophisticated theories exist, the simple Semenov theory gives a direct insight into the mechanisms behind the different ignition properties. Application of this approach yields a uniform relationship for the heat production rate in the case of the Minimum Ignition Temperature (MIT), the Minimum Ignition Energy (MIE) and the Maximum Experimental Safe Gap (MESG). The rates of heat loss are dependent on the test apparatus. The key parameters in all cases are the kinetic data of the combustion. Once the kinetic data are known, the different ignition parameters can be calculated by estimating the heat transfer properties in the test apparatus. The kinetic data of the reaction are traditionally obtained by measuring the reaction rate at several temperatures. However, in the case of dust dispersions this is very difficult due to the rapid deposition of the particles. A new method has therefore been developed. A pulsed IR laser is used to control the temperature in a variable ignition volume. The ignition temperature will be volume dependent and, since the mechanism of heat loss remains the same, the heat production rate is obtained at several temperatures.

The basic principle of this laser ignition method is to heat a known volume of the dust cloud by the use of a laser beam, as shown in Figure 3.6. A proper choice of the wave length of the laser ensures that the particles in the dust cloud heat up sufficiently. The total energy absorbed in the known dust cloud volume can be estimated relatively easily by making intensity measurements on both sides of the dust cloud and by knowledge of the absorption factor. The amount of energy absorbed can also be translated into a dust cloud temperature. Variation of the laser energy intensity as well as the laser beam diameter allows determination of the ignition energy and the ignition temperature of a dust cloud as a function of the ignition volume. Use of this laser ignition method also has the advantage of an ignition source with no electrical effects; the energy brought into the dust cloud is equal to the net ignition energy. This is in contrast with spark ignition, where an unknown amount of the energy is lost through radiation and shock wave formation.

The main disadvantage of the laser ignition method is the heterogenous character of the dust cloud in the experiments. The absorption of the laser energy takes place on the particles, which must be present in the ignition volume. In the case of ignition volume
diameters smaller than the inter-particle distance, a statistically random absorption occurs. Ignition volumes as small as electric sparks will therefore be difficult to investigate with this kind of laser apparatus.

![Diagram showing laser beam and powder beam](image)

**Figure 3.6** Basic principle of the ignition of a defined volume of dust cloud by the use of a laser beam.

3.5.2 Theory of laser ignition

Laser-particle interaction

In Figure 3.7 the different types of laser-particle interactions are shown. The quantity of light absorbed determines the temperature rise of the particle and depends on the reflectivity of the particle and on the particle surface-to-volume ratio. Small black particles absorb more radiation than larger reflective particles.

Semenov relationships for laser ignition

Analogous to the theory of the minimum ignition energy, the following Semenov relations can be formulated for the ignition of dust clouds by laser radiation. Due to the non-spherical shape of the laser ignition volume, the term $6/D$ is replaced by $A/V$. The temperature dependent expansion is presumed to be the same as in the case of
spherically shaped ignition volumes.

\[ Q_{\text{loss}} = -h \frac{A}{V} \left( \frac{T_o}{T} \right)^{\frac{1}{2}} (T - T_o) \]  \hspace{1cm} (17)

\[ Q_{\text{production}} = -aQ_s\text{solid} [O_2] k_0 \exp(-E_A/(RT)) \]  \hspace{1cm} (18)

\[ \text{particle} \]

\[ \text{reflection} \]

\[ \text{absorption} \]

\[ \text{transmission} \]

\[ \text{diffraction} \]

\[ \text{light} \]

**Figure 3.7**  *Schematic drawing of the different types of interaction of a laser beam and a particle.*

3.5.3 Experimental set-up of the laser ignition method

**The laser ignition experiments**

Figure 3.8 (a) shows the experimental laser ignition set-up used to measure dust explosion ignitability. The equipment was centred around a powder-air stream. This stream was generated by a fluidised bed, as shown in Figure 3.8 (b). The advantage of such a stream in comparison with a conventional batch dispersion process is the possibility of continuous operation and the presence of a well-defined dust cloud with no surrounding walls. The fluidised bed was filled with a powder-glass beads mixture or a powder-sand mixture, and the powder was blown from the bed by an adjustable air flow. In practice the powder concentration in the stream remained constant for several
minutes and subsequently decreased slowly; after about 10 minutes the bulk of the powder was elutriated from the fluidised bed. The larger glass beads or sand particles remained in the fluidised bed and served only as a dispersing and fluidising agent to prevent the presence of agglomerates in the particle stream. Table 3.3 summarises the dimensions and experimental circumstances of the fluidised bed.

Table 3.3 Fluidised bed data.

<table>
<thead>
<tr>
<th>Property</th>
<th>aluminium</th>
<th>sulphur</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight of sand [g]</td>
<td>-</td>
<td>500</td>
</tr>
<tr>
<td>( d_{50} = 212-300 \mu m )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>weight of glass beads [g]</td>
<td>550</td>
<td>-</td>
</tr>
<tr>
<td>( d_{50} = 300-500 \mu m )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>weight of powder [g]</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>average particle size [\mu m]</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>air flow [l/min]</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>powder-air beam diameter [mm]</td>
<td>9.5</td>
<td>9.5</td>
</tr>
<tr>
<td>velocity of the powder-air mixture in the laser beam [m/s]</td>
<td>9.4</td>
<td>5.8</td>
</tr>
<tr>
<td>average powder concentration [g/m^3]</td>
<td>840</td>
<td>580</td>
</tr>
<tr>
<td>inter-particle distance</td>
<td>0.22 mm</td>
<td>0.13 mm</td>
</tr>
</tbody>
</table>

The particle stream crossed the laser beam to form the ignition volume. The ignition volume could be varied by adjusting the laser beam diameter with the aid of a convex lens with a focal length of 559 mm. The laser used for the experiments was a Lumenics Nd:YAG pulsed laser (wave length = 1.064 \mu m). In the Q-switched mode the pulse length was 10 ns and the energy could be varied between 5 and 1200 mJ. Without a Q-switch the pulse length was 100 \mu s. The maximum laser pulse frequency was 10 Hz. During the ignition experiments the laser energy could be monitored on both sides of the particle stream. The powder concentration in the particle stream was measured by a light extinction technique, and the occurrence of an ignition was detected by an ionisation detector as well as by visual observation.
Figure 3.8 (a)  Overview of the experimental laser ignition set-up.

Figure 3.8 (b)  Fluidised bed dust-air generator used in the laser ignition experiments.
This experimental set-up allowed dust cloud ignitions at a rate of 10 attempts per second for a period of several minutes. It had the advantage of a well-dispersed dust cloud, a continuously monitored dust concentration, a variable and well-defined ignition volume and measurable ignition energy. It was also possible to perform ignitions at two different ignition durations. The short duration of the laser pulse eliminated any influence of the flow on the ignition.

Absorption factor measurement

An important aspect of the laser ignition experiment was the knowledge of the absorption factor of the particles. This absorption factor accounts for the relative amount of laser radiation which is absorbed by a particle. Exact numerical data for this factor only exists for liquids, gases and reference powders. In the case of other materials the factor must be determined using the appropriate laser wave length and particle size. In Figure 3.9 the method used in these experiments to determine the absorption factor is shown. A glass container was placed in the laser beam filled with a non-absorbing liquid. An accurate thermometer was mounted inside the container and a magnetic stirrer was added to ensure the homogeneity of the contents. Behind the container a laser energy monitor was placed in order to measure the transmitted laser radiation intensity.

Determination of the absorption factor was achieved by successive measurements of the absorption of the laser energy first by the system without particles and subsequently by low concentrations of particles. The energy absorption rates were measured as a temperature increase. Equation 19 relates the respective absorption rates to the absorption factor, \( K_a \), of the powder.

\[
K_a = C_{p,\text{system}}(T) \left( \frac{\dot{T}'(T) - \dot{T}'_0(T)}{\frac{E'}{m} - \frac{E'_0}{m_0}} \right) \tag{19}
\]

with:

\[
C_{p,\text{system}}(T) = \left( \frac{\frac{E'_0}{m_0}}{\dot{T}'_0(T)} \right) \tag{20}
\]

In these equations: \( \dot{T}'_0(T) \) is the rate of temperature rise of the liquid without particles, which is temperature dependent, \( \dot{T}'(T) \) is the rate of temperature rise of the suspension of particles, which is also temperature dependent, \( m \) is the liquid mass in the respective experiment, \( E'_0 \) is the net rate of energy consumption in the experiment without particles, and \( E' \) is the net rate of energy consumption when particles are dispersed in
the liquid.

Two major assumptions are made in this equation. First, the liquid absorbs the same amount of energy with and without dispersed particles. Therefore only low concentration powder dispersions were used. Secondly, the absorption factor of the particles in the liquid is the same as their absorption factor in air. Because the refractive index of the powder differs significantly from the refractive indices of both the air and liquid, the absorption factors will be similar.

![Experimental set-up to determine the absorption factor of dust particles.](image)

3.6 Experimental results

For two model powders experiments were performed using the different ignition methods. The minimum ignition temperature (MIT) was determined in the Godbert-Greenwald oven, the minimum ignition energy was measured with a capacitive spark and attempts were made to ignite the powders with the laser, under various conditions. Neither the quenching distance (QD) nor the maximum experimental safe gap (MESG) were measured. Table 3.4 summarises some properties of the powders and the experimental results of the conventional ignition tests.
Table 3.4  Material properties and experimental data of the sulphur and aluminium dusts used in the ignition experiments.

<table>
<thead>
<tr>
<th>Dust cloud conditions</th>
<th>Sulphur</th>
<th>Aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration</td>
<td>840 g/m$^3$</td>
<td>580 g/m$^3$</td>
</tr>
<tr>
<td>d$_{v,50}$</td>
<td>20 $\mu$m</td>
<td>10 $\mu$m</td>
</tr>
<tr>
<td>Density</td>
<td>2.07 g/ml</td>
<td>2.70 g/ml</td>
</tr>
<tr>
<td>Flame temp.</td>
<td>1200 K</td>
<td>3253 K</td>
</tr>
<tr>
<td>MIT</td>
<td>167 °C</td>
<td>490 °C</td>
</tr>
<tr>
<td>MIE</td>
<td>&lt;3.2 mJ</td>
<td>&lt;3.2 mJ</td>
</tr>
<tr>
<td>$K_a$</td>
<td>0.53</td>
<td>0.61</td>
</tr>
</tbody>
</table>

3.6.1 Laser experiments with sulphur

The laser ignition experiments were performed for two different laser pulse durations (100 $\mu$s and 10 ns). In both cases the minimum ignition energy required was determined for a range of ignition volumes. The net amount of energy supplied by the laser beam was calculated using equation 21.

$$E_{\text{net}} = K_a (E_{\text{beam in}} - E_{\text{beam out}})$$ (21)

The energy density was calculated as a function of the ignition volume by division of the net ignition energy by the ignition volume. This value was translated into an ignition temperature. Due to the heterogenous character of the dispersion, however, it is uncertain what part of the energy was absorbed by the surrounding air during the laser pulse. In the calculations it was assumed that the particles absorb all energy. The heat of melting and vaporization of the sulphur was also incorporated into the calculations.

The results of the experiments with the long (100 $\mu$s) laser pulses show the expected decrease in ignition energy with decreasing ignition kernel diameter (Figure 3.10 (a)). However, a constant minimum value of the ignition energy was not obtained. Also, the minimum ignition energy measured with an electric spark is still lower than the minimum laser energy.
Figure 3.10 (a) Ignition energy versus ignition kernel diameter of sulphur dispersion, measured with 100 μs laser pulses.

Figure 3.10 (b) The calculated temperature of the sulphur particles versus ignition kernel diameter, measured with 100 μs laser pulses. The model represents the fit treated in paragraph 3.7.
For ignition kernels larger than about 0.5 mm the temperature necessary to ignite the kernel is more or less constant (Figure 3.10 (b)). For smaller kernels, the temperature is significantly higher. This fact points to a critical ignition kernel whose ignition temperature is the adiabatic flame temperature, of about 0.5 mm diameter for sulphur with an ignition duration of 100 $\mu$s.

The results of the sulphur experiments using short laser pulses (10 ns) are quite similar to the results using a long pulse (Figure 3.11 (a,b)). The same conclusions about the critical ignition kernel can be drawn.

The energies necessary to ignite the sulphur with longer pulses are somewhat larger than with short pulses. With the short pulse duration plasma phenomena are observed which can increase the amount of laser energy absorbed. Although this makes the ignition more efficient, it is an unwanted effect since it is impossible to determine which portion of the laser energy is absorbed by the particle and which by the plasma. The effect of the ionisation in the plasma on the particle combustion is also unclear. Because of these effects, the long laser pulse durations were preferred for the calculations.

As mentioned, the character of the laser ignition method made it impossible to reproducibly ignite very small volumes. Because the energy must be absorbed by the particles, the ignition kernel diameter must exceed the inter-particle distance. This fact made it impossible to investigate the ignition trends with ignition volumes smaller than the inter-particle distance.

\[ \text{Ignition energy versus ignition kernel diameter of sulphur dispersion,} \]
\[ \text{measured with 10 ns laser pulses.} \]
Figure 3.11(b) The calculated temperature of the sulphur particles versus ignition kernel diameter, measured with 10 ns laser pulses.

3.6.2 Laser experiments with aluminium

For reasons already mentioned, the aluminium ignition experiments were only performed with longer pulses (100 µs). Again, a continuous increase in the ignition energy was found as a function of ignition volume. This is shown in Figure 3.12 (a). All of the particle temperatures calculated are around the MIT, except the particle temperature in the smallest ignition kernel, which is somewhat higher (Figure 3.12 (b)). An estimation of the critical ignition kernel dimension of this aluminium dispersion is a diameter of about 0.5 mm. The lowest laser ignition energy, even lower than the spark MIE, was also obtained at this critical kernel size. It may be that even lower energies can be measured with smaller kernels.

3.7 Calculations

In this paragraph the laser data are used to calculate the kinetic data of the combustion reaction, and with these data the other ignition properties are predicted. Comparison of these predicted data with experimental data gives an indication of the value of the laser ignition method.
**Figure 3.12(a)** Ignition energy versus ignition kernel diameter of aluminium dispersion, measured with 100 μs laser pulses.

**Figure 3.12(b)** The calculated temperature of the aluminium particles versus ignition kernel diameter, measured with 100 μs laser pulses. The model is the fitted line treated in paragraph 3.7.
Table 3.5 lists the assumed heat transfer data for the different ignition methods. The balance between the heat production (Eq. 18) and the heat loss (Eq. 17 and Eq. 25) was used to fit the laser ignition data in the Figures 3.10(b) and 3.12(b). Most attention was paid to the fit at larger volumes because the error in the smaller ignition kernels is higher and because it is expected that the smaller volumes deviate from the Semenov theory (see paragraph 3.3.1). The exact dimensions of the kernel were difficult to measure. The data fit yields the following:

Sulphur: \[ E_A = 1.45 \times 10^{-5} \text{ J/mol} \]
\[ \text{aQ.S}_{\text{solid}}[\text{O}_2],k_0 = 1.7 \times 10^2 \text{ J m}^{-3} \text{ s}^{-1} \]

Aluminium: \[ E_A = 1.65 \times 10^{-5} \text{ J/mol} \]
\[ \text{aQ.S}_{\text{solid}}[\text{O}_2],k_0 = 1.7 \times 10^2 \text{ J m}^{-3} \text{ s}^{-1} \]

Table 3.5  Heat transfer data of different types of dust explosion tests.

GG-oven:
\[ h = \frac{\lambda}{0.5D} \] (22)

Electrical spark:
\[ h = \frac{\lambda}{0.5D} \left( \frac{T_0}{T} \right)^{\frac{1}{3}} \] (23)

MESG:
\[ h = \frac{\lambda}{0.5D} \] (24)

Laser ignition:
\[ h = \frac{\lambda}{0.5D} \left( \frac{T_0}{T} \right)^{\frac{1}{3}} \] (25)

In this table \( \lambda \) is the thermal conductivity of the gas phase. Comparison with literature data is difficult because there is very little information on this type of kinetic data. The only value found [Bodenstein and Karo] was an activation energy of 145000 J/mol for the reaction of sulphur particles. This value was used in the fit procedure and agrees well
with laser data.
With these kinetic data it was possible to calculate the theoretical ignition data of both powders. The results are given in Table 3.6.

<table>
<thead>
<tr>
<th>property</th>
<th>sulphur</th>
<th>aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT-calculated</td>
<td>580 K</td>
<td>675 K</td>
</tr>
<tr>
<td>MIT-experimental</td>
<td>440 K</td>
<td>763 K</td>
</tr>
<tr>
<td>MESG-calculated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1=10 mm, v=300 m/s</td>
<td>0.37 mm</td>
<td>0.38 mm</td>
</tr>
<tr>
<td>1=100 mm, v=300 m/s</td>
<td>0.62 mm</td>
<td>0.67 mm</td>
</tr>
<tr>
<td>Crit. ignition kernel diameter</td>
<td>0.5 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>(approximated from laser experiments)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quenching Distance</td>
<td>-</td>
<td>1 mm</td>
</tr>
<tr>
<td>[Ballal, 1980]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIE-calculated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from MESG (l=10 mm)</td>
<td>0.06 mJ</td>
<td>0.011 mJ</td>
</tr>
<tr>
<td>from MESG (l=100 mm)</td>
<td>0.4 mJ</td>
<td>0.07 mJ</td>
</tr>
<tr>
<td>from Crit. Ign. Kern. Diam.</td>
<td>0.5 mJ</td>
<td>0.10 mJ</td>
</tr>
<tr>
<td>MIE-experimental with elec. spark</td>
<td>&lt; 3.2 mJ</td>
<td>&lt; 3.2 mJ</td>
</tr>
</tbody>
</table>

3.8 Discussion and conclusions on dust explosion ignition

The goals of the investigation described in this chapter were the study of the relationship between the MIE, the MIT and the various quenching parameters and also the gaining of more insight into the ignition mechanisms of dust explosions in general. An important aspect of the latter is the critical ignition kernel [Frendi and Sibulkin, 1990]. For these purposes a new method of ignition was developed, an IR laser.

The relationship between the different dust explosion ignition parameters

From theoretical considerations it can be concluded that the activation energy and the pre-exponential factor in the heat production equation can be regarded as the common
factors linking the various ignition parameters. When the heat transfer rates are also known it is possible to calculate a value for the ignition parameters. With the use of a Nd:YAG pulsed laser, attempts were made to measure the kinetics of the ignition reaction of two powders, sulphur and aluminium. With these kinetics and the estimated heat transfer data shown in Table 3.5, values of the MIE, MIT and the MESG were calculated. The results of these calculations are given in Table 3.6. The calculated MIT was compared to experimental values. Only a poor agreement was found. This can be caused by either incorrect kinetic data, an incorrect ignition model or a badly dimensioned test apparatus.

The MESG which was calculated is equal for both powders and, from the calculations, it appears that this parameter is determined merely by the gap diameter. For aluminium a value for the QD was found in the literature, but this value was determined by a different method. Due to a lower velocity in the gap, the quenching distance is larger than the modelled MESG of aluminium.

The MIE was calculated from the values of the calculated MESG and the experimental critical ignition kernel diameter (see below). The calculated values tend to be much lower than the experimental values determined with electrical sparks, although the modelled values are somewhat higher than the values obtained with the laser (Figures 3.10, 3.11, 3.12). These results support the hypothesis that the spark is a very inefficient ignition source. The formation of a shock wave and the longitudinal shape probably contribute to this inefficiency.

The critical ignition kernel

As predicted by Frendi and Sibulkin [1990] the temperature of an ignition kernel below a certain critical size is larger than with larger kernels. This tendency was also found in these laser experiments. For both powders tested this resulted in a critical ignition kernel of about 0.5 mm. This value is higher than the predicted kernel size for methane of 0.1 mm, the difference probably being caused by the heterogenous character of the dust dispersion. In kernels smaller than the inter-particle distance, insufficient numbers of particles are statistically present. The experiments with laser ignition prove the existence of a critical ignition kernel for dust explosions.

Finally, it can be concluded that knowledge of the kinetics of the ignition reaction of the powder dispersion provides a tool for calculating the MIE, MIT and MESG. Attention must be given to the accuracy of the heat transfer models and the kinetic data. The laser method described in this chapter can be used to measure these kinetic data. More accuracy, however, is required. A more powerful laser, for example, would allow ignition of larger kernels or of less sensitive powders.
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Chapter 4

The laminar burning velocity of dust clouds

4.1 Introduction

Measured under laminar flow conditions the burning velocity can be seen as a combustion parameter dependent only on the dust-air mixture properties. For this reason this parameter is often used to characterise the explosion severity of gaseous fuel-air mixtures. Once turbulence is present it will influence the mechanism and the rate of the flame propagation in a complex way. The laminar burning velocity is thus easier to model than the turbulent burning velocity. In the case of flame propagation in dust clouds, the laminar burning velocity is a rather hypothetical parameter because it is usually necessary to create some level of turbulence in order to disperse the dust in the air. Experimental efforts have been made to measure the laminar burning velocity of dust clouds as closely as possible in order to enable comparison with the results of mathematical calculations of this basic parameter. When the laminar value of the burning velocity is known, relationships can be developed to include the effect of turbulence (Chapter 5) and thus to predict rates of pressure rise in an enclosed space (Chapter 6). The real laminar burning velocity of dust clouds, however, cannot physically exist. The particles present in the flame front will produce some turbulent movement when accelerated during the expansion caused by the increase in temperature. For a proper understanding of the subject some definitions must be given. In the first place a distinction should be made between the burning velocity of a dust cloud and the flame velocity in the same mixture. The flame velocity is the velocity of the flame front measured relative to the burnt matter behind the flame front. The burning velocity, on the other hand, is measured relative to the unburnt mixture in front of the flame, which is still at the initial conditions. The flame velocity is composed of the burning velocity together with the expansion rate of the gaseous components, the latter caused by the increased temperature and to the production of gaseous reactants during combustion. This chapter will concentrate on the burning velocity of dust clouds rather than the flame velocity. The effect of expansion is only exhibited in closed systems and is important in the modelling of flame propagation.

Another important distinction made in flame propagation studies is between premixed combustion and diffusional combustion. Premixed combustion requires a homogeneous fuel-air mixture while in diffusional combustion two regions exist: a fuel-rich zone and a zone containing mainly oxidizer. In the case of gas combustion this division is explicit. However, with dust combustion there are different levels of homogeneity of the combustion. At a macroscopic level it is possible that the observed space is completely filled with particles or that only a part of the space consists of a particle-air mixture. At
a microscopic level the homogeneously filled space can be regarded as a heterogeneous mixture of solids and gases. A useful approach is to define the combustion as premixed whenever the single particles are unable to burn separately from the others. In general this is the case for small particles (<50-200 μm). Large particles are assumed to burn according to a diffusional type of mechanism when an array of individually burning particles composes the flame front. Figure 4.1 illustrates this approach. In this chapter we will deal only with premixed combustion, small reacting particles homogeneously dispersed in air. Larger particles rarely cause dust explosion hazards.

Figure 4.1  

a) A homogeneous dust cloud of small particles which cannot burn individually.
b) Individual flames existing around large particles resulting in a diffusional type of combustion of the dust cloud.

4.2 Theory

4.2.1 Description of the propagation mechanism of flames in dust clouds

In order to obtain a better understanding of the mathematical models, it is necessary to describe the possible mechanisms of flame propagation in a dust cloud. A hypothetical flame travelling through a dust cloud can be divided into several zones, as shown in Figure 4.2. The description given below is valid only for model powder-air mixtures without any turbulent flow and without influence of gravitational forces.
Figure 4.2 The different zones in a flame front.
1) undisturbed, cool fuel-air mixture
2) preheat zone
3) vaporization zone
4) ignition point
5) reaction zone
6) zone with burnt matter
7) luminous zone

Zone 1.
Here the fuel-air mixture in front of the flame is still at the initial density, temperature and chemical composition.

Zone 2.
In this part of the flame the dust cloud becomes heated either by radiation, convection or conduction of heat from the hot flame. The local density of the mixture in this zone is reduced by its adiabatic expansion.

Zone 3.
The next step in flame propagation is a further rise in temperature usually resulting in
vaporization or dissociation of the solid matter. A further expansion of the local dust cloud results. In this expanded dust cloud the properties of inter-particle distance, particle size, pore structure and oxygen concentration can change considerably. The vaporization also absorbs extra energy from the surroundings due to the generally large heat of vaporization of the material.

Zone 4.
The temperature of the suspension has reached the value necessary to ignite the fuel. This "ignition temperature" is often confused with the minimum ignition temperature of the dust cloud, which was described in Chapter 3. The minimum ignition temperature is tested at more or less stationary conditions, and thus the fuel-air mixture has more time to reach thermal equilibrium than in the dynamic case of flame propagation. The ignition temperature in this flame is, therefore, considerably higher.

Zone 5.
Once ignited, the actual combustion of the fuel starts. This exothermic chemical reaction supplies heat and gaseous products which cause the mixture to expand further. The chemical reaction proceeds until one of the reactants, dust or oxygen, is totally consumed.
The chemical reaction can occur in different mechanisms:

**Reaction at the solid surface**
The oxygen has to be transferred towards the solid surface where the reaction takes place. This reaction can either produce gaseous species, which must migrate away from the surface, or it can produce solid or liquid material, which deposits on the surface. This layer at the solid surface can restrict the chemical reaction rate.
The rate of this kind of solid surface reaction is directly proportional to the total available surface area, which depends, in turn, on particle concentration, particle size and pore structure. An example of a solid which reacts to produce gaseous products is pure carbon (e.g. graphite). Alternatively, most metals are powders which form solid reaction products (e.g. zirconium, silicon).

**Reaction in the gas phase**
In this case the dust has partially evaporated in the previous zones of the flame, and these gaseous components react with the oxygen after ignition. The physical state of the products of this type of reaction do not significantly influence the rate of reaction. Relatively simple chemical kinetics can be applied to calculate the rate of combustion in this zone. Sulphur and polyethylene develop flames according to this type of reaction mechanism.

**Combined reaction mechanisms**
Most powders burn by combining both these mechanisms. In practice this means that the powder first evaporates to some extent. The vapour phase starts burning and, if enough oxygen is left, ignites the remaining solid phase. Coal dusts and most powders of an organic nature follow this type of combined reaction.
Zone 6.
This part of the flame is a cooling zone. The combustion reaction is already completed, and the reaction products loose their heat to the surroundings. In the case of closed vessel experiments it is possible that the temperature in this zone still continuous to rise due to the adiabatic compression of the mixture caused by the increasing pressure inside the vessel.

Zone 7.
The visible, luminous part of the flame is not restricted to the combustion zone (zone 5), but can also extend to the preheat part of the flame (zones 2 and 3) and to the cooling zone (zone 6), depending on the local temperature and the emission properties of the powder dispersion.

Closely related to these different regions of a flame is the concept of flame thickness. It is usual to define the thickness of the flame as the total length of zones 1, 2, 3, 4 and 5. This flame thickness can be experimentally determined by measurement of the temperature profile. The asymptotic nature of this profile makes it necessary to define the flame location using arbitrary conditions, for example:

\[
\frac{T_{0'} - T_0}{T_f - T_0} = 0.05 \quad \text{and} \quad \frac{T_{f'} - T_0}{T_f - T_0} = 0.95
\]

Here \( T_0 \) is the temperature at the initial condition, while \( T_{0'} \) is taken as the temperature at the border of the flame front. The subscript \( f \) refers to the maximum temperature in the flame, the so-called flame temperature, and \( T_{f'} \) is taken as the temperature at the other border. Another method often used to determine the flame thickness is photography. In this case the length of the luminous zone, zone 7, is supposed to be equal to the flame thickness. This means that a part of the preheat zone is neglected.
4.2.2 Mathematical modelling of the laminar burning velocity in dust-air mixtures

An extensive range of mathematical models exists to calculate the laminar burning velocity of gaseous mixtures. Their homogeneous reaction kinetics allow sophisticated models to calculate reaction rates and heat and mass transfer velocities. To apply these models directly to dust-air combustion, however would be useless because there is little knowledge of the heterogeneous reaction rates of the various powder dispersions. This chapter will start, therefore, with the application of the thermal theory of Mallard and Le Chatelier from 1883 [Kuo 1986]. Although this theory is rather old, the results usually do not deviate more than 25% from the experimental values or from the results of more advanced calculations. The main reason to apply this classic gas flame theory to dust combustion is its simplicity and in order to illustrate the different parameters involved in flame propagation.

Since this thermal theory assumes an homogeneous fuel-air mixture, another theory is adapted to better understand the role of the particles in the combustion mechanism. This theory is based on the theory of Tanaka and Nomura [1978]. These two theories are here combined and extended to yield a theory of the laminar burning velocity of a dust-air mixture.

4.2.2.1 The thermal theory of flame propagation

When Mallard and Le Chatelier presented their thermal theory of gas flame propagation they supposed the flame front to be composed of only two regions: a preheat region and a chemical reaction region, Figure 4.3.

The classic thermal theory is based on a single energy balance over the preheat zone:

\[ \rho \, S_{u1} \, C_p \, (T_i - T_0) = \lambda \left( \frac{dT}{dx} \right)_i \]  \hspace{1cm} (2)

Here \( \rho \) is the density of the fuel-air mixture having a constant heat capacity \( C_p \), \( S_{u1} \) is the laminar burning velocity relative to the unburnt gases, \( T_i \) is the ignition temperature of the fuel-air mixture and \( T_0 \) the initial temperature. The left side of the balance accounts for the amount of energy absorbed by the fuel-air mixture while passing through the preheat zone. The right hand side of the equation is the heat flux from the reaction zone to the preheat zone. Here \( \lambda \) is the heat conductivity and \( (dT/dx)_i \) the temperature gradient between the two zones. Some assumptions can be made.

**Assumption 1**

\[ \left( \frac{dT}{dx} \right)_i = \frac{T_r - T_i}{\delta_r} \]  \hspace{1cm} (3)

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Assumption 2

\[ \delta_r = S_{u,l} \tau_r \]

Where \( \tau_r \) is the chemical reaction time.

A relationship for the laminar burning velocity can now be written:

\[ S_{u,l} = \frac{\lambda}{\rho C_p} \left( \frac{T_f - T_i}{T_i - T_0} \right) \frac{1}{\tau_r} \]  

(4)

This equation allows calculation of the burning velocities of gases under laminar conditions. In this case the effect of radiation is neglected. The most difficult parameter to know is the ignition temperature, \( T_i \). As mentioned in paragraph 4.2.1, this temperature is much higher than the AIT of the mixture and is assumed to be nearly equal to the flame temperature.

![Diagram showing temperature vs. position with labels](image-url)

**Figure 4.3** Flame front according to Mallard and Le Chatelier [Kuo, 1986].

- \( T_i \): ignition temperature
- \( T_0 \): initial temperature
- \( T_f \): flame temperature
- \( \delta_r \): thickness of the reaction region

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Application of this thermal theory to dust-air flame propagation requires an additional term in the energy balance. Radiation can play an important role in the heat transfer and needs to be incorporated. The energy balance of the preheat zone in a dust-air flame then becomes:

$$\rho \ S_{ul} \ C_p \ (T_i - T_0) = \lambda \ \frac{T_f - T_i}{S_{ul} \ \tau_r} + \alpha \ \sigma \ T_i^4$$

(5)

In this equation the mean temperature of the reaction zone is assumed to be $T_f$ and the radiation flux coming from the preheat zone is neglected. The variable $\alpha$ stands for the emission efficiency of the flame front and is dependent on material, particle size, particle concentration and flame front thickness. $\sigma$ is the Stefan-Boltzmann constant (5.67e-8 W m$^{-2}$ K$^{-4}$).

With this balance the burning velocity of a fuel-air mixture can be written as:

$$S_{ul} = \frac{\alpha \ \sigma \ T_i^4 + \sqrt{\left(\alpha \ \sigma \ T_i^4\right)^2 + 4 \ \rho \ C_p \ (T_i - T_0) \ \lambda \ (T_f - T_i)/\tau_r}}{2 \ \rho \ C_p \ (T_i - T_0)}$$

(6)

For practical application of this equation it is necessary to know the parameters $T_f$, $T_i$, $\alpha$, $C_p$, $\tau_r$, $\lambda$ and $\rho$. To estimate all these parameters, except $\tau_r$, the following relationships can be used.

(a) The gas phase density:

$$\rho_g = \rho_{g,0} \ \frac{T_0}{T}$$

(7)

(b) The dust concentration:

$$C_s = C_{s,0} \ \frac{T_0}{T}$$

(8)

(c) The dust-air mixture density:

$$\rho_{mixture} = \rho_g + C_s - (\rho_{g,0} + C_{s,0}) \ \frac{T_0}{T}$$

(9)
(d) The specific heat of the dust-air mixture:

$$C_{\text{P,mixture}} = \frac{C_s C_{p,s} + \rho_g C_{p,g}}{\rho_{\text{mixture}}} - \frac{C_{s,0} C_{p,s} + \rho_{g,0} C_{p,g}}{\rho_{g,0} + C_{s,0}}$$  \hspace{1cm} (10)

Equation 10 is only valid when the dust particles have more or less the same temperature as the gas phase. In order to assess the particle temperature in the flame front, the dimensionless Fourier number is used:

$$Fo = \frac{\lambda t}{\rho_s C_{p,s} d_p^2} > 0.05$$  \hspace{1cm} (11)

This number is based on an average particle temperature of 90% of the temperature of the surroundings. The time necessary to reach this average temperature is:

$$t = \frac{0.05 \rho_s C_{p,s} d_p^2}{\lambda}$$  \hspace{1cm} (12)

Figure 4.4  Heating time of particles of different size and with different thermal conductivities. The calculations are made with Eq. 12.

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In Figure 4.4 the time necessary to heat a particle up to an average temperature of 90% of the temperature of the surroundings is plotted as a function of the particle diameter.

Equation 10 can be applied if the respective preheat time and reaction time exceed the penetration time as defined by Eq. 12.

The temperature dependence of the thermal conductivity of air is fitted, in the temperature range of 500 K to 2500 K, to be:

\[ \lambda = a T \quad a = 6 \cdot 4 \times 10^{-5} \quad [\text{W m}^{-1} \text{K}^{-2}] \quad (13) \]

With the previous relationships and the assumption that the particles are spheres which radiate towards the unburnt mixture with the half of their surface area, the parameter \( a \) can be written as:

\[ a = \epsilon_s \left( \frac{3 C_s \delta_r}{2 \rho_s d_p} \right) + \epsilon_g \left( 1 - \frac{3 C_s \delta_r}{2 \rho_s d_p} \right) \quad (14) \]

Here \( \epsilon_s \) and \( \epsilon_g \) are the emission factors of the respective solid and gas phase. The flame temperature is estimated with:

\[ T_f - T_0 = \frac{E}{\rho_{\text{mixture}} C_{P,\text{mixture}}} \quad (15) \]

\( E \) is the energy released by the chemical reaction:

\[ E = \phi C_s Q \quad (16) \]

Here \( Q \) is the reaction enthalpy and \( \phi \) is the fraction of reacted solids. This energy must be adjusted for the energies of melting or vaporization of the solid.

In order to calculate the dynamic ignition temperature of the dust-air mixture in the flame front the following assumption is made:

\[ \left( \frac{dT}{dt} \right)_i = \frac{T_f - T_i}{\tau_r} \quad (17) \]

This assumption is analogous to Eq. 3.

The ignition temperature is derived from the energy balance in the ignition point, which equals the sum of the increase in internal energy and the energy production by the chemical reaction.

The relationship for the chemical reaction rate is adapted from the previous chapter on ignition phenomena (Chapter 3, Eqs. 1 and 2).
\[ \rho_{\text{mixture}} C_{p,\text{mixture}} \frac{T_r - T_i}{\tau_r} = a Q S_{\text{solid}} [O_2] k_0 \exp\left(\frac{-E_A}{RT_i}\right) \]

(18)

Usually the kinetics of the combustion are unknown, and the dynamic ignition temperature must therefore be estimated. It is also difficult to give a single equation which estimates the particle combustion time, \( \tau_r \). The models to predict this parameter are therefore given in a separate paragraph (4.2.2.3).

4.2.2.2 The particle-to-particle model

This is again a one dimensional model which is composed of two balances: a gas phase balance and a balance of the solid phase.

The dust-air mixture is supposed to be a one dimensional row of particles, each surrounded by its own volume of air, initially of equal dimensions. Figure 4.5 shows a schematic drawing of the model. The flame travels from left to right. Initially the whole system is at the initial temperature. The first particle is ignited, and the particle and its surrounding air reach the flame temperature instantaneously. The adjacent air is then heated by conduction. Transport by radiation is not included because absorption by the gas phase is usually low. The particles inside the element are heated by radiation from the flame front and by transport of heat from the surrounding element of air. The element expands due to the increase in temperature of the gas phase. When another particle reaches the ignition temperature, that particle as well as the surrounding air instantaneously reaches the flame temperature. The burning velocity can be calculated from the time delay between the ignition of two neighbouring particles and the initial inter-particle distance.

The energy balance of the gas phase becomes:

\[ L^3 \rho_G C_{p,G} \frac{dT_G(x)}{dt} = \lambda L^2 \frac{T_G(x) - T_G(x-L)}{L} - \frac{\lambda L^2 T_G(x+L) - T_G(x)}{L} - h \pi D_p \rho L^2 (T_G(x) - T_p(x)) \]

(19)

The term on the left hand represents the accumulation of heat in the air element whilst the first term on the right hand represents the flow of energy coming from the preceding element. The other terms represents the heat leaving the element by conduction to the next element and heat transport to the particle inside the element.

In this equation the thermal conductivity, \( \lambda \), can be calculated by using Eq. 13 and the density of the gas phase, \( \rho \), by Eq. 7. The inter-particle distance, \( L \), is calculated from the solid mass concentration \( (C_{s,p}) \) and the average particle size \( (d_p) \):
\[ L = \left[ \frac{\pi d_p^3 \rho_s T}{6 c_p C_{s0} T_0} \right]^{\frac{1}{3}} \]  

(20)

The parameter \( h \) is obtained from the dimensionless Nusselt number \( \text{Nu} \):

\[ \text{Nu} = \frac{h d}{\lambda} \]  

(21)

If the penetration time is much longer than the time of heating, the Nusselt number has a numerical value of 2. However, in the pre-heat zone of the flame the heating time usually exceeds the time necessary to transport the heat into the particle. Then \( \text{Nu} = 6.6 \). It is also important to notice that the parameters \( L, \lambda, \rho, \) and \( h \) are all dependent on the temperature of the gas. This temperature dependence must therefore be incorporated in the calculations.

---

**Figure 4.5**  Schematic drawing of the geometry of the particle-to-particle model.

The energy balance of the solid phase is:

\[ \rho_s \frac{\pi d_p^3 C_{ps}}{6} \frac{dT_s(x)}{dt} = h \pi d_p^2 (T_g(x) - T_p(x)) + \frac{\pi a_p (d_p)^2}{2} (\alpha \sigma T_f^4) \]  

(22)
The left hand term stands for the energy accumulation in the particle and the right hand side represents the energy transported from the surrounding gas by conduction and the energy transported by radiation from the flame zone. The parameter $\alpha$ is defined by Eq. 14 in which a reaction zone thickness is used. This thickness depends on the flame velocity and must be estimated at the beginning of the calculations. The term $a_p$ is the absorption factor of the particle. In this balance the heat
loss by radiation from the particle is neglected because the average particle temperature in the preheat zone is relatively low. In any case, the particle receives radiation energy from other particles at a more or less equal level. This model gives a quite detailed description of the pre-heat zone of a flame, but pays no attention to the flame front itself. It has been assumed that the particle and its surrounding gas reach the flame temperature immediately after ignition. This approach introduces an error into the heat transported between the particle which is just ignited and the next particle. To overcome this error it can be assumed that the gas temperature around the particle which is just ignited is given by:

\[ T_{0}(x=0) = \frac{t}{\tau_{r}}(T_{f} - T_{i}) \]  

(23)

Here \( t \) is the time evolved after ignition of the previous particle and \( \tau_{r} \) the combustion time of the particle.

The flow chart of the computer programme used for the calculations with the particle-to-particle model is shown in Figure 4.6.

4.2.2.3 Reaction times

For the calculation of the reaction time, \( \tau_{r} \), in the flame front it is necessary to distinguish two different situations:

**Situation 1**

The particles may already be partially evaporated in the preheat zone, or the vaporization rate may exceed the reaction rate. In both these cases the chemical reaction in the vapour phase is the limiting step in the combustion process. The reaction rate can be calculated from the kinetic data of the homogeneous gas phase reaction.

For example:

\[ \text{A(g) + bB(g)} \rightarrow \text{products} \]

The reaction rate becomes

\[ \frac{-dC_{A}}{dt} = \frac{-dC_{B}}{b \ dt} = k \ C_{A}^{n} \ C_{B}^{m} \]  

(24)

\( C_{A} \) and \( C_{B} \) are the respective concentrations of the reacting species in the gas phase, \( k \) is the reaction rate constant and \( n \) and \( m \) are the respective orders of the reactions. Assume a first order reaction in A and the following boundary conditions:

\[ t = 0: \ C_{A} = C_{A,0} \]

\[ t = \tau_{r}: \ C_{A} = C_{A} \]
The reaction time $\tau_r$ can then be written as:

$$\tau_r = \frac{1}{k} \ln \left( \frac{C_{A,0}}{C_A} \right)$$  \hspace{1cm} (25)

The strong temperature dependence of the reaction rate constant can be expressed by the well-known Arrhenius equation.

$$k = k_0 \exp \left( \frac{-E_a}{R T_F} \right)$$  \hspace{1cm} (26)

This type of reaction rate does not happen very often in dust combustion; it implies an unusual combustion rate independent of particle size.

**Situation 2**

The reaction rate limitation is now related to the particle. Figure 4.7 shows a schematic representation of the particle. It consists of a solid kernel, an ash layer and gaseous film layer. A limitation of the reaction rate can be caused by each of these phases. In all the different cases of reaction, a shrinking particle will be presumed. It is possible that the particle size remains constant, for example, when the particle has a porous structure and the reaction proceeds throughout the whole particle. In practice, however, the pore diffusion rate is usually much too slow to result in an explosively fast reaction. The second assumption made in deriving an expression for the combustion time is that a homogeneous temperature profile exists around and inside the particle. Levenspiel [1972] shows that, in the case of fast reactions, a temperature profile will exist mainly in the gaseous film layer around the particle. The particle itself has a more or less flat temperature profile. Nevertheless, Levenspiel concludes that an assumed homogeneous temperature distribution sufficiently fits the real situation for most cases. Finally the models developed here differ in one important detail from the conventional single particle combustion models. Usually an excess of fuel exists causing the oxygen concentration in the gas phase to decrease considerably. It is, therefore, impossible to presume a constant concentration during the combustion of a particle.

With these considerations, the models for the three different limitations will be developed:

**Model 2A**

- **Limited diffusion in the gas film around the particle**

Usually it is the transport of oxygen towards the particle surface which limits the reaction rate, but it also is possible that the migration of reactants or gaseous reaction products away from the surface restrict the reaction rate. The reaction rate for this type of limitation can be calculated by making an assumption.
Although the particle shrinks by chemical reaction or by vaporization, the dimensions of the gas film around the particle remains constant. The ash layer or flaking solids prevent a shrinkage of the gas film.

The chemical reaction can be represented by:

\[ A(g) + bB(s) \rightarrow \text{products} \]

The reaction rate then becomes:

\[
\frac{-dN_A}{dt} - \frac{-dN_B}{b \ dt} = S_{\text{film}} \ k_s \ (C_{A,g} - C_{A,s}) \tag{27}
\]

Usually the concentration of A near to the surface is zero and the surface area, \(S_{\text{surface}}\) of the diffusion layer is supposed to be equal to the initial particle surface area \(4\pi R^2\). The molar reaction rate for a single particle can be converted into a decrease in particle radius \(r\).

\[
\frac{-\rho_B \ r^2}{M_B \ R^2} \ \frac{dr}{dt} = b \ k \ C_{A,g} \tag{28}
\]

\(M_B\) is the molar mass of the solid and \(\rho_B\) the density of the solid.

The decrease in the concentration of A during the combustion is:

\[
C_{A,g} - C_{A,g,0} = \frac{\rho_B \ \frac{4}{3} \ \pi \ (R^3 - r^3) \ \ n}{M_B \ b} \tag{29}
\]

Here \(n\) is number concentration of the particle.

\[
n = \frac{C_{s,0}}{\rho_B \ \frac{4}{3} \ \pi \ \ R^3} \tag{30}
\]

Rearranging Eqs. 28, 29 and 30 gives:

\[
\int_{r}^{R} \frac{-r^2}{b \ \frac{C_{A,g,0}}{C_{s,0}} \ \frac{M_B \ R^3}{R^3 - R^3 + r^3} \ \ dr} - \int_{0}^{r} \ k_s \ C_{A,g,0} \ dt \tag{31}
\]
The solution is:

$$\tau_r - \frac{\rho_B R}{k_s C_{s,0}} \frac{1}{3} \ln \left[ \frac{\frac{C_{A_{s,0}}}{C_{s,0}} M_B b R^3}{\frac{C_{A_{s,0}}}{C_{s,0}} M_B b R^3 - R^3 + r^3} \right]$$

(32)

**Model 2B**

- **Limited mass transfer in the ash layer** -

When the ash layer around the particle becomes the rate determining step in the combustion mechanism, the reaction rate is too low to sustain a flame propagation. Only in the case of metal combustion, where a thin oxide layer on the particle surface exists, is the rate of heat production sufficiently high. Even then, only a small part of the particle is converted by the combustion reaction. Figure 2.8 in Chapter 2 illustrates this with test results showing the maximum explosion pressure versus the concentration of silicon dust. It is seen that the maximum pressure, which means that all the oxygen is consumed, is attained at concentrations several times higher than the stoichiometric ratio. In order to model this type of combustion mechanism an ash layer of constant thickness around a particle of a constant size is assumed.

The rate equation for a single particle is:

$$-\frac{dN_A}{dt} = -\frac{dN_B}{b \ dt} - 4 \pi R^2 D_{ash} \frac{C_{A_{ash}} - C_{A_{s,0}}}{\delta_{ash}}$$

(33)

$D_{ash}$ is the diffusion coefficient of oxygen in the ash layer of having a thickness $\delta_{ash}$. The concentration $C_{A_{ash}}$ is usually zero. In this rate equation it is supposed that the oxygen diffuses towards the surface where the chemical reaction occurs. If the fuel first evaporates and then diffuses through the ash layer towards the gas phase and reacts with the oxygen exactly the same rate equation appertains. This mechanism is therefore given no further attention.

Equation 33 in combination with Eq. 30 can be written as:

$$\int_{C_{A_{s,0}}}^{C_{A_{ash}}} \frac{\frac{-dC_{A_{ash}}}{c_{A_{s,0}}}}{C_{A_{s,0}}} = \int_{0}^{\tau_r} \frac{D_{ash} C_{s,0}}{\rho_B R^3} \frac{dt}{\delta_{ash}}$$

(34)
The solution for the reaction time is:

\[
\tau_r = \frac{\rho_B}{D_{ash}} \left( \frac{R}{3} \delta_{ash} \right) \ln \left( \frac{C_{A_{g,0}}}{C_{A_{s}}} \right)
\]  

\[35\]

*Figure 4.7 Schematic drawing of the transport limitations around a particle.*

**Model 2C**

*The chemical reaction at the particle surface limits the combustion*

In this model the particle shrinks, and therefore the particle surface area, \( S_{\text{particle}} \), is reduced. The reaction rate equation for a single particle is:

\[
\frac{-dN_A}{dt} = \frac{-dN_B}{b \, dt} - k \, S_{\text{particle}} \, C_{A_s}
\]  

\[36\]

Here \( k \) is the reaction rate constant.

The concentration of A at the particle surface is assumed to be equal to the bulk concentration. The equivalent to Eq. 31 of Model A can be written as:

\[
\int_{R}^{r} \frac{-1}{a^2 + r^2} dr - \int_{0}^{R} \frac{C_{s,0} k}{\rho_B \, R^2} dt
\]  

\[37\]
With:
\[
a^3 = \sqrt[3]{\frac{C_{A,0}}{C_{s,0}}} M_B b R^3 - R^3
\]  

(38)

The solution of Eq. 37 is:
\[
\tau_r = \rho_B \frac{R^3}{C_{s,0}} k \left( \frac{1}{6a^2} \left[ \frac{(R+a)^2 (r^2-ar+a^2)}{(R^2-ar+a^2)} \right] + \frac{1}{a^2 \sqrt{3}} \left[ \tan^{-1}\left(\frac{2R-a}{a\sqrt{3}}\right) - \tan^{-1}\left(\frac{2r-a}{a\sqrt{3}}\right) \right] \right)
\]

(39)

Using this analysis of time scales involved in particle combustion, Figure 4.8, which shows the various time scales as a function of the particle diameter, can be plotted.

Figure 4.8  Time scales involved in particle combustion in a hot environment. Film diffusion, ash diffusion and chemical reaction at the particle surface are compared with chemical reaction in the gas phase. As an example the experimentally obtained combustion times of coal particles are also given [from: Essenhigh and Fells].

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Figure 4.8 indicates that the limiting step in particle combustion at high temperatures is usually the film diffusion of material to or from the particle surface. At these high temperatures the chemical reaction at the surface is usually very fast. In some cases an ash layer can become the limiting step. Aluminium, for example, is supposed to build up an ash layer which can become the limiting step when sufficiently thick. The experimental data on coal combustion [Essenhigh and Fells] shows, according to the slope of the line, that even for this type of ash forming material the combustion time is determined by film diffusion.

For small particles (< 10 μm) which evaporate easily it is possible that gas phase combustion limits the reaction rate. The reaction time of gaseous fuel-air mixtures then exceeds the mass transfer rate.

Comparison of Figures 4.8 and 4.4 shows that the heating time of a particle is usually much shorter than the combustion time. The assumption can therefore be made that the particles have the same temperature as the surrounding gas during combustion.

4.2.3 Model testing and evaluation

In this paragraph the proposed models are tested, and the influence of some major model parameters is demonstrated.

4.2.3.1 Comparison of the thermal-theory model and the particle-to-particle model

A carbon powder which has the properties given in Table 4.1 is chosen as an example. With these properties calculations were made with both models. A particle size of 20 μm was chosen and different dust concentrations were calculated. The results are given in Figure 4.9. This figure shows that the thermal-theory predicts burning velocities which are somewhat lower than the burning velocities predicted by the particle-to-particle model. The reason for this difference is the less accurate description of the transport of heat in the unburnt region. The thermal theory does not account for the temperature difference between the gas phase and the solid phase. The particle-to-particle model is therefore preferred.

The different ignition temperatures used in the calculations result in different burning velocities. Since it is very difficult to obtain the real ignition temperature in the flame front, this parameter must be optimised by comparison with the experimental data. In general, however, the dynamic ignition temperature is much higher than the minimum ignition temperature of the dust, as described in Chapter 3.

The effect of the concentration observed in Figure 4.9 seems to match the experimental results obtained with activated carbon in the explosion vessels. As explained in chapter 6, it appears that the burning velocity is related to the rate of pressure rise in closed explosion vessels. The calculation results were therefore compared with Figure 2.9. Both figures show an initial steep increase in 'burning rate' at low concentrations. The maximum burning rate in both cases is found at a concentration considerably higher than the stoichiometric ratio, and the development of the burning rate at high concentrations is also comparable.

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Table 4.1  Chemical and physical properties of the activated carbon powder used for modelling.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>density</td>
<td>600 [kg/m³]</td>
</tr>
<tr>
<td>heat of combustion</td>
<td>32.9 (10^6) [J/kg]</td>
</tr>
<tr>
<td>molar mass</td>
<td>12 (10^{-3}) [1/kg]</td>
</tr>
<tr>
<td>specific heat</td>
<td>690 [J kg(^{-1}) K(^{-1})]</td>
</tr>
<tr>
<td>melting point</td>
<td>3730 [K]</td>
</tr>
<tr>
<td>boiling point</td>
<td>4830 [K]</td>
</tr>
<tr>
<td>emissivity factor</td>
<td>1 [-]</td>
</tr>
<tr>
<td>absorption factor</td>
<td>1 [-]</td>
</tr>
</tbody>
</table>

Figure 4.9  Comparison of the thermal-theory model and the particle-to-particle model for activated carbon dust particles of 20 μm diameter.
4.2.3.2 Effect of particle size on calculated burning velocity

Using the particle-to-particle model the concentration dependence of activated carbon powder was calculated for different particle sizes. Figure 4.10 shows the results. A decrease in particle size increases the burning velocity. This is caused by the decreased combustion time of the single particle; the resulting flame front is then thinner, and the heat transport by conduction is enhanced by the increased temperature gradient. This trend is also found in the experimental data. In Figures 2.11 explosion indices are shown for various powders with different size ranges. Here also the smaller particles have higher burning rates. The experimental results for the activated carbon samples also show a tendency to maximum burning rate at lower concentration for smaller particles. This effect is not predicted by the calculations. A possible reason is the effect of turbulence on the combustion of these small particles. The short combustion times of the small carbon particles causes an interaction which is different from the usual mechanism. Instead of enhanced conduction, the thin flame is now accelerated by wrinkling of the flame front. The resulting velocity is thus influenced by particle size and through this interaction mechanism.

![Graph showing the calculated burning velocity of activated carbon for samples of different particle size distribution. The calculations are made using the particle-to-particle model.](image)

**Figure 4.10** Calculated burning velocity of activated carbon for samples of different particle size distribution. The calculations are made using the particle-to-particle model.
4.2.3.3 Effect of density of the dust on the calculated burning velocity

To study the effect of the density of the powder on the burning velocity calculations were made, using the particle-to-particle model, for powder densities of 600 kg/m$^3$ (activated carbon) and 2250 kg/m$^3$ (graphite). Figure 4.11 shows the results. Similar results are found in explosion experiments using samples of activated carbon and graphite, as shown in Figure 2.13. The hypothesis is proposed that it is not the pore area which influences the burning rate, but merely the increased number of particles with lower densities which cause an increase in available surface area.

![Graph showing effect of density on burning velocity]

Figure 4.11 Calculations of the effect of the powder density on the burning velocity.

4.2.3.4 Effect of the heat of combustion on the calculated burning velocity

In order to investigate the effect of the flame temperature on the propagation of a dust explosion, calculations were made with an artificially high heat of combustion (49.4 MJ/kg instead of 32.9 MJ/kg). As expected the burning rate increases with higher heat of combustion. The high flame temperature induces a higher temperature gradient, and this in turn enhances the heat transport by conduction. A higher burning velocity is the result.
Figure 4.12  Calculated effect of flame temperature on the burning rate of dust-air mixtures. The flame temperature is increased by an increase in combustion heat whilst the other properties remain constant.

Figure 4.13  Effect of the diffusion coefficient on the burning velocity, calculated with the particle-to-particle model.
4.2.3.5 The effect of the diffusing species on the calculated burning velocity

In the case of activated carbon it is oxygen which must diffuse towards the particle surface and carbon dioxide which moves away from the surface. These gases have similar diffusion coefficients. In order to investigate the effect of a limited film diffusion of a heavier component, calculations were made with a different diffusion coefficient (0.05e-4 instead of 0.178e-4 m²/s). This is the diffusion coefficient of hydrocarbons with a molecular mass of about 150 g/mole, diffusing in air. The decreased diffusion rate increases the combustion time of the particle and thus lowers the burning velocity. This effect is shown in Figure 4.13.

4.2.3.6 The role of radiation and conduction in the propagation of dust explosions.

Much discussion occurs about the role of radiation in the propagation of dust explosions. Sometimes it is stated that the main difference between gas and dust combustion is the role of radiation. Gas flames propagate mainly by conductive heat transport whilst dusts are supposed to propagate by radiation because of the high absorption of radiation by the particles.

In order to investigate this phenomenon the individual contributions of the radiative and conductive heat transfer rates were calculated. It appears, however, that even in the case of activated carbon with a particularly high absorption factor, the rate of radiative transport never exceeds 8% of the total heat transferred. The maximum rate of radiative transfer is found for dusts with high flame temperatures and large, slow burning particles. The temperature gradient is then relatively small. These results justify the assumption that dust flames propagate by conduction.

4.3 Experimental

4.3.1 Review of the experimental techniques for measuring the laminar burning velocity

In the literature several methods can be found for measuring the laminar burning velocity of premixed fuel-air mixtures [Rallis and Garforth, Kuo]. Although these methods have been all developed for determination of the laminar burning velocity of gaseous mixtures, some researchers have attempted to apply them to dust-air experiments. The methods are usually divided into stationary flames, moving flame fronts and closed vessel experiments.

Stationary flame front methods

The stationary flame front technique is the most direct method of measuring the burning
velocity. The fuel-air mixture is blown into a burner on which a flame is stabilised. Two different types of burner geometry are applied: a conical flame burner and a flat flame burner. Figure 4.14 shows the two types of burners.

![Diagram of a conical flame burner and a flat flame burner]

\[\textit{a) conical flame burner} \quad \textit{b) flat flame burner}\]

\textit{Figure 4.14 Two types of fuel-air burners.}

In the case of the flat flame burner, the burning velocity is equal to the velocity of the unburnt fuel-air mixture in front of the flame. Stabilization of the flame is achieved by creating a slightly divergent flow of the mixture leaving the burner. Cassel [1964] describes experiments on stabilizing flames of coal dust on a flat flame burner. The flame was positioned about one inch above the burner of unstated dimensions. Mason and Wilson [1967] used a plain tube of 10.9 mm diameter to sustain flames of lycopodium in air. Dependent on the flow rate they obtained flat flames or hollow, saucer shaped flames, due to the velocity profile developed in the flow inside the tube. They measured a concentration gradient and thus a burning velocity gradient over the tube diameter.

Bryant [1971] and Smoot et.al. [1976] used larger burner diameters and straightened the flow inside the burner by using screens. This stabilising construction tends to work well, but usually the burner absorbs heat from the flame over the whole area. When the flame
is attached on the burner mouth, this phenomenon can have a unacceptably large influence on the numerical value of the burning velocity. Milne and Beachey [1977] describe experiments with a flat flame burner equipped with a honeycomb structure. They claimed to stabilise flames of pulverized coal-air mixtures directly on this honeycomb without influencing the burning velocity, even though they measured temperatures of the honeycomb material up to 270 °C!

The other type of stationary flame often used to study flame propagation is the conical or bunsen type of flame. Kaesche-Krische [1959] carried out experiments with lycopodium and polyvinyl alcohol (PVA) dust in air using a 12 mm diameter tube. Cassel [1964] describes conical aluminium flames on burner tubes of 14 and 19 mm diameter. In both cases the burner was composed only of an empty tube, thus allowing a laminar flow profile to be developed. The flow velocity deliberately exceeded the burning velocity, and the flame was stabilised on the burner rim, where the flow profile caused a lower flow velocity. The burning velocity was obtained by determining the flow velocity perpendicular to the conical flame front.

**Moving flame front**

It is also possible to study the propagation of a flame front in a dust cloud in a partially open tube filled with a quiescent fuel-air mixture. Figure 4.15 shows the principle of this method. The tube is filled with a powder dispersion which is usually ignited at the open end of the tube. The developing flame front travels towards the closed end of the tube.

![Diagram of moving flame front](image)

*Figure 4.15  Moving flame front method of measuring the burning velocity of fuel-air mixtures.*
The expanding gaseous reaction products are able to leave the tube at the open end, thus maintaining atmospheric pressure inside the tube. The burning velocity is presumed to be equal to the velocity of the flame front, since the expanding gases do not accelerate the flame propagation. The main disadvantage of this method is the presence of the tube wall. This surrounding wall slows down the flame front close to the wall, which results in a gradual stretching of the flame front during its development. The use of tubes of larger diameter to overcome this problem introduces an increased instability which, on turn, influences the burning velocity. Provision of small holes at the closed end of the tube seems to have a stabilizing effect on this instability in gaseous flame fronts [Rallis and Garforth].

**Figure 4.16**  A starch-air flame
(150 g/m³) developed after
1.5 m distance in a
200 mm x 200 mm square tube.
From Proust and
Veysiere [1988].

Despite these disadvantages researchers have used this method to study quiescent dust-air mixture combustion. Essenhigh and Woodhead [1958] carried out experiments in tubes, approximately 5 meter in length and 50 and 75 mm in diameters, which were filled with dust dispersions by feeding particles from the top. The free falling particles were
presumed to form a non-turbulent dust cloud. After closing the tube at the top the mixture was ignited at the bottom. The burning velocity was determined by recording the flame front position using photography. A similar configuration was applied by Butlin [1971]. The tube he used had a length of 2 meter and its diameter was 75 mm. He also used photographic techniques to measure the burning velocity. Proust and Veysierre [1988] filled their tube (length 2 m, 200 x 200 mm square cross section) with a fluidised bed. When the tube was observed to be filled sufficiently with the powder-air dispersion, the fluidised bed was removed, the top was closed and the mixture was ignited at the open ended bottom.
A rather new technique was applied by Lee et.al [1992] and Gardiner and Bardon [1990]. They used an electric field to produce a quiescent dust cloud inside a tube shaped combustion chamber. The square tube was placed horizontally, and the bottom wall acts as an earthed electrode. The top wall was connected to a high voltage supply (10-50 kV). The two electrodes were insulated in order to prevent short circuit of the electric field by passing flame fronts.

The authors of both papers report experiments with aluminium powder. Due to the strong electric field inside the tube, the particles were successively attracted and charged or discharged by the two electrodes. The particles constantly moved up and down. Lee et al. report particle velocities of 20-50 cm/s. According to both papers the final result was a non-turbulent cloud of particles. It is, however, questionable whether particles moving with velocities of 20-50 cm/s will not cause some degree of micro-turbulence. It is also possible that the charged particles have a combustion mechanism different from neutral particles. These questions need to be answered before this kind of suspension method should be used as a standard to measure burning velocities of powder-air mixtures.

High speed photographs of the flame fronts developed in all the conventional tube shaped experimental devices presented above illustrate the stretching effect of the wall on the shape of the flame front. Figure 4.16 shows a photograph published by Proust and Veysierre [1988] of a flame front developing in a cloud of starch particles.

It is difficult to say to what extent the wall is still influencing the flame propagation in the centre of the tube, but its spherical shape in the centre indicates that the flame actually develops spherically rather than flat. This will make an essential difference to the propagation velocity measured.

**Constant volume vessel method**

In this method a rigid closed spherical vessel is used to measure the burning velocity. A fuel-air mixture is fed into the vessel, and this dispersion is ignited in the centre of the vessel. The flame front developed from the centre travels towards the wall. During the propagation of the flame the pressure inside the vessel rises due to the increase in temperature of the contents. Recordings of the pressure history and knowledge of the position of the flame front with time yield information about the burning velocity of the
fuel-air mixture. Because of its importance for dust explosion testing in general, this closed vessel technique will be treated extensively in Chapter 6. An overview of results obtained by the various burner types is presented in Table 4.2. This table gives information about the dust and the techniques used to measure the laminar burning velocity.

4.3.2 Experiments

In order to obtain experimental data three measuring methods were used. Stationary burners were constructed for measuring the laminar burning velocity directly. Because of the difficulties arising in operating these burners, closed vessel equipment was also used.

4.3.2.1 Flat flame burner experiments

Special effort was devoted to the construction of a burner for stabilizing a laminar powder-air flame. The final design is shown in Figure 4.17.

![Diagram of flat flame burner](image)

**Figure 4.17** The flat flame burner for stabilising laminar flames of dust-air mixtures. The burner is equipped with: a powder feeder, a fluidised bed, an air supply, a rotameter, a vibrator, a burner, equipped with a honey comb structure, a natural gas pilot flame and a concentration measurement device.
Table 4.2  Numerical values of laminar burning velocities of various material measured in flat flame burners or Bunsen burners.

<table>
<thead>
<tr>
<th>material/particle size [μm]</th>
<th>dust concentration [g/m³]</th>
<th>burning velocity [cm/s]</th>
<th>test method</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>starch 20</td>
<td>50</td>
<td>63</td>
<td>moving flame in tube</td>
<td>PV88</td>
</tr>
<tr>
<td>cork 'fine'</td>
<td>50</td>
<td>40</td>
<td>moving flame in tube</td>
<td>EW58</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>100</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td>cork 'coarse'</td>
<td>50</td>
<td>70-80</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>40</td>
<td>idem</td>
<td></td>
</tr>
<tr>
<td>lycopodium 30 μm</td>
<td>200</td>
<td>26</td>
<td>Bunsen</td>
<td>KK59</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>17</td>
<td>Bunsen</td>
<td>KK59</td>
</tr>
<tr>
<td>PVA dₚ unknown</td>
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<td>25</td>
<td>Bunsen</td>
<td>Ca64</td>
</tr>
<tr>
<td></td>
<td>400</td>
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<td>Bunsen</td>
<td></td>
</tr>
<tr>
<td>aluminium 30 μm</td>
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<td>Bunsen</td>
<td></td>
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<td>aluminium 10 μm</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>42</td>
<td>Bunsen</td>
<td></td>
</tr>
<tr>
<td>lycopodium 30 μm</td>
<td>200</td>
<td>8.25</td>
<td>Bunsen</td>
<td>MW67</td>
</tr>
<tr>
<td>Pittsburgh coal 10 μm</td>
<td>150</td>
<td>20</td>
<td>flat flame</td>
<td>SH76</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>32</td>
<td>flat flame</td>
<td></td>
</tr>
<tr>
<td>Pittsburgh coal 30 μm</td>
<td>120</td>
<td>13</td>
<td>flat flame</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>21</td>
<td>flat flame</td>
<td></td>
</tr>
<tr>
<td>Pittsburgh seam coal 10-20 μm</td>
<td>270</td>
<td>8.8</td>
<td>flat flame</td>
<td>MB77</td>
</tr>
</tbody>
</table>
The aim of the burner was the stabilization of a laminar flame of a dust-air mixture in open air. The flame should not be attached to the burner mouth or to some other stabilizing fixture. A pilot flame was therefore introduced. This small flame ignited the powder-air mixture. By adjusting the flow velocity, it was planned to develop a laminar flame front having a small angle. Measurement of this angle and of the flow velocity result in the desired burning velocity. Figure 4.18 shows photographs of a flame at various flow velocities, resulting in different angles.

Figure 4.18  Corn starch flames  
(C is about 0.5 kg/m$^3$) stabilised on the flat flame burner at various flow velocities.

a) $v = 20 \text{ cm/s}$

b) $v = 25 \text{ cm/s}$

c) $v = 29 \text{ cm/s}$
In order to control the conditions inside the flame, the apparatus was equipped with a fluidised bed which acted as buffer for variations in the feed rate and also improved the degree of dispersion of the powder in the flame. A vibrator was fitted to the equipment in order to prevent deposition of the powder inside the honey comb structure of the burner.

Laminar flow in the flame was achieved by the honey comb structure inside the burner. The spacing of this structure was 7 mm. For an expected maximum flow velocity of 0.50 m/s the Reynolds number was then 250, which is laminar.

In order to measure the concentration in the flame, two different methods were used. The average concentration was determined by calibrating the feeder. The instantaneous dust concentration was measured using a light attenuation technique. This apparatus was calibrated against the feeder over a long period.

Figure 4.19 shows some typical measurements of the burning velocity of a powder. The results are typical of measurements made with a flat flame burner. The average value approaches the values found in the literature, but the variation in the results is considerable. Average measurements of the burning velocity of three powders, made using the flat flame burner, are summarised in Table 4.3. In this table a range of concentrations and velocities is given. This means that in the experiments a range of data points was found with this spread. It was not possible to observe a more specific trend in the measurements.

![Figure 4.19](image.png)

*Figure 4.19  Results of the measurement of burning velocities of potato starch (d=20 μm).*
Table 4.3  \textit{Experimental results of measurements of the burning velocity of some dusts using the flat flame burner.}

<table>
<thead>
<tr>
<th>dust:</th>
<th>concentration [kg/m$^3$]</th>
<th>burning velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>lycopodium (d=33 $\mu$m)</td>
<td>0.15 - 0.45</td>
<td>0.15 - 0.30</td>
</tr>
<tr>
<td>corn starch (d=15 $\mu$m)</td>
<td>0.43 - 0.8</td>
<td>0.06 - 0.18</td>
</tr>
<tr>
<td>potato starch (d=26 $\mu$m)</td>
<td>0.5 - 2.1</td>
<td>0.1 - 0.17</td>
</tr>
</tbody>
</table>

4.3.2.2  The tube-shaped burner experiments

In order to reduce the large variation in the results from the flat flame burner, a tube-shaped burner was also tested. Figure 4.20 shows the experimental set-up used for the experiments.

\begin{figure}[h]
\centering
\includegraphics[width=0.75\textwidth]{figure420.png}
\caption{Experimental set-up for the measurement of burning velocities of powder-air mixtures using a tube-shaped burner.}
\end{figure}

100
The burner length was kept short in order to prevent the development of a laminar flow pattern. The powder was fed from the fluidised bed which was operated batch wise. The dust was mixed with a coarse powder and gradually elutriated. The dust concentration was monitored.

Figure 4.21 shows a photograph of a typical dust flame stabilised on the tube shape burner.

![Photograph of a corn starch flame stabilised on a 25 mm diameter tube. The burning velocity is 0.17 m/s.](image)

The burning velocity of the dust-air mixture was obtained by dividing the burner area by the flame front area and then multiplying by the flow velocity. Although the variation in the results using this type of burner was smaller, it still was difficult to apply this apparatus. The fluidised bed only operates properly in a certain flow region, and the burner diameter must be varied in order to obtain the desired flow velocity inside the burner. Extensive trial and error is therefore needed to measure the burning velocity. The flame also tends to propagate into the burner very easily, which makes it necessary to frequently clean the fluidised bed.

Table 4.4 summarises the measurements using the tube shaped burner.
Table 4.4  Experimental measurements of the burning velocity of some dusts using the tube shaped burner.

<table>
<thead>
<tr>
<th>dust:</th>
<th>concentration [kg/m³]</th>
<th>burner diameter [mm]</th>
<th>burning velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>corn starch (d=15 μm)</td>
<td>0.4-0.6</td>
<td>25 and 33</td>
<td>0.13-0.20</td>
</tr>
<tr>
<td>sulphur (d=20 μm)</td>
<td>0.2-0.3</td>
<td>33</td>
<td>0.17-0.25</td>
</tr>
</tbody>
</table>

4.3.2.3  Closed vessel experiments

The closed vessel experiments were performed in the 20 litre sphere described in Chapter 2. The method used to calculate the burning velocity from the rate of pressure rise during an explosion is treated in Chapter 6. The experimental data are shown in Figures 5.8 to 5.11 in Chapter 5. These data were used to extrapolate the burning velocity to a turbulence level of zero. The resulting laminar burning velocities are summarized in Table 4.5.

Table 4.5  Extrapolated burning velocity at zero turbulence, calculated from pressure measurements in the 20 litre sphere.

<table>
<thead>
<tr>
<th>dust</th>
<th>dp [μm]</th>
<th>conc. [kg/m³]</th>
<th>$S_{(u'=0)}$ [m/s]</th>
<th>$P$ [bara]</th>
<th>$P_{max}$ [bara]</th>
</tr>
</thead>
<tbody>
<tr>
<td>activated carbon</td>
<td>20</td>
<td>0.25</td>
<td>0.12</td>
<td>5.8</td>
<td>8.0</td>
</tr>
<tr>
<td>sulphur</td>
<td>20</td>
<td>0.5</td>
<td>0.15</td>
<td>5.2</td>
<td>7.5</td>
</tr>
<tr>
<td>maize starch</td>
<td>20</td>
<td>0.5</td>
<td>0.25</td>
<td>3.0</td>
<td>5.6</td>
</tr>
<tr>
<td>aluminium</td>
<td>20</td>
<td>0.25</td>
<td>0.13</td>
<td>4.5</td>
<td>7.0</td>
</tr>
<tr>
<td>potato starch</td>
<td>20</td>
<td>0.5</td>
<td>0.20</td>
<td>5.0</td>
<td>8.0</td>
</tr>
<tr>
<td>lycopodium</td>
<td>26</td>
<td>1.0</td>
<td>0.08</td>
<td>4.5</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>0.5</td>
<td>0.17</td>
<td>5.0</td>
<td>8.3</td>
</tr>
</tbody>
</table>

The pressures given in this table refer to the pressures at which the rate of pressure rise was measured. The average maximum explosion pressure is also given in order to enable
calculation of the flame temperature, which is necessary for modelling. The latter is an important advantage of the closed vessel method. Disadvantages are the doubtful accuracy of the extrapolation to zero turbulence conditions and the fact that the burning velocity is determined at an elevated pressure and temperature.

4.3.2.4 Comparison of experimental burning velocities and the calculated burning velocities

The most important facts which can be learnt from a comparison of the results obtained using the different experimental methods are as follows:
1) the results for all powders using all the methods are burning velocities in the range of 0.1 to 0.4 m/s,
2) it is difficult to perform accurate measurements
3) the results are comparable with the data found in the literature (Table 4.2), at least in their order of magnitude.

Table 4.6 Calculated burning velocities of the dusts used in the closed vessel experiments described in paragraph 4.3.2.3.
The ignition temperature is used to match the calculated burning velocities and the experimental results.

<table>
<thead>
<tr>
<th>dust</th>
<th>conc. [kg/m³]</th>
<th>burning velocity [m/s]</th>
<th>ignition temperature [%Tᵢ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>activated carbon (d = 20 μm)</td>
<td>.25</td>
<td>0.12</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>.50</td>
<td>0.15</td>
<td>94</td>
</tr>
<tr>
<td>sulphur (d = 20 μm)</td>
<td>0.5</td>
<td>0.25</td>
<td>26</td>
</tr>
<tr>
<td>corn starch (d = 15 μm)</td>
<td>0.4</td>
<td>0.13</td>
<td>88</td>
</tr>
<tr>
<td>aluminium (d = 20 μm)</td>
<td>0.25</td>
<td>0.2</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.4</td>
<td>17</td>
</tr>
<tr>
<td>potato starch (d = 26 μm)</td>
<td>1.0</td>
<td>0.08</td>
<td>92</td>
</tr>
<tr>
<td>lycopodium (d = 33 μm)</td>
<td>0.5</td>
<td>0.17</td>
<td>83</td>
</tr>
</tbody>
</table>
In order to test the particle-to-particle model the burning velocities of the powders shown in Table 4.5 were calculated. The elevated pressure and temperature were incorporated in these calculations. It is possible to obtain similar burning velocities by adjusting the ignition temperature. Table 4.6 shows the results of the calculations. From these data it appears that it is impossible to propose a single value of the ignition temperature. It is even difficult to discover a trend in the data. Sulphur and aluminium ignite at a relatively low temperature and have low ignition energies whilst lycopodium also has a low ignition energy, but ignites at a high temperature.

4.4 Conclusions

The propagation mechanism

From models of the propagation of flames in quiescent dust clouds it appears that they mainly propagate by conduction of heat in the gas phase. According to calculations made with the thermal theory model, radiation seems to play only a minor role in the heat transport mechanism in the flame front. The temperature and the temperature gradient in the flame determine the rate of heat conduction. The temperature gradient can be calculated from the flame temperature, the ignition temperature and the particle combustion time. The latter can usually be calculated from the rate of mass diffusion in the film layer around the particle. The flame temperature can be obtained by thermodynamic calculations. The ignition temperature in the flame front is more difficult to obtain. Its value lies between the initial temperature and the flame temperature. Combustion kinetics and transport rates in the flame front define the actual value of this dynamic ignition temperature.

The mathematical models

Both the thermal theory model and the particle-to-particle model are useful for understanding the influence of the various parameters on the rate of propagation of dust explosions. The particle-to-particle model incorporates more details of the particle-gas interactions and is, therefore, preferred. The absolute value of the burning velocity is difficult to calculate because the necessary dynamic ignition temperature is unknown.

The experimental determination of the laminar burning velocity

Three different experimental methods were used to measure the laminar burning velocity of a dust cloud: a flat flame burner, a tube-shaped burner and a closed vessel. Both burners are difficult to operate. Trial-and-error is needed to obtain the burning velocity of a powder. The methods are not very accurate and many powders are hard to measure
in the burners. The closed vessel equipment is easier to operate, but the accuracy of the extrapolations is doubtful.

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Chapter 5

The role of turbulence in the propagation of dust explosions

5.1 Introduction

Although it is possible to calculate the laminar burning velocity of dust-air mixtures, the experimental determination is difficult. In addition to the problem of stabilising the dust-air flame on the burner, difficulties arise when attempts are made to sustain laminar flow conditions in the dust-air mixture. Due to sedimentation of the dust particles it is always necessary to cause some turbulent movement in the dust-air mixture in order to assure a homogeneous mixture of the fuel. This necessary turbulence is called the pre-ignition turbulence since it is present in advance of the ignition. The other component of the turbulence is the post-ignition turbulence, induced by the expansion of the hot gases in the burning fuel-air mixture. This expansion can cause the unburnt mixture in front of the flame to become turbulent by interaction with obstacles or confining walls. This division of the sources of turbulence is especially important in assessing the possible hazards due to the geometry and flow conditions in specified pieces of equipment. In this chapter, however, attention will only be given to the interaction of the flame propagation and turbulence, regardless of its source.

In order to understand the influence of turbulence on the propagation of dust-air flames it is useful first to give a short description of the phenomenon of turbulence. A descriptive mechanism is then presented of the possible interactions between the turbulence and the dust-air flames. Finally an attempt is made to quantify the effect of turbulence on dust combustion.

5.2 The phenomenon of turbulence

Although it is hard to give a single definition of the phenomenon of turbulence, it is still possible to list the properties a flow must fulfil to be turbulent [Tennekes and Lumley, 1972]:

- The flow has an irregular character.
- The flow is diffusive: the rate of heat, mass and momentum is increased.
- The flow has a high Reynolds number.
- The eddies continuously fluctuate in size and direction: the eddies have a three-dimensional character.
- The eddies in the flow lose their energy via a cascade process: large eddies transfer their kinetic energy to smaller eddies, and the smallest eddies lose their
kinetic energy in viscous dissipation.

- The flow is still a continuum: even the smallest eddies are considerably larger than the molecules in the flow.
- The phenomenon of turbulence is not related to the fluid, but only to the flow of the fluid.

These properties are all necessary in recognising a flow to be turbulent. In practice, however, it is more useful to be able to characterise the turbulent flow quantitatively. For this purpose several parameters are defined. The most important parameters are the Reynolds number, the turbulence intensity and the scale of the turbulent fluctuations.

5.2.1 The Reynolds number (Re)

This dimensionless number is usually applied to characterise a fluid flow. It is defined as the quotient of the transport of momentum by drag and the transport of momentum by viscous dissipation:

\[
Re = \frac{\rho vv}{\eta v/D} = \frac{\rho vD}{\eta}
\]

(1)

Here \( \rho \) is the density of the fluid, \( v \) is the average velocity of the flow, \( D \) is tube diameter and \( \eta \) is the viscosity of the fluid. In general a flow is turbulent at Re numbers greater than 2300.

5.2.2 The turbulence intensity

To define the intensity of turbulence it is necessary to adapt the so-called Reynolds decomposition of the instantaneous velocity of the fluid flow. Then the instantaneous velocity \( v \) is composed of a time averaged velocity, \( V \), and an instantaneous velocity fluctuation, \( v' \).

The time averaged velocity \( V \) is calculated by:

\[
V = \frac{1}{t} \int_0^t v dt
\]

(2)

Then the Reynolds decomposition can be written as:

\[
v = V + v'
\]

(3)
With this Reynolds decomposition it is possible to define the turbulence intensity, \( I \):

\[
I = \frac{\sqrt{\langle v' \rangle^2}}{V}
\]  

(4)

Here \( u' \), the RMS value of \( v' \), is obtained from:

\[
u' = \sqrt{\langle v' \rangle^2} = \left[ \frac{1}{t} \int_0^t (v')^2 \right]^{1/2}
\]  

(5)

This definition of the turbulence intensity is only valid for homogeneous and isotropic turbulent flow. A homogeneous turbulent flow is a flow in which \( V \) is equal in all positions. An isotropic turbulent flow is defined as a flow in which the RMS values of the velocity fluctuations are equal in all directions. This definition of turbulence intensity does not allow zero average velocities and, therefore, is not applicable in closed vessels without mean flow. In this case the intensity is usually defined as the RMS value of \( v \).

5.2.3 Scales in turbulent flow

Due to the cascade process in a turbulent flow, a spectrum of eddy sizes exists in the flow. To characterise the scales in this turbulent flow the whole spectrum should be given. In practice, however, the scale of turbulence is often represented by a single number. For this purpose several different scales of turbulence have been defined. Usually these turbulence scales are length scales, but, since it is more convenient in the study of dust flames, they will be defined here as time scales. The most important time scales in turbulent flow are presented below, together with the equations necessary to calculate the time scale spectrum.

The largest time scale

This scale has the dimension of the equipment itself and it is defined as:

\[
\tau_L = \frac{L}{V}
\]  

(6)
Where $L$ is the characteristic dimension of the equipment and $V$ is the mean velocity of the flow. In the case that the mean velocity is zero this time scale does not exist.

**The Lagrange integral time scale**

The Lagrange integral time scale is defined as:

$$
\tau_{int} = \int_0^\infty R(\tau) \, d\tau
$$

(7)

Here $R(\tau)$ is the correlation coefficient of the instantaneous velocity fluctuations:

$$
R(\tau) = \frac{\overline{v'(t) v'(t+\tau)}}{(\overline{v'^2(t)})}
$$

(8)

This integral time scale can be regarded as the average time for an eddy to lose its identity.

**The Taylor micro time scale**

The Taylor micro time scale is a measure of the smaller eddies in the spectrum. It is also defined by the correlation coefficient of the instantaneous velocity fluctuations (Eq. 8).

The Taylor micro time scale is:

$$
\frac{1}{\tau} = \left[ \frac{dR(\tau)}{d\tau} \right]_{\tau=0}
$$

(9)

**The Kolmogorov time scale**

The Kolmogorov time scale is the smallest time scale in the spectrum. These eddies lose their kinetic energy directly into viscous dissipation. Their time scale is therefore defined by the rate of energy dissipation per unit of mass of fluid ($E$) and the kinematic viscosity of the fluid ($\nu$):

$$
\tau = \sqrt{\frac{\nu}{E}}
$$

(10)
Calabrese and Middleman [1979] show that the rate of energy dissipation per unit mass can be calculated from the integral time scale:

\[ E \sim \frac{5}{8} \frac{(u')^2}{\tau} \]  

(11)

**The turbulent frequency spectrum**

The spectrum of the times scales in turbulent flow is obtained by the Fourier transform of the correlation coefficient, defined by Eq. 8. This spectrum, usually referred to as the power density spectrum, gives the relative intensity of the different eddies as a function of the reciprocal time scale. Since the spectrum contains all eddy sizes, it allows qualitative determination of the important time scales for the propagation of a dust-air flame.

5.3 The interaction mechanism between dust-air flames and turbulence

This description of the interaction mechanism between turbulence and the propagating dust-air flame is based on the comparison of time scales. The reason why time scales are chosen instead of length scales lies in the invariance of the combustion time of the particles. The flame front thickness, which is often used in the literature, varies with flame speed whilst the burning time inside the flame front remains constant.

The description below is based upon a well established theory of gas flame-turbulent flow interactions. There are, however, some important differences between homogeneous gas phase combustion and heterogeneous solid/gas phase combustion processes. In general, the flame front thickness in heterogeneous combustion is much thicker than in homogeneous combustion: several millimetres or more instead of tenths of millimetres. Another difference in comparison with gas flames is the turbulence which is usually already present in the dust clouds. In order to create airborne dust particles a minimal level of turbulence is necessary, while homogeneous gas mixtures can simply be produced by molecular diffusion.

In the following several time scales are used:

- A turbulence time scale, \( t_t \), representing some average time scale in the turbulent flow.
- The burning time of the particle, \( t_b \).
- The relaxation time of the particle to the fluid flow, \( t_r \). This represents the average time a particle needs to adapt to fluctuations in the fluid flow.
Wrinkled flame front region 1

Here the turbulence time scale exceeds the burning time of the particles as well as the relaxation time of the particles:

\[ t_t > t_b \quad \text{and} \quad t_t > t_r \]

The result is a flame front of the original thickness which is more or less wrinkled, dependent on the turbulence intensity. The solid particles in this flame front have the same velocity as the fluid. Therefore, no extra transport of heat or mass increases the flame velocity perpendicular to the flame front. Rather it is the larger flame area that causes an increased rate of mass combustion. The total burning velocity is thus increased proportionally to the increase in flame front area. Figure 5.1 illustrates the wrinkling process.

\[ u'_1 < u'_2 < u'_3 < u'_4 \]

*Figure 5.1* The process of wrinkled flame fronts by turbulent eddies having a size larger than the flame front thickness. The flame front is shown at different levels of turbulence intensity.

A further increase in turbulence intensity stretches the wrinkles until they break up. Then single flame front kernels are produced which have a size larger than the flame front thickness. From Chapter 3 it was learned that ignition kernels larger than the flame front thickness are stable, and thus this high turbulence level increases the burning velocity. In practical situations, however, an increase in turbulence intensity also induces a decrease in the turbulent time scale. A different type of interaction mechanism therefore occurs.
Wrinkled flame front region 2

The flame front is still wrinkled by the turbulent eddies. However, the relaxation time of the particles now exceeds the time scale of the turbulence:

\[ t_i > t_b \quad \text{and} \quad t_i < t_r \]

This affects the exchange of heat and mass at the solid surface of the particles. The movement of the particles relative to the fluid induces some small scale turbulence which increases the mixing of the gases around the particle. Dependent on the combustion mechanism of the particle (Chapter 4), this process can increase the combustion rate and thus shorten the burning time of the particles.

This type of interaction mechanism only occurs, however, for sufficiently large and very fast reacting particles in a turbulent flow field with large eddies. This situation is not very common in dust explosion practice; usually the larger particles react relatively slowly.

Mixed flame front region 1

In this interaction region the conditions are just the opposite of the conditions in the former region (wrinkled flame front region 2):

\[ t_i < t_b \quad \text{and} \quad t_i > t_r \]

The eddies are now too small to wrinkle the flame front, and it remains more or less flat. In this case the transport of mass and heat in front of the flame front is enhanced by the small eddies. Although the eddies cause some mixing inside the flame front, this only slightly affects the burning rate of the particles. The net effect of this interaction mechanism is an increased burning velocity due to the increased transport in front of the flame. Since the burning time of the particles remains more or less constant, the increased burning velocity thickens the flame front.

Mixed flame front region 2

In this region the turbulence time scale is smaller than both other time scales:

\[ t_i < t_b \quad \text{and} \quad t_i < t_r \]

Along with an enhanced transport in front of the flame front by the small eddies, this turbulence also causes a movement of the particles relative to the fluid. This improves the exchange of heat and mass between the particle and the gas phase inside the flame.
front. Thus two effects both cause an increase of the burning velocity, an increase in the transport rate in front of the flame as well as a decrease of the particle burning time. More intense turbulence in the mixed flame front interaction can possibly lead to the break-up of the flame front into pieces of the order of the eddy size. These fragments of the flame front have a dimension smaller than the flame front thickness and are thus incapable of producing ignition kernels. High intensity turbulence can therefore cause quenching of the flame. Figure 5.2 illustrates a mixed flame front. An important deduction of this approach to the different interactions between dust flames and turbulence is the minor role of radiative heat transport. In all the different cases of enhanced transport by turbulence, it is the diffusive or convective transport which is influenced by the turbulence. Since the flame temperature is not affected by the turbulent flow, the rate of radiative transport remains constant!

![Diagram of mixed flame front](image)

**Figure 5.2** The mixed flame front.

5.4 Calculation of the turbulent burning velocity

The basic assumption in this paragraph is that the turbulent burning velocity can be derived from the laminar burning velocity by superimposing the influence of the turbulence on the laminar burning velocity. Methods to calculate the laminar burning velocity of dust-air flames were extensively treated in Chapter 4. In order to account for
the influence of turbulence, the different types of interaction must be modelled. 
The distinction of different interaction mechanisms is based upon the time scales of the 
processes involved: the turbulent time scale, the chemical reaction time of the particles 
and the relaxation time of the particles. 
Dependent on the type of interaction (see Figure 5.2), one or more of the following 
adjustments can be made to the laminar burning velocity. 
The different types of turbulent interaction can be modelled as follows: 

\[ t_t > t_b \]

\[ \frac{S_{\text{turbulent}}}{S_{\text{laminar}}} = \frac{A_{\text{turbulent}}}{A_{\text{laminar}}} \]  

(12)

The turbulent eddies are modelled as increasing the flame front area by producing cone-
shaped lumps in the flame front. Following the classic analysis of Shchelkin [Lewis and 
Von Elbe, 1985], it is possible to quantify their effect on the burning velocity. The ratio 
of the laminar flame front area and the turbulent flame front area is assumed to be 
equal to the ratio of the lateral area of the cone and its base area. 
The cone base is assumed to be dependent on the average eddy size (l) and the height 
of the cone (h) dependent on the average velocity fluctuations (u') in the flow and an 
interaction time scale (e.g. 1/S_{\text{laminar}}).

Eq. 12 then becomes:

\[ \frac{S_{\text{turb}}}{S_{\text{laminar}}} = \frac{\text{lateral cone area}}{\text{cone base area}} = \frac{\pi r \sqrt{r^2 + h^2}}{\pi r^2} \]  

(13)

Here r is the radius of the base of the cone. With r = 0.5 l and h = u' l / S_{\text{laminar}}.

Eq. 13 becomes:

\[ \frac{S_{\text{turb}}}{S_{\text{laminar}}} = \sqrt{1 + \left( \frac{2 u'}{S_{\text{laminar}}} \right)^2} \]  

(14)

In the literature on wrinkled gas flames [Gülder, 1990] this theory fits the experimental 
results quite well. For example Liu and Lenze [1988] found their experimental results for 
hydrogen-methane-air flames to fit the equation:
\[
\frac{S_{\text{turb}}}{S_{\text{laminar}}} = 1 + 5.3 \frac{u'}{\sqrt{S_{\text{laminar}}}}
\]  
(15)

\[t_t < t_b\]

The small scale turbulence only slightly contributes to the wrinkling of the flame front; the disturbances are very small and increase the flame front area only marginally. The most important effect of the small scale turbulent eddies is to increase the diffusive transport of heat in front of the flame. This turbulent diffusivity is defined as the product of a velocity and a length scale of the turbulence, analogous to molecular diffusivity, which is the product of the molecular velocity and the mean free path. The total rate of diffusive transport of heat in front of the flame can then be written as the sum of the molecular diffusivity and the turbulent diffusivity:

\[D = D_m + D_t\]  
(16)

The turbulence scales are the integral time scale and the RMS of the turbulent velocity fluctuations. The turbulent length scale is taken to be the product of these two. From equation 16 the turbulent thermal conductivity can then be written as:

\[\lambda = \lambda_m + \rho C_p D_t = \lambda_m + \rho C_p u'^2 \tau\]  
(17)

\[t_t < t_r\]

This type of interaction model accounts for the difference in velocity of the particles and the flow; in this case the particles cannot follow the turbulent fluctuations. This influences the rate of transport of mass through the film layer around the particle. If, however, the combustion of the particle is limited by diffusion through the ash layer or by the chemical reaction rate, the eddies of this size do not influence the combustion rate.

It is possible to calculate the influence of the turbulence on the transport of mass through the film layer around the particle using the Ranz-Marshall equation [Levenspiel, 1972]:

\[\frac{k_s d_p}{D} = 2 + 0.6 (Sc)^{\frac{1}{3}} (Re)^{\frac{1}{2}}\]

\[= 2 + 0.6 \left(\frac{\mu}{\rho D}\right)^{\frac{1}{3}} \left(\frac{d_p u'}{\mu}\right)^{\frac{1}{2}}\]  
(18)
Using this equation a turbulent film diffusion coefficient can be calculated. The Reynolds number in this equation is based upon the particle, whose velocity is taken to be equal to the RMS of the velocity fluctuations. It is assumed that the particle relaxation time exceeds the turbulent time scale to such an extent that the velocity difference approaches the turbulent velocity fluctuations $u'$. For low velocity differences, that is, small turbulence intensities, this equation shows that the $k_\text{g}$ value approaches a constant value, the laminar condition.

5.5 Experimental

The objective of the experiments in this chapter was to determine the turbulence characteristics of the flow in the different pieces of test equipment used in this thesis, to measure the relationship between the burning velocity of dust clouds and the level of turbulence and thus to obtain more information about the interaction mechanisms between dust flames and turbulent flow.

5.5.1 The turbulent characteristics of the flow in various pieces of test equipment

The burner

This apparatus was described in Chapter 4. It was shown there that it has a negligible level of turbulence under normal operating conditions. It is possible to increase the level of turbulence in the powder dispersion leaving the burner by inserting grids. However, the problems of stabilising flames on this burner were the main reason to use closed vessels to measure the turbulent burning velocity of dust clouds. A grid also introduces an extra possibility for the accumulation of dust inside the burner.

The 20 litre sphere and the 1 m³ vessel

Pu et al. [1990] carried out extensive research on the turbulent velocity fluctuations in a 20 litre sphere. There was therefore no need to duplicate these experiments in this small vessel. However, additional measurements were made of the integral time scales in both explosion vessels and the velocity fluctuations in the large vessel at the standardised delay time of 600 ms. Also, power density spectra were determined in both vessels for several delay times. The measurements were performed with a hot wire anemometer. The necessary data were sampled at a rate of 50 kHz. In order to calculate the different turbulence parameters, the decaying turbulent flow was averaged over a period of 20 ms (1024 data points).

By the use of Eq. 11 the Kolmogorov time scales in both vessels were calculated from the integral time scales and the RMS values of the velocity fluctuations.
Figure 5.3  The RMS value of the turbulent velocity fluctuations in the 20 litre sphere versus delay time, after Pu et al. [1990]. The dashed line represents the RMS value in the 1 m$^3$ vessel at a 600 ms delay.

Figure 5.4  The integral time scale of the turbulent flow in the 20 litre sphere versus delay time as measured by hot wire anemometry. The dashed line represents the values in the 1 m$^3$ vessel.
In the following figures are shown the results of determinations of the different parameters. In the case of the 1 m³ vessel only the data for a delay time of 600 ms after the beginning of the dispersion process are given. This is the standard vessel and delay time, as defined by the ISO-norm [1985]. The data for the 20 litre sphere are shown for a range of delay times for two reasons. In the first place there are some doubts about the generally accepted delay time of 60 ms [Van der Wel et al., 1992], which could be too short to create turbulent conditions equal to the larger standard vessel. Secondly the small vessel was used here to determine the role of turbulence in the propagation of a dust explosion and the explosions had therefore to be carried out at a range of conditions.

Figures 5.3, 5.4 and 5.5 clearly show that the turbulent conditions in the 20 litre sphere at a delay time of 60 ms are considerably more intense than the conditions in the large vessel at the standard time. A delay time of about 170 ms in the 20 litre sphere results in much more comparable conditions. This fact is verified by the power density spectra obtained at the several delay times in both vessels and shown in Figure 5.6.

![Graph](image)

**Figure 5.5**  
The calculated Kolmogorov time scale of the turbulent flow in the 20 litre sphere versus delay time. The dashed line represents the value in the 1 m³ vessel at a 600 ms delay.
Figure 5.6(a)  Power density spectrum measured in the 1 m$^3$ vessel at a delay time of 600 ms.

Figure 5.6(b)  Power density spectrum measured in the 20 litre sphere at a delay time of 60 ms.
5.5.2 The relationship between burning velocity of dust clouds and the level of turbulence

The relationship between the burning velocity of dust clouds and the level of turbulence was determined by use of the 20 litre sphere. The burning velocity of the dust cloud was calculated from the maximum rate of pressure rise, the initial pressure and the maximum explosion pressure. The calculation procedure was treated in paragraph 4.3.1. The level of turbulence appropriate to that burning velocity was determined by the delay time between the beginning of the powder dispersion and the moment the maximum rate of pressure rise is reached. The RMS value of the velocity fluctuations $u'$ serves as a characteristic parameter of the turbulent flow. The integral time scale varied only slightly during the decay of the turbulent flow and therefore merely dictates the type of interaction mechanism rather than the rate of interaction.

It should be stressed that the burning velocity calculated from the explosion results in the 20 litre sphere is only valid for the conditions in the vessel during the explosion. On average the pressure existing at the moment the maximum rate of pressure rise was reached was about 6 bar, and the temperature in the unburned mixture was about 450 °C. Although the burning velocity at standard conditions is certainly different from the experimental values, it is assumed later in Chapter 6 that the variation of the burning velocity during adiabatic compression is relatively small.

In the following figures the relationship between the burning velocity and the RMS value of the turbulent velocity fluctuations is given for several materials.
Figure 5.7  
*The burning velocity of stoichiometric methane-air mixtures versus the RMS of the turbulent velocity fluctuations, measured in a 20 litre sphere. Two types of igniter were used.*

Figure 5.8  
*The burning velocity of lycopodium powder (500 g/m³) versus the RMS value of the turbulent velocity fluctuations, measured in the 20 litre sphere. (10 kJ igniter)*
Figure 5.9  
The burning velocity of potato starch (1000 g/m$^3$) versus the RMS value of the turbulent velocity fluctuations, measured in the 20 litre sphere. (10 kJ igniter)

Figure 5.10  
The burning velocity of activated carbon (500 g/m$^3$) versus the RMS value of the turbulent velocity fluctuations, measured in the 20 litre sphere. (10 kJ igniter)
As a first approximation it can be concluded from all these results that, in the range of \( u' = 0.5 \) to \( u' = 2.0 \, \text{m/s} \), there is a linear relationship between the burning velocity of dust clouds and the \( u' \) value of the flow. Lower values of \( u' \) are not realistic because of the onset of sedimentation in the dust cloud, and higher values than \( u' = 2 \, \text{m/s} \) are impossible to reach in the 20 litre sphere under normal operating conditions. Possibly increased injection pressures or the addition of a fan in the vessel could enhance the level of turbulence.

5.5.3 Experimental studies of the interaction mechanism between turbulent flow and dust-air flames

As seen in the former paragraphs, the mechanism of interaction between the burning dust and the turbulent flow is determined by the relative magnitude of the various time scales involved in the interaction process. For the case of the experiments performed in the 20 litre sphere and described in the last paragraph, the time scales are summarized in table 5.1.

The relaxation time of the particles was calculated using the equation given by Fuchs (1989):

\[
\tau_r = \frac{d_p^2 \rho_s}{18 \eta}
\]  

(19)

This equation is only applicable for low Reynolds number, based on the particle diameter. However, since only the order of magnitude of the relaxation time is of interest, it approaches the real situation sufficiently.

Based upon the information shown in Table 5.1 the different interaction mechanisms can be identified. Dust combustion interacts with the turbulent flow in the 20 litre sphere according the mixed flame theory. This means that the heat transport is enhanced by the turbulent diffusion. Since the relaxation time of the particles is of the same order of magnitude as the turbulence time scales, it is obvious that the transport rates around the particles are slightly increased, which shortens the combustion time of the particles. From theory, however, it can be learnt that the absolute variation of the burning time will be small (paragraph 5.4).

In the case of gas combustion the reaction time is usually smaller than all the turbulent time scales involved in these experiments. The wrinkled flame theory is therefore applicable for gas combustion under the conditions existing in the 20 litre sphere.

The experimentally obtained linear relationship seems to match Eq. 15 derived in paragraph 5.4, as well as the mixed flame theory. Eq. 18 in combination with the thermal theory of Chapter 4 (Eq. 6), and the assumption of negligible radiative transport yields:

\[
S_{turb} - S_{laminar} = \sqrt{1 + \frac{\rho C_p \tau_{integral} u^2}{\lambda_m}}
\]  

(20)
Table 5.1  Time scales involved in the dust combustion in a 20 litre explosion testing sphere. The injection pressure was 2.1 MPa. The vessel was equipped with a dispersion ring.

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integral time scale</td>
<td>3 ms</td>
</tr>
<tr>
<td>Kolmogorov time scale</td>
<td></td>
</tr>
<tr>
<td>- delay time = 50 ms</td>
<td>0.095 ms</td>
</tr>
<tr>
<td>- delay time = 300 ms</td>
<td>0.76 ms</td>
</tr>
<tr>
<td>Burning time</td>
<td></td>
</tr>
<tr>
<td>- act. carbon (d=19.7 μm)</td>
<td>1 - 10 ms</td>
</tr>
<tr>
<td>- potato starch (d=16.0 μm)</td>
<td>10 - 100 ms</td>
</tr>
<tr>
<td>- lycopodium (d=32.8 μm)</td>
<td></td>
</tr>
<tr>
<td>- aluminium (d=20.0 μm)</td>
<td></td>
</tr>
<tr>
<td>- methane (9.5 vol%)</td>
<td>0.1 - 1 ms</td>
</tr>
<tr>
<td>Relaxation time of the particles</td>
<td></td>
</tr>
<tr>
<td>- act. carbon (d=19.7 μm)</td>
<td>5 ms</td>
</tr>
<tr>
<td>- potato starch (d=16.0 μm)</td>
<td>13 ms</td>
</tr>
<tr>
<td>- lycopodium (d=32.8 μm)</td>
<td>8 ms</td>
</tr>
<tr>
<td>- aluminium (d=20.0 μm)</td>
<td>0.9 ms</td>
</tr>
</tbody>
</table>

Thus, as a first approximation both interaction mechanisms, wrinkled flame fronts and mixed flame fronts, predict a linear relationship between the burning velocity and the level of turbulence. The distinction between the two models must be based upon the value of the slope of the equation. Substitution of the parameters from Table 5.2 in Eq. 20 result in an estimation of the slope of the equation for mixed flames, dependent on the temperature of the point of ignition in the flame. In Chapter 4 it was shown that the heat conductivity of the air at that point determines the burning velocity. It was also stated that the ignition temperature is close to the flame temperature.

Table 5.2

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>1.2 kg/m³</td>
</tr>
<tr>
<td>$C_p$</td>
<td>1000 J/kg/K</td>
</tr>
<tr>
<td>$\lambda_m$</td>
<td>0.192 W m⁻¹ K⁻¹ (T=3000 K)</td>
</tr>
<tr>
<td></td>
<td>0.128 W m⁻¹ K⁻¹ (T=2000 K)</td>
</tr>
<tr>
<td></td>
<td>0.064 W m⁻¹ K⁻¹ (T=1000 K)</td>
</tr>
<tr>
<td>$\tau_{\text{integral}}$</td>
<td>0.0030 s</td>
</tr>
</tbody>
</table>

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In the case of wrinkled flames it is not possible to give an explicit relationship. There is still the laminar burning velocity which depends upon the fuel composition. Figures 5.11 and 5.12 show values calculated using Eq. 20. Here, normalised values of the burning velocity are plotted against the RMS value of the velocity fluctuations for the different dusts and for several gases. The equations for gases are obtained both from literature [Liu and Lenze, 1988]. It is shown that the data for the dusts are comparable to each other, and they are also in good agreement with Eq. 20; that is, as predicted by the mixed flame theory. The gas equations deviate completely from the dust data. These observations indicate that also in the case of gas combustion the dependence of the burning velocity on turbulence is determined by the laminar burning velocity. In the case of dust combustion, there is a relationship between the burning velocity and the level of turbulence which varies only slightly with the flame temperature. The latter makes it surprisingly easy to predict the relationship for other dusts; a single point on the line is enough to construct it completely.

In extreme cases, however, there is a possibility that the dust particles react so fast that they start to behave like gases. Then the relationship between the normalised burning
velocity and the turbulence intensity also becomes dependent on the laminar burning velocity.

![Graph showing normalised burning velocities of several dusts. The theoretical equations were obtained from Eq. 20 for different temperatures resulting in different values of the thermal conductivity at the ignition point in the flame.]

Another factor is the effect of radiation, which might become important at high flame temperatures. Because the turbulence does not affect transport by radiation, the dependence on the level of turbulence will not be affected.

5.6 Conclusions

The main conclusion of this chapter is that dust flames usually interact with turbulent eddies according to a mixed flame theory. Because the time scale of most burning particles exceeds the turbulent time scales in explosion vessels, like the 20 litre sphere,
the burning velocity is increased by enhancement of the turbulent diffusivity. In the case of burning gases in the 20 litre sphere, the reaction time is usually smaller than the turbulence scales, and the flame front interacts according to the wrinkled flame theory. These conclusions are supported by measurements of the dependence of the burning velocity on the level of turbulence. The dusts behave exactly according to the mixed flame theory whilst gases also show a dependence on the laminar burning velocity.

Another important result of this chapter is the observation that in order to obtain equivalent turbulence conditions in the 20 litre sphere and in the standardised 1 m³ vessel, it is necessary to increase the ignition delay time in the smaller vessel from 60 ms to 170 ms. The reason why most experimental results seem to support the empirically determined 60 ms is discussed in Chapter 6.

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Chapter 6

The relationship between the burning velocity of dust clouds and the pressure rise in closed spherical vessels

6.1 Introduction

In this chapter the relationship between the burning velocity of a dust cloud and the consequent pressure rise inside a closed spherical vessel will be discussed. The complexity of this relationship is explained by the following description of the processes which take place during an explosion in a closed container.

After a local ignition of the mixture inside the vessel a flame front is developed, travelling from the ignition point towards the walls of the enclosed space. As the temperature inside the flame front is increased by the combustion reaction the gaseous species expand. This expansion causes the flame front velocity to increase. The pressure inside the vessel also rises by the compression of the gases. Due to the compression of the gases inside the vessel the temperature on both sides of the flame front increases. Both the temperature and pressure rise in front of the flame affect the burning velocity of the dust cloud by changing the transport rates and by influencing the character of the turbulence. The increase in temperature of the burnt material behind the flame front can initiate secondary chemical reactions.

Another complexity is the thickness of the reaction zone. An infinitely thin flame front never occurs in exploding dust-air mixtures. If the flame front has a certain thickness this influences the rise of pressure both at the beginning of the explosion and at the end, when the flame front reaches the wall. The maximum rate of pressure rise is then not found at the end of the explosion, but when the front of the flame reaches the walls. An additional complication is the variation of the thickness of the flame with increasing temperature and pressure, and thus a variation of the flame thickness during the development of the explosion in the vessel. Finally, the approach of the flame front to the wall induces an extra loss of heat to the wall. With thick flames which already reach the wall while the rear part of the flame is still burning, this phenomenon causes the pressure to start to decrease before the explosion is completed.

To model the pressure rise in a closed vessel it is convenient to assume ignition at the centre of a spherical vessel. Vessels of different shape or eccentric ignitions induce a flow of material along the walls of the vessel. This flow creates extra turbulence which can only be modelled by extensive numerical calculations, which fall outside the scope of this thesis.
6.2 Mathematical models

Two different models will be treated in this paragraph. First a relatively simple model, obtained from the literature, is derived. This model yields a single equation for the relationship between the burning velocity and the rate of pressure rise for the case of an infinitely thin flame front. Next a more sophisticated model is presented which accounts for the thickness of the flame. It divides the contents of the vessel into three zones and thus yields a mathematical relationship in three parts dependent on the radial position of the flame in the vessel.

The two models are compared, and the results are used to assess the usefulness of the 'cubic law' described in Chapter 2.

6.2.1 The simple model

Assuming a spherical geometry, an infinitely thin flame front and a centrally located ignition source, this model describes the pressure rise due to the development of a smooth flame front propagating from the centre of the vessel towards the wall.

Lewis and Von Elbe showed that the mass fraction of unburnt material ($m_u/m_0$) during the explosion is a function of the dynamic pressure ($P$).

$$\frac{m_u}{m_0} = \frac{P_e - P}{P_e - P_0}$$  \hspace{1cm} (1)

The rate of pressure rise is found by differentiating this equation:

$$\frac{dP}{dt} = -\frac{P_e - P_0}{m_0} \frac{dm_u}{dt}$$  \hspace{1cm} (2)

Here $P_e$ is the final pressure and $P_0$ the initial pressure in the explosion vessel.

The unburnt mass consumption rate ($dm_u/dt$) follows from the definition of the burning velocity $S_u$ [Bradley and Mitcheson, 1976]:

$$\frac{dm_u}{dt} = -4\pi r_f^2 \rho_u S_u$$  \hspace{1cm} (3)

$r_f$ is the time dependent radius of the flame front and $\rho_u$ is the density of the unburnt mixture, which gradually increases due to the pressure rise.

The density of the unburnt mixture can be calculated by assuming adiabatic compression of the gaseous components of the mixture:

$T$ is the temperature of the mixture and $\gamma$ the ratio of the specific heats of the gas, both parameters applying to the unburnt mixture. The density then becomes:
\[
\frac{T_u}{T_0} = \left( \frac{P}{P_0} \right) \left( \frac{\gamma_s}{\gamma_s - 1} \right)
\]

\[
\rho_u = \frac{m_0}{V_0} \frac{P}{P_0} \frac{T}{T_0} = m_0 \left( \frac{P}{P_0} \right) \left( \frac{\gamma_s}{\gamma_s - 1} \right)
\]

\(V_0\) is the volume of the vessel.
The radius \(r_f\) of the flame front is calculated from the volume of the unburnt material, assuming ideal behaviour of the unburnt gas phase.

\[
r_f = \left( \frac{V_0 - \frac{m_0 R T_u}{P}}{\frac{4}{3} \pi} \right)^{\frac{1}{3}}
\]

Here \(R\) is the universal gas constant.
Combining Eq. 2 and Eq. 3 together with Eq. 1, 5 and 6, a relationship is found between the rate of pressure rise at a certain pressure and the burning velocity:

\[
\frac{dP}{dt} = \frac{3(P_e - P_0)}{R_{\text{vessel}}} \left( \frac{P}{P_0} \right)^{\frac{1}{\gamma_s}} S_u \left( 1 - \left( \frac{P_0}{P} \right)^{\frac{1}{\gamma_s}} \left( \frac{P_e - P}{P_e - P_0} \right) \right)^{\frac{2}{3}}
\]

The important restriction of this equation is the assumption of an infinitely thin flame front. The use of Eq. 3 concentrates the combustion reaction into an infinitely thin flame front located at position \(r_f\).
Knowledge of the final explosion pressure, from experiments or thermodynamic calculations, and of the burning velocity allow prediction of the pressure-time curve of the explosion in the vessel. Since the burning velocity depends on the pressure and temperature of the mixture to be burnt, it would improve the reliability of the calculations if these relationships were available. In practice, however, it is difficult to obtain a single value of the burning velocity of dust clouds at standard conditions. Unfortunately, the only method of any practical use to measure the turbulent burning velocities of dust clouds is the closed explosion vessel method discussed here. However, this method uses the same equation to calculate the burning velocity from the rate of pressure rise!
6.2.2 The three zone model

The model presented in this paragraph extends this simple model. It assumes a burnt and an unburnt zone and a zone which is still burning. In this zone the material can be regarded as partially reacted. Figure 6.1 shows the three zones at a certain radial position of the flame in the vessel. In practice, of course, the fraction of burnt material in the reacting zone as a function of radial position can have all kind of shapes.

Figure 6.1 Profile of the fraction of reacted material during an explosion in a closed vessel, assuming a flame front with a finite thickness.

Figure 6.2 illustrates some possible compositions of the reaction zone. The flame front can be wrinkled by large scale turbulence or by instabilities caused by the explosion (a), the flame front can also show a mixed character by intense turbulence (b) or the flame front is broadened by slowly reacting particles (c).

This model also assumes the fraction of unburnt material to be related to the actual pressure in the vessel according to Eqs. 1 and 2.

The mass consumption rate is now no longer located in an infinitely thin reaction zone, but it is distributed over a distinct range of radial positions. It is assumed here that the unburnt mass fraction increases linearly with increasing radial position between the flame front boundaries, _rb_ and _ru_.

The mass consumption rate then becomes:

$$\frac{dm_u}{dt} = \int_{r_b}^{r_u} 4\pi r^2 \frac{S_u \rho_u}{\delta_f} dr$$

$$= \frac{4}{3} \pi (r_b^3 - r_u^3) \frac{S_u \rho_u}{\delta_f}$$

(8)
Here $\delta_f$ is the flame front thickness.

The boundaries $r_b$ and $r_u$ of the reacting zone can be calculated from Eq. 1 and with knowledge of the thickness of the reacting zone, $\delta_f$. Dependent on the position of the flame front, different equations are necessary to determine their value:

---

**Figure 6.2**

- **a.** A flame thickened front by turbulent wrinkles or instability of the flame front induced by the explosion.
- **b.** A mixed flame front with high intensity turbulence.
- **c.** A thick flame front due to slowly reacting particles.

---

**Phase 1**

In this early phase of the explosion the flame front is just developing from the ignition source. The rear end of the flame is still located in the centre of the vessel.

Thus:

$r_u \leq \delta_f$

and $r_b = 0$
The radial profile of the unburnt material in the early phase of an explosion.

The boundary, \( r_u \), can then be calculated from the total volume, \( V_b \), of the burnt material:

\[
V_b = V_0 - V_u \\
= \int_0^{r_u} 4\pi r^2 \frac{r_u - r}{\delta_f} \, dr
\]

The solution of Eq. 9 is:

\[
r_u = \left( \frac{3\delta_f}{\pi} (V_0 - V_u) \right)^{\frac{1}{4}}
\]

\( V_u \) is calculated from:

\[
V_u = \frac{m_u R T_u}{P}
\]

Phase 2

The flame front is now fully developed and propagates towards the wall.

\[
\delta_f < r_u \leq R_{\text{vessel}}
\]

and \( r_b = r_u - \delta_f \)
The volume of the unburnt mass fraction, calculated with Eq. 11, can now be used to determine the position of the boundaries.

$$V_u = \frac{4}{3} \pi (R_{\text{vessel}}^3 - r_u^3) + \int_{r_b}^{r_u} 4\pi r^2 \frac{r + r_u - \delta_f}{\delta_f} dr$$

$$= \frac{4\pi}{3} R_{\text{vessel}}^3 \left( 1 - \frac{r_u^4}{3\delta_f^4} \right) - \frac{\pi}{3\delta_f^4} (r_u^4 - (r_u - \delta_f)^4) \quad (12)$$

**Phase 3**

In the final phase of the explosion the flame front has reached the wall of the vessel whilst the rear end of the flame is still moving towards the wall.

$$r_b > R_{\text{vessel}} - \delta_f$$
and
$$r_u = R_{\text{vessel}}$$

In this last phase of the explosion the volume of the unburnt material is given by:

$$V_u = \int_{r_b}^{R_{\text{vessel}}} 4\pi r^2 \frac{r - r_b}{\delta_f} dr$$

$$= \frac{\pi}{\delta_f} R^4 + \frac{\pi}{3\delta_f^4} (r_b^4 - 4r_b^2 R_{\text{vessel}}^2) \quad (13)$$
The numerical calculation procedure of this model is as follows: From an initial value of the parameters $P$, $S_u$ and $\delta_p$, a value of $m_u$ is calculated (Eq. 1). Then the radial positions of the rear and the front of the flame are calculated by use of Eqs. 10, 12 or 13. The equations are solved numerically. The local rate of pressure rise is obtained by using Eq. 8 and a new value of $P$ can then be calculated. This computation scheme is repeated until the rear of the flame has reached the wall, when $P$ will have the value of $P_c$. The time interval must be small enough to ensure a stable calculation. During the repeated calculations the values of $S_u$ and $\delta_p$ can be adapted to the actual pressure and temperature in the unburnt portion of the fuel-air mixture.

![Diagram](image)

**Figure 6.5** Radial profile of the mass fraction of unburnt material at the end of an explosion.

6.2.3 The dependence of the burning velocity on pressure and temperature

A continuous increase of pressure and temperature of the unburnt mixture in front of the flame is inherent to the development of an explosion in a closed vessel. These changing circumstances affect the course of the explosion in several ways. The increased temperature and pressure can directly influence the propagation of the explosion by changing the rate of heat and mass transfer as well as the chemical reaction rate. Secondly, the variation in density and temperature of the unburnt mixture alters the turbulent character of the flow present in the closed vessel. Finally, the flame thickness are pressure and temperature dependent. Since it appears to be very difficult to propose a single relationship between the temperature and pressure and the propagation velocity of dust cloud flames in closed vessels, a more qualitative description will be given. This description also explains the problems in defining quantitative equations.
The effect of pressure and temperature on dust flame propagation

In order to understand the complexity of the interaction between pressure and temperature on the one hand and the propagation velocity on the other, it is useful the study the models described in Chapter 4. In the simple model the following parameters are to a certain extent influenced by pressure and temperature: the mixture density \( \rho \), the specific heat of the mixture \( C_p \), the ignition temperature in the flame front \( T_i \), the thermal conductivity of the gas phase \( \lambda \), the flame temperature \( T_f \), the reaction time of the particles and the emission factor \( \alpha \). All these parameters are mentioned in the simple propagation model in Chapter 4.

In the particle-to-particle model even more parameters are pressure and temperature dependent: the inter-particle distance, \( L \) and the heat transfer coefficient, \( h \). The relative importance of the different parameters varies greatly with the circumstances, and it is impossible to give a general purpose relationship. However, it is clear from the discussion in Chapter 4 that heat conduction plays a dominant role in the propagation of flames in dust clouds. As a first approximation, therefore, the dependence of this parameter on pressure and temperature might be modelled. In Chapter 4 the following equation can be found:

\[
\lambda = c \frac{T}{T_0} \quad c = 0.019 \text{ W m}^{-1} \text{K}^{-1}
\]  

(14)

Because \( \lambda \) is more or less independent of pressure, Eq. 14 can be combined with Eq. 4:

\[
\lambda = c \left( \frac{P}{P_0} \right)^{\gamma_s^{-1} \gamma_s^{-1}}
\]  

(15)

In the equation for the simple propagation model, the thermal conductivity is located under the root sign. Thus as a first approximation the burning velocity dependence on pressure becomes:

\[
S_u = S_{u,0} \left( \frac{P}{P_0} \right)^{\gamma_s^{-1} \gamma_s^{-1}}
\]  

(16)

The effect of pressure and temperature on the character of the turbulence

In Chapter 5 turbulent flow was described by two parameters, scale and intensity. The intensity was defined as the root mean square of the turbulent velocity fluctuations, which represents an average rotational velocity of the eddies. Due to compression of the turbulent medium, the density increases and the size of the eddies decreases. Application
of classical mechanics shows the resulting rotational velocity to be independent of pressure and thus also independent of temperature. For constant turbulence intensity and adiabatic compression, the pressure relationship for the integral time scale of the compressed eddies becomes:

\[
t = t_0 \left( \frac{P_i}{P_0} \frac{T_i}{T_0} \right)^{\frac{1}{3}} = t_0 \left( \frac{P}{P_0} \right)^{\frac{-1}{3T_i}}
\]

(17)

With Eq. 11 of Chapter 5 the rate of energy dissipation can be estimated using the following equation:

\[
E = E_0 \left( \frac{P}{P_0} \right)^{\frac{1}{3T_i}}
\]

(18)

From the literature [Perry, 1973] and the assumption of adiabatic compression the pressure dependence of the kinematic viscosity can be estimated using:

\[
v = v_0 \left( \frac{P}{P_0} \right)^{\frac{\gamma_n - 1}{2\gamma_n}}
\]

(19)

Combination of Eq. 18 and Eq. 19 with Eq. 10 of Chapter 5 yields an approximate pressure dependence of the Kolmogorov time scale, \( \tau_k \), for the case of adiabatic compression:

\[
\tau_k = \tau_{k,0} \left( \frac{P}{P_0} \right)^{\frac{1}{4} \frac{5\gamma_n}{12}}
\]

(20)

The effect of pressure and temperature on the flame front thickness

The flame front thickness is determined either by the reaction time of the particles or by the scale of the turbulent eddies, dependent upon their relative dimensions. The effect of pressure and temperature on the turbulence scales is already explained in section 6.2.2. The variation of the reaction time with pressure and temperature is dictated by the limiting mechanism of the reaction. For the different limitations explained in Chapter 4 the following analysis can be made:
In the case of a gas phase reaction limitation, the dependence of the reaction time on pressure and temperature is usually positive. The well-known Arrhenius equation describes the dependence of the reaction rate on temperature.

When the mass transfer is controlled by the particle surface area the reaction time of the particles is inversely proportional to a mass diffusion coefficient and to the mass concentration. The mass concentration is related to the pressure and temperature by:

\[ C_s = C_{s0} \frac{P}{P_0} \frac{T_0}{T} = C_s^0 \left( \frac{P}{P_0} \right)^{\frac{1}{\gamma_k}} \]  \hspace{1cm} (21)

The diffusion coefficient is approximately independent of pressure and depends only on temperature. In the case of adiabatic compression this becomes:

\[ D = D_0 \left( \frac{T}{T_0} \right)^{1.5} \frac{P_0}{P} = D_0 \left( \frac{P}{P_0} \right)^{\frac{\gamma_k - 3}{2\gamma_k}} \]  \hspace{1cm} (22)

In the case of a chemical reaction rate limitation at the particle surface, the reaction time is inversely proportional to the solid concentration and to the reaction rate constant. Both parameters have been discussed above.

Although it is possible to give more insight into the role of pressure and temperature in closed vessel explosions, it appears to be impossible to produce an universally applicable relationship. From the previous discussion it might be concluded that although the flame velocity, flame front thickness as well as the turbulence characteristics all depend on pressure and temperature, their absolute variation during an explosion is not significant. Using a numerical value of 1.395 for the parameter \( \gamma_w \), typical orders of magnitude of the variation of the various parameters during an explosion can be calculated. The results are given in Table 6.1.

Table 6.1, which shows the dependence of the different parameters, exhibits only small powers of the pressure dependence. Thus the assumptions of constant burning velocity, constant flame front thickness and constant turbulence parameters during an explosion do not seem to introduce large errors into the calculations.

6.3 Calculation examples

To illustrate the two models some calculations are made. As an example a hypothetical explosion is simulated. Constant burning velocities of .16, .32 and .64 m/s are assumed. Both a 20 litre sphere and a 1 m\(^3\) vessel are simulated. The flame front thickness is varied between 0 and 10 cm and is presumed to be independent of the pressure and
temperature. Despite these simplifications the results of these calculations can be considered to provide more information about the role of the vessel volume, the burning velocity and the flame front thickness during the pressure build-up in closed vessel explosions.

In Figure 6.6 explosions in the 20 litre sphere are simulated with varying burning velocity. A flame front thickness of 1 cm has been assumed. From this figure it becomes clear that a variation in the burning velocity has several effects. First, the maximum rate of pressure rise decreases with a decrease of the burning velocity. This maximum is also reached at lower pressures, which causes a further decrease in the rate of pressure rise. Furthermore a decrease of the burning velocity apparently introduces a delay time before the explosion starts. This fact stresses the influence of the burning velocity on the initial stage of the explosion.

![Pressure-time traces](image)

**Figure 6.6** Calculated pressure-time traces for different burning velocities and a flame front thickness of 1 cm in the 20 litre sphere. The three zone model has been used.
Table 6.1  Order of magnitude of the parameters during an explosion. Adiabatic compression of the unburnt gas is assumed.

<table>
<thead>
<tr>
<th>assumptions</th>
<th>( T = T_0 \left( \frac{P}{P_0} \right)^{\frac{\gamma_u - 1}{\gamma_u}} ) (23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>burning velocity</td>
<td>( \gamma_u = 1.395 ) (24)</td>
</tr>
<tr>
<td>particle combustion time</td>
<td>( S_u = S_{u,0} \left( \frac{P}{P_0} \right)^{0.14} ) (25)</td>
</tr>
<tr>
<td>- limited by chemical reaction in the gas phase</td>
<td>strongly material dependent</td>
</tr>
<tr>
<td>- limited by diffusion near particle</td>
<td></td>
</tr>
<tr>
<td>- limited by chemical reaction at particle surface limits</td>
<td>strongly material dependent</td>
</tr>
<tr>
<td>turbulence intensity</td>
<td>( u' = \text{constant} )</td>
</tr>
<tr>
<td>integral time scale</td>
<td>( T_{\text{integral}} = \left( \frac{P}{P_0} \right)^{-0.24} ) (27)</td>
</tr>
<tr>
<td>Kolomogorov time scale</td>
<td>( \tau_k = \left( \frac{P}{P_0} \right)^{-0.33} ) (28)</td>
</tr>
</tbody>
</table>

Figure 6.7 shows the development of the pressure in a 20 litre sphere at several flame front thicknesses and at a constant burning velocity of 32 cm/s. The calculations using zero flame front thickness were calculated using the simple model. The others were obtained with the three zone model. In Figure 6.8 the same calculations are shown for a 1 m³ vessel.

An increase in the flame front thickness has a similar effect on the pressure rise as that
of a decrease in the burning velocity. They both cause a delay of the beginning of the explosion, a decrease in the rate of pressure rise, and a lower value of the maximum pressure. Even thin flame fronts ($\delta_f = 1$ mm) tend to delay the explosion, although the pressure plot itself is identical to the results with zero flame front thickness. This behaviour again emphasises the importance of the initial phase on the rest of the explosion.

The effect of the vessel volume is most pronounced with thicker flames. In the case of the 20 litre sphere the pressure-time plot for a flame thickness of 1 cm starts to deviate from that for a 1 mm thick flame at about 6 bar. The same plot for a 1 m$^3$ vessel is identical with the thinner flame over the whole pressure range. With a 10 cm flame front this effect is even more striking. In this case the resulting plot for the smaller vessel completely deviates from the thinner flames whilst the results in the larger vessel still match for the first half of the explosion. The simulations show thus that flame thickness can greatly influence the rate of pressure rise. It's effect becomes larger as the flame front thickness relative to vessel dimensions increases and as the burning velocity decreases.

![Diagram showing pressure-time plots for different flame front thicknesses.](image)

**Figure 6.7** Calculated pressure-time plots in a 20 litre sphere with different thicknesses of the flame front. The burning velocity is constant at 32 cm/s.
Figure 6.8  *Calculated pressure-time plots in a spherical 1 m³ vessel with different thicknesses of the flame front. The burning velocity is constant at 32 cm/s.*

6.4 The cubic law

In practical dust explosion research the cubic law is an important tool in judging the explosion severity of powders. Powders are classified according their K-value, and this classification is in designing pressure relief systems or suppression equipment. In this paragraph an attempt is made to establish the physical and mathematical back-ground of this cubic law.

The cubic law is given by:

$$K_{St} = V^\frac{1}{3} \left( \frac{dP}{dt} \right)_{\text{max}}$$  \hspace{1cm} (29)

Here V is the volume of the vessel. The index 'max' refers to the maximum value of the rate of pressure rise during the explosion.

From paragraph 6.2.4 (Figure 6.7 and Figure 6.8) it is clear that the maximum rate of pressure rise is maximum for the case of infinitely thin flames. As the flames become thicker, the maximum value is reached at lower pressures. The consequences of this effect might be important in dust explosion testing because dusts tend to burn with relatively thick flames. The data of Figures 6.7 and 6.8 are used to construct Figure 6.9.
In this figure the $K_{St}$ values for both vessels are plotted against the relative flame front thickness, which is defined as the ratio of the flame front thickness and the vessel radius.

![Graph showing $K_{St}$ values vs. relative flame front thickness.]

**Figure 6.9** Calculated $K_{St}$ values of explosions in two explosion vessels. A burning velocity of 32 cm/s was used in the three-zone-model.

It can be postulated that a relative flame front thickness of less than 1% results in $K$-values which are independent of the vessel volume. If the flame front becomes thicker the $K$-value becomes a function of its relative value. A fuel-air mixture with a given burning velocity and a given flame front thickness will then have a $K$-value which depends on the vessel volume.

Since the cubic law seems to be valid only for flames of negligible thickness, it is reasonable to apply the simple model given in paragraph 6.2.1 to this case. Combination of Eq. 29 and Eq. 7 results in an expression for the $K$-value:

$$K_{St} = \frac{3(P_e - P_0)}{(\frac{3}{4 \pi})^{1/3}} \left( \frac{P}{P_0} \right)^{1/3} \left( \frac{1}{\gamma_s} \left( \frac{P_0}{P} \right)^{1/3} \left( \frac{P_e - P}{P_0} \right) \right)^{2/3} S_u$$

The use of Eq. 7 already implies that Eq. 30 is valid only for thin flames. In order to obtain a constant value of the explosion index, $K_{St}$, it is also necessary that both the burning velocity, $S_u$, and the pressure, $P$, at which the maximum rate of pressure rise is measured are equal in the different vessels. Explosions with infinitely thin flames reach their maximum rate of pressure rise at the maximum explosion pressure $P_e$. If the
burning velocity is constant, this type of explosion satisfies the requirements for a proper use of the cubic law.

From Figure 6.7 and Figure 6.8 it appears that explosions with thicker flames have an initial pressure development which is similar to thin flame explosions. At the moment the front of the flame reaches the wall the rate of pressure rise starts to decrease and deviates from the thin flame case. The rate of pressure rise thus has its maximum value at a point where the explosion still behaves like a thin flame explosion. The reason the K-values decrease with thicker flames is due to the fact that the pressure at which the maximum rate of rise is attained becomes lower. In theory it should be possible to relate the K-value of a thick flame explosion, measured at pressure \( P \), to the higher K-values of a thin flame front explosions, measured at pressure \( P_e \).

Eq. 30 is used to derive the quotient of the two K-values.

\[
\frac{K_{S_e}(P_e)}{K_{S}(P)} = \left( \frac{P}{P_0} \right)^{\gamma_s} \left( 1 - \frac{P_0}{P} \left( \frac{P_e - P}{P_e - P_0} \right)^{2/3} \right)^{-\gamma_s} \]  

(31)

The practical significance of this relationship is the fact that, in practice, test results are usually obtained in rather small test facilities in which the flame is relatively thick. The actual process equipment, however, is usually large, inducing relatively thin flames.

Figure 6.10 shows the results of applying Eq. 31 to the simulated explosions. Both the K-value calculated with the cubic law and the corrected K-value are shown.

The effect of incorporating the pressure at which the maximum rate of pressure rise is measured is clearly shown in Figure 6.10. The original results obtained with the cubic law already start to deviate at a relative flame thickness of 1 % whilst the improved K-values remain constant up to relative thicknesses of 10-20 %. The reason that the improved K-values also deviate from the thin flame value for very thick flames is explained by Figure 6.7. Here it can be seen that the explosion curve at a flame front thickness of 10 cm is different from the thin flame explosion. The maximum rate of pressure rise is apparently attained at a point before the front of the flame has reached the wall. The simple thin flame model can then no longer be applied.

There is a further technique for matching the K-values of thick flame explosions in different explosion vessel volumes. Originally this technique was used in developing the 20 litre sphere for dust explosion testing. From Eq. 30 it can be seen that besides incorporating the actual pressure at which the K-value is measured, it is also possible to increase the burning velocity of the fuel-air mixture. Siwek found empirically that the K-values of most powders in the 20 litre sphere with an ignition delay time of 60 ms match the results in the larger 1 m\(^3\) vessel at a standardised delay time of 600 ms. In Chapter 5 it was shown that the level of turbulence in the 20 litre sphere at this ignition delay time is significantly higher than the level of turbulence in the 1 m\(^3\) vessel. Due to the
higher level of turbulence in the small vessel, the burning velocity is increased relative to the burning velocity in the larger vessel. In the next paragraph experiments are described which illustrate this phenomenon by varying of the level of turbulence in the 20 litre sphere. The method of adjusting the $K$-values will also be tested.

<table>
<thead>
<tr>
<th>cubic law</th>
<th>optimised K-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>△ 20 l.</td>
<td>■ 20 l.</td>
</tr>
<tr>
<td>△ 1 m3</td>
<td>□ 1 m3</td>
</tr>
</tbody>
</table>

Figure 6.10 *K*-values of simulated explosions in different vessels, calculated with the cubic law and also with Eq. 31.

Another aspect which is related to practical dust explosion testing in the 20 litre sphere is the use of an igniter with an energy content of 10 kJ. This type of igniter causes an initial pressure rise in the 20 litre sphere of about 1.5 bar over-pressure when fired without any powder present. In order to investigate the influence of this pressure rise on the development of a dust explosion, some calculations have been made. To incorporate the effect of the igniter an extra rate of pressure rise is added to the model during the first part of the explosion. The following equation is obtained experimentally.

\[
\left(\frac{dP}{dt}\right)_{\text{ign.}} = 0.32 \frac{t}{\text{bar/s}}
\]  

(32)
The effect of this igniter on the hypothetical explosion is shown in Figure 6.11.

![Graph showing pressure over time with different flame thicknesses.]

**Figure 6.11** Calculated development of an explosion in a 20 litre sphere of a fuel-air mixture having a laminar burning velocity of .32 m/s and different thicknesses of the flame. The results of two types of igniters are shown: a 10 kJ igniter and an igniter of negligible size.

The most striking effect of the large igniter is the translation of the curve to smaller explosion times. Apparently the igniter is large enough to quickly create a flame size and a pressure which are only reached after much longer times when using small igniters. The extra pressure rise caused by the large igniter is not completely added to the final explosion pressure. From experiments with igniters fired in air and in pure nitrogen it is known that the igniter itself consumes oxygen and thus reduces the amount of fuel burnt.

The theoretical effect of the use of the large igniter on the value of explosion index K in the 20 litre sphere is demonstrated in Table 6.2. Although the large igniter completely changes the overall course of the explosion, the effect on the K-values is only marginal. The high initial pressure immediately after the ignition seems only to disturb the first part of the explosion. The second part, in which the explosion indices are measured, is nearly independent of the igniter size. It should be remembered that the initial compression of the powder dispersion increases the initial dust concentration. This effectively decreases the lower explosion limit when this type of igniter is used in the 20 litre sphere, see Chapter 2. Experiments presented in the next paragraph illustrate the practical importance of these phenomena.
Table 6.2  Calculated K-values and corresponding improved K-values of explosions in the 20 litre sphere. Two types of ignition sources are compared at various conditions.

<table>
<thead>
<tr>
<th>$S_u$ [m/s]</th>
<th>$\delta_f$ [m]</th>
<th>Infinitely small igniter</th>
<th>10 kJ igniter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K [bar.m/s]</td>
<td>K(impr.) [bar.m/s]</td>
</tr>
<tr>
<td>0.16</td>
<td>0.001</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>0.16</td>
<td>0.1</td>
<td>5.3</td>
<td>7.1</td>
</tr>
<tr>
<td>0.32</td>
<td>0.001</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>0.32</td>
<td>0.1</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>0.64</td>
<td>0.001</td>
<td>82</td>
<td>84</td>
</tr>
<tr>
<td>0.64</td>
<td>0.1</td>
<td>21</td>
<td>27</td>
</tr>
</tbody>
</table>

6.5 Experiments

The experiments were performed to investigate some aspects of closed vessel dust explosion testing:
- the role of the large 10 kJ ignition source in small test vessels like the 20 litre sphere.
- the effect of the flame front thickness on the course of explosions in smaller equipment.
- the method of improved K-values in practical situations.

The effect of the size of the ignition source

Since the size of the ignition source is most significant in smaller test equipment, experiments were performed in a 20 litre sphere using 10 kJ and 0.3 kJ igniters. The experimental procedure for the 20 litre sphere was described in Chapter 2. Figure 6.12 shows the characteristic difference between explosions with relatively small and large igniters. Dust explosions ignited with small energies tend to be delayed, while large ignition energies accelerate the explosion in the first part. This difference was explained in paragraph 6.3. Because explosions with small ignition energy reach the maximum value of the rate of pressure rise considerably later than explosions ignited with large energies, their effective ignition delay time has to be adjusted. In Figures 6.13, 6.14 and 6.15 the ignition delay times of the explosion tests with small ignition energies have been adjusted, and the K-values are compared with explosions with large ignition energy.
Figure 6.12  Experimental results of potato starch explosions in a 20 litre sphere using a small 0.3 kJ ignition source and a large 10 kJ ignition source.

Figure 6.13  K-values versus adjusted delay time of (± 9.5 vol%) methane explosions in a 20 litre sphere using a small 3.6 J electric spark ignition source as well as a 10 kJ chemical ignition source.
Figure 6.14  
*K*-values versus adjusted delay times of activated carbon explosions using 0.3 kJ chemical igniters as well as 10 kJ chemical igniters, tested in a 20 litre sphere.

Figure 6.15  
*K*-values versus adjusted delay times of potato starch explosions using 0.3 kJ chemical igniters as well as 10 kJ chemical igniters, tested in a 20 litre sphere.
Except for a dramatic effect on the effective ignition delay time, small igniters result in K-values comparable to the K-values of dust explosions with large igniters. Due to the strong influence of the ignition delay time, it seems to be impossible to perform dust explosions with a small igniter at delay times below 100-150 ms. From these results the use of large, 10 kJ igniters in the 20 litre sphere seems to be justified when measuring K-values, especially because sometimes the small igniter failed to ignite the highly turbulent dust-air mixture. The resulting pressure-time plot, however, is far from the plot of an ideal explosion, as calculated in paragraph 6.3. The distorting effect of the large igniters on the lower explosion limits was demonstrated in Chapter 2.

The effect of the flame front thickness on the explosion results

From paragraph 6.3 it was postulated that relative flame front thicknesses of less than 1 % do not influence the K-value of an explosion measured in different sized explosion vessels. Larger relative thicknesses tend to lower the K-value. In order to verify this hypothesis, tests in explosion vessels with different volumes, in this case the standardised 1 m³ vessel and the 20 litre sphere, were carried out. In the case of negligible flame thickness the results should be comparable; in other cases the resulting K-value in the smaller vessel may be lower than that in the large vessel. In identical circumstances the flame front is then relatively thinner.

The results of some experiments are shown in the Figures 6.16 to 6.19.

![Graph showing comparison of K-values](image)

**Figure 6.16** Comparison of K-values of activated carbon (500 g/m³) measured in the 1 m³ vessel with a fixed delay time of 600 ms and in the 20 litre sphere with various delay times.
Figure 6.17  
Comparison of $K$-values of lycopodium ($500 \text{ g/m}^3$) measured in the 1 m$^3$ vessel with a fixed delay time of 600 ms and in the 20 litre sphere with various delay times.

Figure 6.18  
Comparison of $K$-values of potato starch ($1000 \text{ g/m}^3$) measured in the 1 m$^3$ vessel with a fixed delay time of 600 ms and in the 20 litre sphere with various delay times.
From Chapter 5 it appears that the turbulent conditions in the 20 litre sphere are identical to the conditions in the 1 m³ vessel at a delay time of about 165 ms, instead of the time of 60 ms which is commonly used. The results in Figures 6.19 and 6.16 prove this fact. Methane and activated carbon burn with thin flames and thus in these cases equal K-values can be measured in the 20 litre sphere with a delay time of 165 ms and in the 1 m³ vessel. Like most powders, lycopodium and starch burn with excessive flame thicknesses, which results in lower K-values than those measured in the smaller explosion vessel. This behaviour also causes the empirically chosen delay time in the 20 litre sphere to be 60 ms. As most powders have thick flame fronts, the burning velocity of the mixtures in smaller vessels must be increased to match the test results in the 1 m³ vessel. This necessity demonstrates that the 20 litre sphere is too small to reliably test many powders!

The method of improved K-values

In addition to identical conditions in the different vessels, the verification of this theory also requires the explosion vessels to be spherical. The 20 litre sphere can be supposed to be spherical, but the standardised 1 m³ has a cylindrical shape. Figure 6.20 shows a schematic drawing of the vessel with its physical dimensions.
The vessel seems to resemble a sphere approximately, but, in fact, the spherical flame front developing from the centre reaches the side walls after combustion of less than 80\% of the mixture volume. This implies that the pressure-time plot starts to deviate from a spherical explosion at a pressure of less than 80\% of the maximum explosion pressure.

Although the method of improved K-values has not been experimentally confirmed, the theoretical basis supports its value for practical situations. The method predicts K-values to be higher than values measured in most tests, when the flame is thick or when the vessel is not spherical. This means that under similar conditions in larger pieces of equipment the conventional test results underestimate the K-values. The improved K-value method corrects these measured K-values for relative flame thicknesses up to 10 \% and improves the K-values for thicker flames.

6.6 Conclusions

From the theoretical considerations and the experimental results several conclusions can be drawn concerning explosion models, the effect of thick flames and strong igniters on the applicability of the cubic law for small explosion vessels and the possibilities of improvement for the K-values. These conclusions are:

- The three-zone-explosion model can be used to simulate the effect of a thick flame on the development of the explosion pressure in a closed spherical vessel.
- In the case of relatively thin flames, or assumed thin flames, it is possible to translate the explosion index $K$ into a burning velocity at the conditions at which its value is determined.

- Flames with a relative thickness of up to 1% of the vessel radius behave according to the cubic law.

- Strong igniters in relatively small explosion vessels (e.g. 10 kJ in a 20 litre sphere) affect the initial part of the explosion whilst the final part of the explosion, in which the $K$-value is usually determined, remains unchanged.

- The method of improved $K$-values offers a possibility to use the cubic law for thicker flames, up to relative flame front thicknesses of 10%.

- The improved $K$-value usually exceeds the experimental $K$-value, which indicates that the $K$-value in larger equipment is higher under similar conditions.

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Chapter 7

The mechanism of ignition and propagation of dust explosions: Summary and conclusions

By the use of models, literature data and experiments described in this thesis it is possible to better understand the overall picture of a dust explosion. The phenomena occurring during the ignition and the propagation of dust explosions have been discussed in the preceding chapters. Due to the wide variety of subjects which were investigated the various aspects are not complete in this thesis, and this incompleteness should encourage further research.
In this chapter the information from Chapters 3, 4, 5 and 6 is used to construct a more complete picture of a dust explosion. Then some suggestions for future work are given in order to make the picture more accurate.

7.1 The mechanism of ignition

According to the theory in Chapter 3, the various ignition properties can all be related to three fundamental aspects of ignition:

The reaction kinetics of the combustion
Ignitions occur because the production of energy by the chemical reaction exceeds the rate of energy loss. According to the Arrhenius model, the production of energy is strongly influenced by the temperature of the medium, the activation energy of the chemical reaction, the reaction enthalpy and the concentration of the reactants. The ignition properties of dusts are, therefore, dependent on oxygen concentration, particle size, solids concentration and the chemical composition of the material.

Heat transfer and ignition geometry
The heat produced by the combustion is partially removed by heat loss to the surroundings. The rate of heat loss depends on the ignition geometry: heated walls in case of a Godbert-Greenwald oven and cold air in the case of electrical spark ignition. The rate of heat loss is determined by the heat transfer coefficient, the heat exchange area and the temperature difference. The heat transfer coefficient is related to temperature, material properties and flow properties.

The occurrence of a critical ignition kernel
Although most sources of ignition behave according to the balance between heat production and heat loss (Semenov theory), an exception must be made for very small ignition volumes. Below a certain size extra energy must be supplied to facilitate the expansion of the volume to the so-called critical ignition kernel. The dimensions of this kernel are related to the quenching distance of the dust dispersion. There may also be
a connection to the inter-particle distance in the dust cloud. Ignition volumes below this size contain few or no particles, which makes the application of the Semenov theory unrealistic.

In principle it is possible to calculate from these data the different ignition properties. Thus, the different ignition properties, such as MIT, MIE and MESG, are related to each other. A major problem in the calculations is the accurate estimation of the value of the parameters. The laser ignition method offers a method for measuring in-situ the ignition kinetics of the combustion. The heat transfer data should also be obtained from experiments, as the estimated data in Chapter 3 are far too inaccurate.

7.2 The mechanism of propagation

The propagation mechanism of explosions in dust-air mixtures has been studied in this thesis in three steps:
- the laminar burning velocity
- the influence of flow properties on the burning velocity
- the translation of a burning velocity into a rate of pressure rise in a closed vessel.

7.2.1 The laminar burning velocity

From the investigations described in Chapter 4, the laminar burning velocity of a dust cloud is determined mainly by conduction. Radiation plays a minor role in the propagation of the flame. The absolute conduction rate depends on the flame temperature, the dynamic ignition temperature and the particle burning time. These three parameters decide the temperature gradient in the flame. In most cases the particle burning time seems to be defined by film diffusion, and the flame temperature can then be estimated from thermodynamic calculations. The dynamic ignition temperature is far more difficult to obtain since it depends on the chemical reaction kinetics. Perhaps it is possible to make calculations on the basis of the ignition properties; otherwise its value should be experimentally determined.

7.2.2 The influence of flow properties on the burning velocity

It is suggested in Chapter 5 that the effect of the level of turbulence on the propagation velocity of dust explosions can be described on the basis of a comparison of time scales. The particle burning time and the integral time scale of the turbulent flow can be used to investigate the interaction between turbulence and burning velocity. In closed vessels with initial dust dispersion, the burning time of the particles usually exceeds the integral time scale of the velocity fluctuations of the flow. This results in an enhanced thermal conductivity of the air around the flame front. Addition of the turbulent diffusion coefficient to the molecular thermal diffusion coefficient results in good agreement between theory and experiments.
7.2.3 The translation of a burning velocity into a rate of pressure rise in a closed vessel

Once a turbulent burning velocity is known, it is necessary for practical situations to translate this velocity into the development of pressure during an explosion in a closed vessel. For accurate calculations, the thickness of the flame front must be incorporated. This thickness is determined by the turbulent burning velocity and the particle burning time. The calculations for non-spherical vessels are not treated in this thesis. For such vessels the flow produced by the expansion of gases near to the wall affect the initial flow properties. Obstacles in the path of the explosion also influence the turbulence in a complicated way.

7.3 Future work

Although it is possible to sketch a picture of an explosion propagating in a dust cloud a lot of research certainly remains to be done! Different powders and different circumstances must be investigated to check the hypothesis given in this study.

7.3.1 Improving the theory of ignition

The proposed ignition method using a IR laser must be improved to enable testing of a wide variety of powders. The measurement of the kinetic data of the ignition reaction must also be more accurate. The occurrence of a critical ignition kernel can then be observed in more detail. This means that the laser beam diameter must be measured more precisely and that the laser energy is variable over a larger range. It will also be interesting to apply a laser beam with a different wave length which heats the gas instead of the particles.

To compare the calculated ignition parameters with the standard test results, it is also necessary to better describe the physical phenomena occurring during ignition in these standard tests. This means better knowledge of the heat transfer data in the equipment and in the dust cloud, controlled turbulence and residence time and a better method of dust dispersion. In order to obtain more accurate results when using the electric spark test for measuring the minimum ignition energy it is also necessary to increase the number of ignition attempts, since the spark ignition of dust clouds is a stochastic process.

7.3.2 Improving the theory of propagation

In order to model the laminar burning velocity of dust clouds, it must be possible to calculate the ignition temperature in the flame. Calculation from the kinetic data of the ignition reaction may offer a possibility. Again, an accurate laser ignition method is necessary. A method of obtaining experimental values of the particle burning time at high temperature would be useful to get a better insight into the rate controlling steps of the combustion mechanism. The particle burning time is an essential parameter in the model for describing the turbulence interaction mechanism and for calculating the
laminar burning velocity.

The effect of turbulence on the burning velocity in a dust cloud needs to be investigated at different pressures and temperatures in order to assess their influence. Alternative dispersion methods could be applied to generate turbulence with different scales or intensities.

The modelling of explosions in vessels having a shape other than spherical will make it possible to more realistically predict explosion severity in typical industrial equipment.

**Figure 7.1**  The high pressure, high temperature 20 litre sphere.
At Delft University of Technology a begin has been made with these investigations. A unique 20 litre sphere has been designed and constructed, see Figure 7.1. In this vessel the initial temperature and the initial pressure of the explosion can be varied over a wide range, and the vessel is equipped with dust storage chambers of different size. These dust chambers can be pressurized up to 210 bar. The apparatus is suitable for use with pure oxygen in order to enable dust explosions to be carried out over a very wide range of concentrations and varying stoichiometric conditions.

The thesis thus offers not only experimental results, models and ideas, but has also resulted in the creation of a sophisticated new piece of equipment. It is hoped that this high pressure, high temperature explosion cell will enable the ideas and models presented to become more firmly researched.

Reference

P.G.J. van der Wel; F.J. Neervoort; S.M. Lemkowitz; B. Scarlett; "Construction, development and use of a new explosion cell for high pressure, high temperature dust explosion testing", 7th Int. Symp. on Loss Prevention and Safety Promotion in the Process Industries, Taormina, Italy, 4-8 May 1992, pp 112-1 / 112-15
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Peter van der Wel
Delft, 28 februari 1993
Curriculum vitae

Peter van der Wel werd op 15 maart 1963 geboren in Papendrecht. Zijn middelbare schooltijd is hij aanvankelijk begonnen op het Johan de Wit Gymnasium in Dordrecht, maar na een jaar is hij overgestapt op het Titus Brandsma College in Dordrecht waar hij het ongedeeld VWO heeft gevolgd. In 1981 is hij begonnen met de studie Scheikundige Technologie aan de Technische Hogeschool Delft, alwaar hij in januari 1987 de titel van Ingenieur heeft behaald. Na een jaar het land verdedigd te hebben als chauffeur-gewonden verzorger is hij in april 1988 begonnen met een promotie aan de TU Delft bij Professor Scarlett. Het onderwerp van die promotie vormt de basis van dit boekje.