

Influence of gaseous and solid inert substances on gas, dust and hybrid explosions

An experimental study in a 20-litre explosion vessel

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Abstract

Gas, dust and hybrid explosions represent a serious hazard in the petroleum, process and mining industries, and inert substances are frequently employed as part of risk-reducing measures such as inerting, suppression, and partial inerting or suppression. Solid inert substances, such as sodium bicarbonate (SBC), are used in systems for suppression or isolation of explosions, especially in facilities that handle combustible dust. The minimum inerting concentration (MIC) specifies the amount of a solid suppressant required for extinguishing a flame in a given fuel-air mixture, regardless of the fuel concentration. Similarly, diluting the air to a level below the limiting oxygen concentration (LOC) with inert gases, such as nitrogen and carbon dioxide, is an effective means of preventing the formation of explosive atmospheres, and hence accidental explosions. Furthermore, partial inerting is an effective means of reducing the risk of accidental explosions in confined environments, and systems for chemical inhibition have recently been developed for mitigating the consequences of vapour cloud explosions (VCEs) in congested process plants.

The present study aimed at investigating the mitigating effect of inert substances on the severity of fuel-air explosions, quantified by the explosion pressure P_m and the rate of pressure rise $(dp/dt)_m$. In particular, it was of interest to compare the relative efficiency of partial inerting by gaseous or solid inert substances applied to gaseous and solid fuels, as well as hybrid mixtures. To this end, various amounts of the inert substances nitrogen (N_2), carbon dioxide (CO_2) and sodium bicarbonate ($NaHCO_3$) were added to constant-volume fuel-air explosions with the fuels methane (CH_4) and maize starch, as well as hybrid mixtures of methane and maize starch. The experiments were conducted in a 20-litre explosion vessel at the dust explosion laboratory at the Department of Physics and Technology (IFT) at the University of Bergen (UiB). Initially, turbulent mixtures were ignited using a 1 kJ chemical igniter, triggered at a fixed ignition delay time of 60 milliseconds after the onset of dispersion.

The results confirm observation from previous studies, demonstrating that relatively modest amounts of inert substances can reduce the rate of combustion in fuel-air explosions significantly. The addition of 100-200 g/m^3 of the solid inert diluent SBC resulted in a 60-80 % reduction in the rate of pressure rise for methane, maize starch and hybrid (methane and maize starch) explosions. The results imply that partial inerting or suppression represent effective means of reducing the explosion risk, either as isolated measures or in combination with for instance deflagration venting.

Further work should elaborate on the mitigating effect of different types of solid inert diluents on fuel-air explosions in confined and/or congested geometries, as well as the effect of the particle size of the solid suppressant. It is also relevant to explore the possibility of mitigating the consequences of explosions involving highly reactive fuels, such as hydrogen. This is particularly relevant for hydrogen systems located in relatively weak enclosures, such as containers, buildings or fuel cell rooms in trains, ships and planes. Deflagration venting is not very effective for highly reactive fuels, but a combination of partial suppression and venting may reduce the risk to an acceptable level.

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1 Introduction

Gas, dust and hybrid explosions represent a serious hazard in the petroleum, process and mining industries, such as oil platforms, refineries, chemical factories, the food and feed industry, tank facilities, coal mines, refuelling/bunkering facilities, etc. Accidental explosions can result in loss of life and property, as well as deterioration of the environment.

Flammable gases and vapours are processed in various industries, from extraction and processing of natural gas to distribution and consumption of a wide range of gaseous products and fuels in industry and society at large. Approximately 70% of the dust encountered in the process industries are combustible and most of the reported dust explosions involved organic products from agricultural, food and pharmaceutical industries (CSB, 2006). Hybrid mixtures are typically encountered in facilities such as paint factories (pigments and solvents), mining (coal dust and methane gas), grain elevators (grain dust and fermentation gases), pharmaceutical industries (incipient and solvents), etc. (Addai *et al.*, 2016).

Throughout the history of the process industries, continuous efforts have been made to develop and improve measures to prevent and mitigate accidental explosions (Mannan, 2013; Khan & Abbasi, 1999; Eckhoff, 2016). This has resulted in a hierarchy of principles for risk reduction:

1. Inherent safety – the concept of inherent safety entails the four principles minimisation, substitution, moderation and simplification (Kletz, 1978).
2. Preventive measures, including:
 - a. Preventing the formation of explosive atmospheres
 - b. Preventing or controlling ignition sources
3. Mitigative measures, including:
 - a. Passive mitigation, such as explosion venting devices and passive isolation/sectioning
 - b. Active mitigation, such as suppression systems and active isolation/sectioning
4. Procedural safety, such as hot work permits, mandatory use of personal protection equipment, etc.

Safety engineers should seek to apply the principles for inherent safety first, and procedural safety is the last resort. Several strategies for controlling the hazard of fuel-air explosions entail the use of inert substances:

- *Inerting* is the process of diluting air with a sufficient amount of an inert (gaseous) substance, such as nitrogen (N₂) or carbon dioxide (CO₂), to ensure that the concentration of oxygen in a potential combustible fuel-air mixture is sufficiently below the limiting oxygen concentration (LOC). As such, inerting can be an effective means of preventing the formation of explosive atmospheres in confined systems, and hence accidental explosions (Eckhoff, 2003; Razus *et al.*, 2013). The value of the LOC depends on several factors, including the experimental apparatus, the ignition energy, the criteria for evaluating whether flame propagation takes place, and the inert substance, or diluent (Zlochower & Green, 2009; Babrauskas, 2003; Britton *et al.*, 2016). The higher molar heat capacity of CO₂, compared to N₂, implies that CO₂ is more efficient for inerting flammable mixtures. The use of carbon dioxide is also preferred for situations where the inert gas should be heavier than air (Serafin & Damec, 2011).

- *Partial inerting* is similar to inerting, but the oxygen concentration is not reduced below the LOC. As such, an explosion can still take place, but the reduced oxygen content may reduce the explosion violence significantly (Hartmann, 1948; Eckhoff, 2003). The reduced oxygen content also increases the energy required for igniting the flammable mixture, and partial inerting can, for instance, be combined with deflagration venting of weak enclosures.
- *Active suppression* involves the protection of isolated process vessels, such as dust collectors, dryers, or conveyors, where the signal from a sensor triggers the release of a suppressant that extinguishes an explosion at a sufficiently early stage to mitigate the consequences to an acceptable level (Moore, 1984; Moore, 1996). The minimum inerting concentration (MIC) specifies the amount of a solid suppressant required for extinguishing a flame in a given fuel-air mixture, regardless of the fuel concentration. Most systems for protection against dust explosion use sodium bicarbonate (NaHCO_3) as the suppressant.
- *Active explosion isolation, or sectioning*, by triggered extinguishing barriers can protect connected process vessels by preventing flame propagation between the units (Moore & Spring, 2004).
- *Partial suppression, or chemical inhibition*, can be used for mitigating the consequences of vapour cloud explosions (VCEs) in congested process plants (Roser *et al.*, 1963; Mitani, 1981; Eckhoff, 1983). Total and cooperation partners have demonstrated that flame inhibitors injected into flammable hydrocarbon-air clouds represents an effective means of mitigating the consequences of VCEs (Hoorelbeke & van Wingerden, 2009; van Wingerden *et al.*, 2013; Roosendans & Hoorelbeke, 2019).

The aim of the present study is to investigate the mitigating effect of inert substances on the severity of fuel-air explosions, quantified by the *corrected explosion pressure* P_m and the *rate of pressure rise* $(dp/dt)_m$. In particular, the objective is to compare the relative efficiency of partial inerting/suppression by two gaseous inert diluents (nitrogen and carbon dioxide) and one solid inert diluent (sodium bicarbonate) applied to fuel-air mixtures with a gaseous fuel (methane), a solid fuel (maize starch), and hybrid mixtures of methane and maize starch.

The study complements previous investigations on the effect of various gaseous or solid inert diluents on gaseous or solid fuels, where the results are limited to one type of diluents, or one type of fuels. The results can be directly applicable for the design and optimisation of risk-reducing measures in industry and can also lead to a better understanding of the physical and chemical processes involved in premixed combustion processes that involve solid fuels and/or solid inert diluents.

2 Theoretical background

2.1. Chemical explosions

A chemical explosion entails the sudden release of chemical energy. According to Eckhoff (2003), an explosion entails “an exothermal chemical process that, when occurring at constant volume, gives rise to a sudden and significant pressure rise”. Fuel-air explosions involve the rapid combustion of either a homogeneous mixture of a gaseous fuel, a mechanical suspension of liquid fuel droplets or combustible solid particles, or a hybrid mixture of droplets or particles and vapour, in air.

Figure 2.1 illustrates the explosion pentagon (Kauffman, 1982), which illustrates that a fuel-air explosion can take place if fuel and air mixed in an area with sufficient degree of confinement and/or congestion, and there is an ignition source present. Although the explosion pentagon is most often used in connection with dust explosions, it also applies to gas, mist and hybrid explosions, especially when congestion is included alongside confinement.

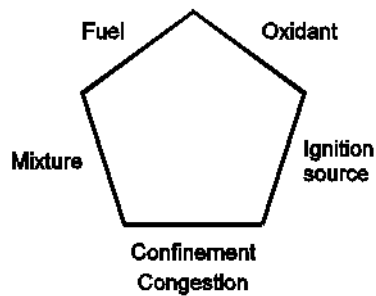


Figure 2.1: The explosion pentagon.

The fuel-air mixture must be within the flammable range, i.e. above the lower flammability limit (LFL) and above the upper flammability limit (UFL). The reactivity of the mixture depends on the type of fuel, as well as the equivalence ratio for a given fuel. In general, a more reactive mixture requires a lower degree of confinement and/or congestion to generate a certain overpressure, compared to a less reactive mixture. The addition of an inert diluent to a flammable fuel-air mixture will typically reduce the reactivity, narrow down the flammable range, and increase the amount of energy required for igniting the mixture.

2.1.1. Explosion severity parameters

The present work will focus on explosion severity parameters that can be determined in constant-volume explosion vessels (Bartknecht, 1981; Eckhoff, 2003; Cesana & Siwek, 2016):

- The **corrected explosion pressure** P_m is the highest pressure measured for a random concentration in a constant volume explosion vessel, after correction for heat losses and the effect of the ignition source. This parameter indicates the energy content of the mixture, as well as the damage potential of a constant volume explosion.
- The **rate of pressure rise** $(dp/dt)_m$ is the derivative in the inflection point of the pressure-time curves measured for a random concentration in a constant volume explosion vessel. This parameter indicates the reactivity of the mixture.

Both P_m and $(dp/dt)_m$ are determined in the same tests, and are used in standards and guidelines for the design of explosion protection systems. Related parameters include:

- The **maximum explosion pressure** P_{max} is the maximum value of the explosion pressures (P_m) measured over a wide range of fuel concentrations according to the standardised procedure described in the European standard EN 14034-1.
- The **maximum rate of pressure rise** $(dp/dt)_{max}$ is the maximum value measured for the rate of pressure rise $(dp/dt)_m$ measured over a wide range of fuel concentrations according to the standardised procedure described in the European standard EN 14034-2.

Since the rate of pressure rise depends on the volume V of the test vessel, it is customary to introduce a so-called deflagration index by normalising the experimental $(dp/dt)_{max}$ values with the cube root of the vessel volume:

$$\text{For dust (initially turbulent):} \quad K_{St} = V^{1/3} (dp/dt)_{max} \quad (2.1)$$

$$\text{For gas (initially quiescent):} \quad K_G = V^{1/3} (dp/dt)_{max} \quad (2.2)$$

The difference in test conditions implies that K_{St} values cannot be compared directly with K_G values. To this end, the experiments in the present work will all be conducted under initially turbulent flow conditions, similar to those used for determining K_{St} values for dust. However, since the aim of the present work is not to determine standard values for P_{max} , $(dp/dt)_{max}$ and K_{St} , the results will focus on the parameters P_m and $(dp/dt)_m$ obtained for the specified test conditions, including the effect of inert diluents and/or deviations from optimal fuel-air concentrations.

It can be mentioned that the laminar burning velocity S_L is a more fundamental parameter for quantifying the reactivity of flammable fuel-air mixtures (Konnov *et al.*, 2018). However, it is not straightforward to determine unambiguous values for the laminar burning velocity in general, and especially not for flames in dust clouds and hybrid mixtures. The use of the $(dp/dt)_m$ parameter, determined for similar turbulent flow conditions using same ignition source, provide a measure of reactivity that is fairly consistent for the different types of fuel-air mixtures.

Examples of other empirical parameters that can be used to characterise safety-related properties of gas, dust and hybrid mixtures include:

- The **lower flammability limit** (LFL), also referred to as the lower explosion limit (LEL) or the minimum explosion concentration (MEC) – the latter is mostly used for dust.
- The **upper flammability limit** (UFL), also referred to as the upper explosion limit (UEL) – this parameter is primarily relevant for gases and vapours.
- The **limiting oxygen concentration** (LOC), also referred to as the minimum oxygen concentration (MOC), is used for gaseous inert diluents. Section 2.2 elaborates on LOC.
- The **minimum inerting concentration** (MIC) is the minimum concentration of a solid suppressant required for preventing flame propagation in a fuel-air mixture.
- The **minimum ignition energy** (MIE).
- The **minimum ignition temperature** (MIT).

The present work will primarily focus on the effect of inert diluents on the explosion severity parameters P_m and $(dp/dt)_m$.

2.1.2. Gas and vapour explosions

Gas is defined as the state of matter characterized by complete molecular movement (Zabetakis, 1965). Burning of combustible gases is well known from daily life. A gas explosion is an explosion resulting from mixing of flammable gas (typically from an accidental gas leak) with the surrounding air to form an explosive cloud. An explosion occurs if the fuel-air ratio is within the

explosible range and an ignition source is present. For example, the explosive range of methane is from 5 to 15 vol.% methane in air.

Gas combustion is a homogenous process where the fuel and oxidiser are mixed on the molecular level. Several factors influence the development and consequences of fuel-air explosions, including the reactivity of the fuel and the degree of congestion and confinement (Maremonti *et al.*, 1999).

Confined gas explosions occur within process units or buildings, such as pipes, tanks, process equipment, sewage systems, closed rooms and underground installations. The unvented pressure rise in a confined explosion can in principle be estimated from the volume of the enclosure and the size and concentration of the flammable cloud. This class of explosions are most common and usually result in injury to the building inhabitants and extensive damage and there are two types involving explosive vapours and explosive dust.

Unconfined gas explosions result from the release and dispersion of flammable gases or vapours into the atmosphere and its subsequent ignition of the flammable cloud (Bjerketvedt *et al.*, 1997). The positive feedback loop involving the expansion of combustion products, turbulence generation in wakes behind obstacles, flame folding, and enhanced rate of turbulent combustion, can result in strong flame acceleration, pressure build-up and formation of blast waves. Large vapour cloud explosions (VCEs) can cause extensive damage and considerable losses. Many accidental explosions in industry take place in partly confined and congested geometries (Bjerketvedt *et al.*, 1997).

Gas or vapour explosions can be prevented or mitigated by measures such as prevention and control of combustible gases leakage, good ventilation to minimize the explosive atmosphere due to gas release, prevention and control of possible ignition sources and installation of blast and fire barriers (Bjerketvedt *et al.*, 1997; Shao *et al.*, 2013; Crowl & Louvar, 2001; Johnson & Vasey, 1996).

2.1.3. Dust explosions

The phenomenon of dust explosion is quite simple and easy to envision in terms of daily life experience. Any solid material that can burn in air will do so with a violence and speed that increases with increasing degree of subdivision of the material (Eckhoff, 2003; Amyotte & Eckhoff, 2010). In general, dust clouds will be easier to ignite and burn more violently the smaller the dust particles are, down to some limiting particle size that depends on the type of material. When a dust explosion takes place inside process equipment or workrooms, the pressure may rise rapidly, the process equipment or building may burst, and life, limb and property can be lost. A dust cloud ignited in an unconfined space will typically result in a flash fire.

Figure 2.2 illustrates that a dust cloud is a mechanical suspension, a system of fine particles dispersed by turbulence (Skjold *et al.*, 2006). The process of dispersing, or lifting, the dust particles from a heap or layer can be inherently complex, and without agitation the particles will settle out of suspension. The complex interactions between dust particles and turbulent flow structures in the dust cloud include collisions, agglomeration and local concentration gradients. The explosion pentagon in *Figure 2.1* illustrates that a dust explosion can take place when a flammable dust cloud is present in a volume that is sufficiently confined or congested, and there is an ignition source present.

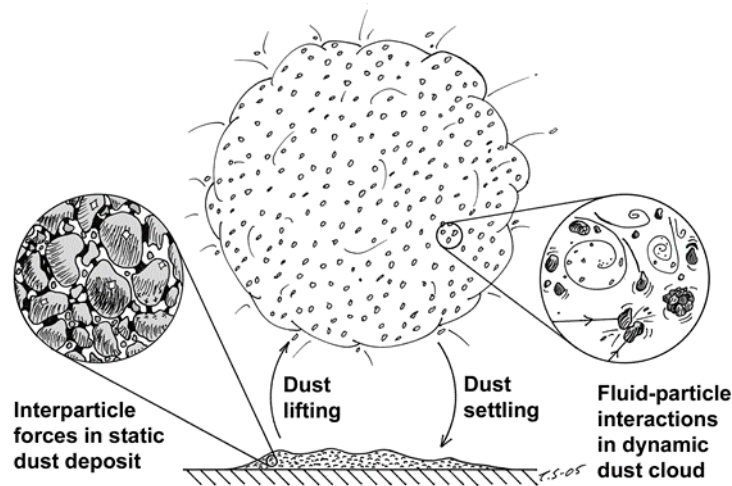
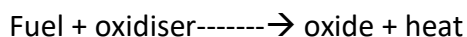


Figure 2.2: Dust clouds are mechanical suspensions, from Skjold *et al.* (2006)

The lower flammability limit (LFL) represents the minimum concentration of dust that can propagate a self-sustained flame. In principle, there is also an upper flammability limit (UFL) for dust clouds, but this parameter is inherently difficult to measure (no standard test has been widely adopted) and has limited practical interest. The LFL of dust clouds depends on factors such as material, particle size distribution, temperature, volatile matter, oxygen and moisture content, the volume of the test vessel, the ignition source, the criteria for defining successful ignition, etc. (Cashdollar, 2000; Amyotte *et al.*, 1991; Eckhoff, 2003). For example, the LFL increase with increasing particle size, until a size is reached that cannot be ignited. An increase in particle size leads to a reduction of the specific surface area of the particles, and hence a reduction in the effective surface area available for heat transfer, devolatilisation/pyrolysis and possible surface reactions. Moreover, the LFL decreases with an increase in initial temperature. One explanation can be that at higher temperatures, more volatile matter vaporises, and can contribute to the gas phase combustion.

Materials that cause dust explosions

As described by Eckhoff (2003), a dust explosion is caused by the rapid release of heat from chemical reactions:



In some special cases, metal dust can also react exothermically with nitrogen or carbon dioxide, but most often oxidation by oxygen is the heat-generating process in dust explosions. This means that only materials that are not already stable oxides can give rise to dust explosions, including:

- Natural organic materials, such as grain, wood, linen, sugar and starch.
- Synthetic organic materials, such as plastics, organic pigments, pesticides and pharmaceuticals.
- Coal and peat.
- Metals, such as aluminium, magnesium, titanium, zinc and iron.

Non-combustible dust are mostly materials that are already stable oxides, such as silicates, sulphates, nitrates, carbonates, phosphates, Portland cement, sand and limestone.

Factors influencing the ignitability and explosibility of dust clouds

Several factors influence the ignitability and explosibility of dust clouds:

- The chemical composition of the dust, including its moisture content.
- The chemical composition and initial pressure and temperature of the gaseous oxidiser, including humidity.
- The distribution of particle sizes and shapes in the dust, including the specific surface area of the dust in the fully dispersed state.
- The possibility of significant radiative heat transfer during flame propagation (highly dependent on flame temperature, which in turn depends on particle chemistry).
- The degree of dispersion, or agglomeration, of dust particles, determining the effective specific surface area available to the combustion process in the dust cloud in the actual industrial situation.
- The dust concentration in the actual cloud.
- The initial turbulence in the actual cloud.
- The explosion-induced turbulence in the dust cloud (the location of the ignition source and internal congestion will typically be important parameters).
- The possibility of flame front distortion by other mechanisms than turbulence.

Prevention and mitigation of dust explosion in the process industries

Table 2.1 summarises the primary means of preventing and mitigating dust explosions (Eckhoff, 2003). The topic of this thesis is primarily relevant for partial inerting, and to some extent suppression.

Table 2.1: Means for preventing and mitigating dust explosions in the process industries, from Eckhoff (2003).

Prevention		Mitigation
Preventing ignition sources	Preventing explosible dust clouds	
Smouldering combustion in dust, dust flames	Inerting by N ₂ , CO ₂ , and rare gases	Partial inerting by inert gas
Other types of open flames (e.g. hot work)	Intrinsic inerting	Isolation (sectioning)
Hot surfaces	Inerting by adding inert dust	Venting
Electric sparks and arcs, electrostatic discharges	Dust concentration outside the explosible range	Pressure-resistant construction
Heat from mechanical impact (metal sparks and hot spots)		Automatic suppression
		Good housekeeping (dust removal, cleaning)

2.1.4. Hybrid explosions

Hybrid mixtures consist of at least two combustible substances in a different state of aggregation, e.g. dust and flammable gas or vapour. The ignition sensitivity and explosion severity of hybrid mixtures differ from that of the single components (Pilao *et al.*, 2006; Bartknecht, 1981; Cashdollar, 1996; Siwek, 1996). In particular, the combination of a dust cloud and vapour that both are below the respective LFLs for the individual components can result in a flammable hybrid mixture (Eckhoff, 2003; Addai *et al.*, 2014). The need for generating a mechanical suspension of particles implies that experimental methods and test parameters for hybrid dust-gas mixtures resemble the corresponding methods and parameters for dust explosions.

2.2. Inerting and suppression

Inerting usually describes the process of adding an inert substance to a combustible mixture to reduce the concentration of oxygen below the limiting oxygen concentration (LOC) to prevent the formation of an explosive atmosphere (Barton, 2002). As such, inerting is only applicable for closed or highly confined systems. The term inerting is also used for describing the addition of sufficient amounts of an inert substance to combustible dust, to render a dust cloud non-flammable. This approach is for instance used in coal mines.

The limiting oxygen concentration (LOC), also known as the minimum oxygen concentration (MOC), is defined as the limiting concentration of oxygen below which combustion is not possible, independent of the concentration of the fuel (Zlochower & Green, 2009). The value of the LOC depends on the type of inert substance, the volume of the test vessel, the ignition source, etc. The effect of increasing the concentration of the inert substance is a reduction in flame temperature until the flame cannot exist. Carbon dioxide is more effective as an inert substance compared to nitrogen because of higher heat capacity.

Explosion suppression is a well-established technology for protecting equipment in the process industries against the consequences of accidental dust explosions (Moore, 1984; Moore, 1996; Amyotte, 2006). Active suppression involves the protection of isolated process vessels, such as dust collectors, dryers or conveyors where the signal from a sensor triggers the release of a suppressant that extinguishes the explosion at a sufficiently early stage to mitigate the consequences to an acceptable level. Active explosion isolation by triggered extinguishing barriers can protect connected process vessels by preventing flame propagation between the units (Moore & Spring, 2004). Most systems for protection against dust explosion use sodium bicarbonate (NaHCO_3) as the suppressant. Whether the term 'inerting' or 'suppression' is used depends on the context: 'Inerting' refers to the prevention of explosions, and the term 'suppression' refers to the mitigation of the consequences of the explosions. The physical phenomena involved are essentially the same: to remove the heat necessary for sustained combustion and thus limit the generation of destructive overpressures in an enclosed volume. This distinction is clearly articulated by Eckhoff (2003) in the chapter on dust explosion research and development during the period 1990-2002, wherein he presents different sections entitled: inerting by adding non-combustible dust and automatic explosion suppression.

Partial inerting is similar to inerting, but the oxygen concentration is not reduced below LOC. As such, an explosion can still take place, but the reduced oxygen content may reduce the explosion violence significantly (Hartmann, 1948; Eckhoff, 2003). The reduced oxygen content also increases the energy required for igniting the flammable mixture, and partial inerting can, for instance, be combined with deflagration venting of weak enclosures.

Partial suppression or chemical inhibition can also be used for mitigating the consequences of vapour cloud explosions (VCEs) in congested process plants (Eckhoff, 1983). Recent work by Total and cooperation partners has demonstrated that flame inhibitors injected into flammable hydrocarbon-air clouds represents an effective means of mitigating the consequences of vapour cloud explosions (Hoorelbeke & van Wingerden, 2009; van Wingerden *et al.*, 2013; Roosendans & Hoorelbeke, 2019).

2.2.1. Inerting by gaseous diluents

Inerting entails the partial or complete substitution of the oxygen in the air (or any other reactive atmosphere) by an inert gas. Explosions can be eliminated if oxygen is excluded completely or if the oxygen content is reduced to a level below the limiting oxygen concentration (LOC) for the given combination of fuel and inert substance (Barton, 2002). This approach is only applicable to confined systems, where the addition of inert gases can be controlled. Asphyxiation represents a risk whenever there is a possibility of forming an inert atmosphere in places accessible to people.

Typical inert gases used in process industries include nitrogen, carbon dioxide, argon, helium, flue gases and steam. The choice of inert gas depends on several factors like cost, availability, reliability of supply, the likelihood of contamination of gas/dust by inert gas constituents including moisture and the effectiveness of the diluent for reducing explosibility (Barton, 2002). Nitrogen and carbon dioxide are used as inert gases in this study.

Figure 2.3 shows the inerting effectiveness of nitrogen on the maximum explosion pressure and the maximum rate of pressure rise of a brown coal sample. The figure indicates a LOC of 11 vol.% N₂ (i.e. zero values of overpressure and rate of pressure rise). The steady reduction in explosion pressure, and especially the maximum rate of pressure rise, as the oxygen concentration is reduced from 21 vol.%, illustrates the potential for using partial inerting as a means of risk reduction.

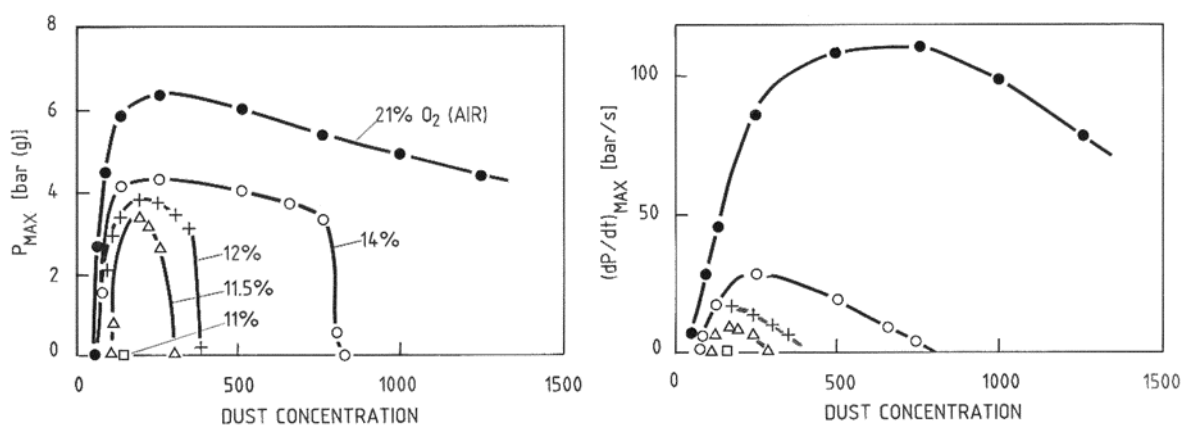


Figure 2.3: The inerting effectiveness of nitrogen on the maximum explosion pressure and maximum rate of pressure rise of a sample of brown coal, data from Wiemann, reported by Eckhoff (2003).

According to Chan *et al.* (2015), Benedetto *et al.* (2009) studied the role of CO₂ as inert gas on the flammability of CH₄/O₂/N₂/CO₂ mixtures and has found that the main effect of CO₂ was not on the kinetics or diffusive transport fluxes, but largely thermal i.e. the presence of CO₂ increased the specific heat of the mixture, lowering the flame temperature and combustion rate. Hu *et al.* (2014) have attributed the decreasing trend of flame speed (with increasing CO₂ level) to the dilution, transport, thermal and kinetic effects.

Gant *et al.* (2011) undertook an experimental study in a 20-litre explosion vessel to examine the effect of CO₂ as inert gas on the ignition of methane-air mixture. Increasing the CO₂ concentration resulted in a decrease in both P_m and $(dp/dt)_m$. In particular, the maximum rate of pressure rise was greatly reduced in all tests where CO₂ was present.

Wu *et al.* (2010) investigated the flammability and explosion characteristics of methane-air mixture with various concentrations of three different inert gases (CO₂, N₂ & Ar) in a 20-litre

apparatus. The results confirm that carbon dioxide (CO₂) is more efficient for inerting, compared to nitrogen (N₂) and argon (Ar). The ranking of inerting efficiency was as follows: CO₂>N₂>Ar. Razus *et al.* (2016) conducted a similar study for four inert gases (He, Ar, N₂ & CO₂) in two spherical vessels of different volumes using methane concentrations in the range 6-12 vol.% and inert concentrations in the range 5-40 vol.%. The ranking of inerting efficiency was as follows: CO₂>N₂>Ar>He.

2.2.2. Suppression by solid diluents

Explosible gas or dust can be made non-explosible by diluting them with inert dust such as calcium sulphate, limestone, sodium bicarbonate, common salt, various silicates or stone dust. Such materials may act as a heat sink or otherwise interfere with flame propagation. In most cases at least 60% diluent dust is required, and the diluent dust must be intimately mixed with the explosible dust (Barton, 2002). The quantity of diluent dust required can be determined using the explosibility tests. Except coal mines, where rock dust (e.g. limestone or dolomite) is extensively applied as a preventive measure, diluent dust inerting is rarely used because of the large quantities needed and potential contamination of products.

According to Chan *et al.* (2015), Zahedi *et al.* (2014) reported that for any diluent, the effect of its addition could be either dilution, transport and thermal diffusion, chemical inhibition or combinations thereof:

- Dilution effect: In the presence of the diluent, the concentrations of the fuel and oxidant are reduced, leading to a lower net reaction rate and thus lower flame speed.
- Transport and thermal effects: when a diluent is added, the mass/thermal diffusivities and the specific heat capacity of the mixture change, affecting the burning velocity.
- Chemical inhibition: The diluent takes active part in the chemical reactions, altering the reaction kinetics and consequently the burning velocity.

Over the last decade, Total has developed systems for partial suppression of VCEs that utilise chemical inhibition of combustion reactions (WIPO, 2010; WIPO, 2018; Hoorelbeke, 2011; Roosendans, 2018; Roosendans & Hoorelbeke, 2019). *Figure 2.4* illustrates the effect of inhibition by various amounts of potassium carbonate on the peak vented explosion pressures measured in a 50-m³ congested module for different hydrocarbon fuels (van Wingerden & Hoorelbeke, 2011). Babushok *et al.* (2017) develop a detailed gas-phase kinetic model of the influence of potassium-containing compounds on hydrocarbon-air flames. The mechanism included 85 reactions and twelve potassium-containing species. Simulations of laminar burning velocity using the proposed mechanism agreed reasonably well with available experimental data, indicating short evaporation times of the inhibitor particles in the flame reaction zone.

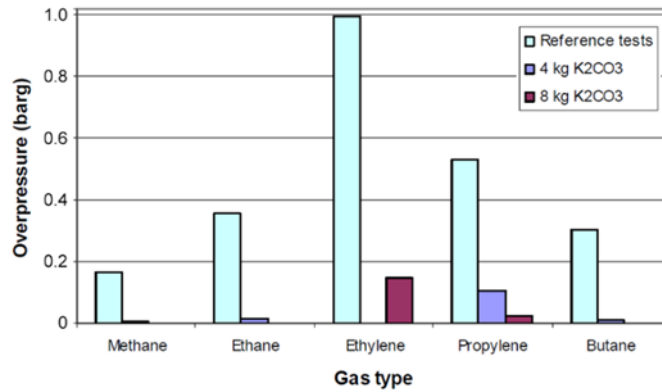


Figure 2.4: The effect of inhibition by potassium carbonate for five hydrocarbon fuels.

Amyotte *et al.* (1991a; 2003) investigated the inerting effect of dolomite and petroleum coke on coal dust explosions in a Siwek 20-litre vessel. Both studies showed a significant decrease in the maximum rate of pressure rise when petroleum coke and dolomite were added to the coal dust. The low volatile content of petroleum coke exerts an ‘inerting -like’ influence when mixed with coal dust.

Chatrathi & Going (2000) and Dastidar *et al.* (1999) investigated the LOC of aluminium, anthraquinone and polyethylene by the inert diluents mono-ammonium phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$ or MAP) and sodium bicarbonate (NaHCO_3 or SBC) in the 1-m³ explosion chamber at Fike, using two 5 kJ igniters as the ignition source. The results showed that limestone was the least effective inhibitor and MAP was most effective. This was likely a combined effect of the inability of limestone to decompose in the rapidly advancing flame front and the chemical inhibition properties of MAP and SBC. The results also indicated that the effect of the inert diluent depends on the composition of the explosible dust.

Dastidar *et al.* (2002) also undertook an experimental study of the effect of ignition energy and vessel volume on the inerting level. Results obtained in a 20-litre Siwek vessel were compared with the data from the 1-m³ Fike vessel (Dastidar *et al.*, 1999). A reduction in the ignition energy in the 20-litre vessel from 5 to 1 kJ lowered the LOC from 1500 to 500 g/m³.

Amyotte *et al.* (1991a) reported that for mixtures of fuel dust and inert substance, the co-presence of a flammable gas leads to an increase in the inerting level. The magnitude of this increase in inerting level can be significant. The author conducted a series of tests in a 26-litre chamber where the inerting level for one of the coal dust examined was raised from 84 wt.% dolomite to 89 wt.% dolomite when 2 vol.% of methane was added to the oxidizing atmosphere. Concerning the coal mining industry, the results reflect the inefficiency of rock dust as protection against methane explosions. Considering that it is essentially gas flame propagation in gaseous volatiles that must be arrested during a coal dust explosion, the results also help to explain why large amounts of rock dust are required even in the absence of methane. On a general note, these data demonstrate that inerting levels based on the presence of explosible dust alone can be entirely inadequate when applied to hybrid mixtures of solid and gaseous fuels.

Omar *et al.* (2018) reported that the higher effectiveness per mass basis of sodium bicarbonate (NaHCO_3) compared to other inhibitors motivates for the choice of NaHCO_3 as solid inert in case of methane-air explosions. This efficiency is attributed to the chemical nature of flame interaction. Sodium bicarbonate particles undergo thermal decomposition when exposed to

flame temperature. As a result, a gaseous agent NaOH is liberated and acts as a scavenger for radical species reducing the heat release, and hence the flame speed.

Tamanini *et al.* (2000) investigated the performance characteristics of two solid inert powders namely sodium bicarbonate (SBC) and mono-ammonium phosphate (MAP) and water as inerting agents in a 2.5 m³ test vessel with 10 vol.% methane-air mixture (near-stoichiometric), both under initially quiescent and turbulent conditions. Tests with the two powder agents (SBC & MAP) at a concentration of 1200 g/m³ resulted in similarly successful suppression of quiescent mixtures, with small increase in final overpressure. Successful suppression was also obtained with turbulent mixtures, although with greater overpressure than for quiescent mixtures.

As noted by Eckhoff (2003), suppression is more applicable than inerting in the process industries.

3 Experimental apparatus and procedure

This chapter describes the experimental set-up and test procedures. The experimental results are presented and discussed in chapters 4 and 5, respectively. All experiments were conducted in the dust explosion laboratory at the Department of Physics and Technology (IFT), UiB.

3.1. Experimental apparatus

All the explosion experiments were performed in a 20-litre vessel of the type developed by the US Bureau of Mines (USBM) but equipped with the dispersion, control and data acquisition systems developed by Kühner for the standard 20-litre Siwek sphere (Skjold, 2003). *Figure 3.1* shows the explosion vessel and *Figure 3.2*: The 20-litre explosion vessel and associated systems inside a ventilated laboratory hood. The auxiliary systems include a vacuum pump for evacuating the explosion chamber, the supply of compressed air (20 bar overpressure) from a 50-litre bottle for the 0.6-litre dust reservoir, two piezoelectric pressure sensors (Kistler 701A) and charge amplifiers (Kistler 5041) for recording the pressure-time histories (part of the KSEP 332 control and measurement system from Kühner), and a computer running the KSEP software from Kühner. Dust from the pressurized dust reservoir is dispersed into the explosion vessel through a standard rebound nozzle (*Figure 3.3*). The outlet valve that separates the dust reservoir and the vessel is pneumatically opened and closed by an auxiliary piston. All tests used the same ignition source: a 1 kJ chemical igniter placed in the centre of the explosion vessel, pointing downwards and triggered at a fixed ignition delay time $t_v=60$ ms after the onset of dispersion. *Figure 3.4* and *Figure 3.5* shows the heater and scale for drying and weighing dust samples, respectively.



Figure 3.1: 20-litre explosion vessel



Figure 3.2: The 20-litre explosion vessel and associated systems



Figure 3.3: Rebound nozzle



Figure 3.4: A 1 kJ chemical igniter (left) and the igniter fixed in the centre of the vessel (right).



Figure 3.5: The oven (left) and scale (right) used for drying and weighing dust samples.

3.2. Experimental procedure

3.2.1. Materials

The combustible dust used in the present study was maize starch (Meritena A), dried at 50 °C for at least 24 hours and later stored in an autoclave with moisture-absorbing material. The flammable gas was methane and the hybrid mixtures consisted of various proportions of maize starch and methane. The inert substances used in the tests were gaseous nitrogen and carbon dioxide, and solid sodium bicarbonate of the type used in explosion suppression systems. *Table 3.1* summarises the material properties of the compressed gases used in the present study.

Table 3.1: Material properties of the gases used in the present work

Gas	Quality	Purity (%)
Nitrogen	5.0 ULTRA	99.999
Carbon dioxide	5.0 ULTRA	99.999
Methane	2.5	99.5

Figure 3.6 and *Figure 3.7* shows the particle size distributions for maize starch of type Meritena A and sodium bicarbonate, respectively. The particle size distributions were measured with a Malvern Mastersizer 3000 at the Earth Surface Sediment Laboratory (EARTH LAB) at the Department of Earth Science, University of Bergen. The dust samples were dispersed in air using the 'AERO S' module. Each plot shows the results from ten samples, as well as average values. *Figure 3.8* and *Table 3.2* summarise the average particle distributions and characteristic measures for particle size for the dust (i.e. the 10, 50 and 90 percentiles Dv10, Dv50 and Dv90 from the cumulative volume distribution).

Table 3.2: Characteristic measures of particle size for the dust used in the present work

Percentile	Maize starch (Meritena A)		Sodium bicarbonate (SBC)	
	Average (µm)	St.dev. (µm)	Average (µm)	St.dev. (µm)
Dv10	7.6	0.49	4.9	0.19
Dv50	13.7	0.26	22.5	0.43
Dv90	24.4	0.67	58.1	1.24

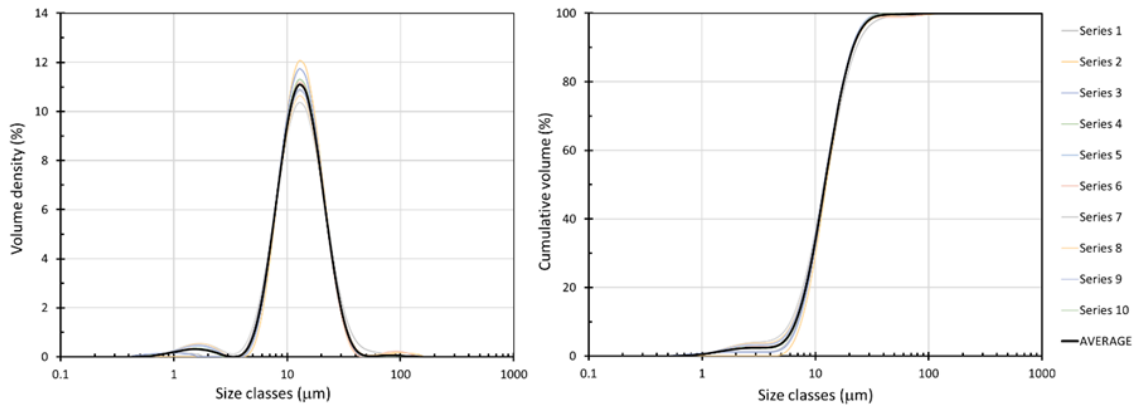


Figure 3.6: Volume density (left) and cumulative volume for Meritena A (right).

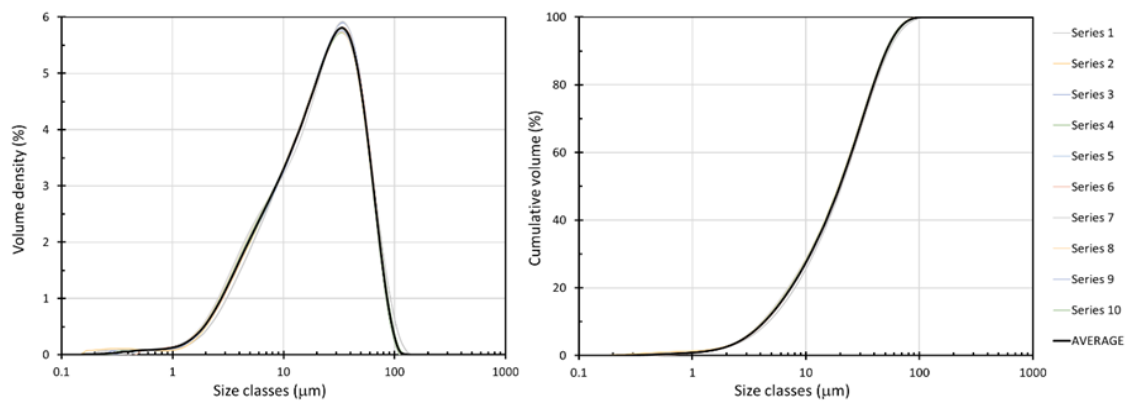


Figure 3.7: Volume density (left) and cumulative volume for SBC (right).

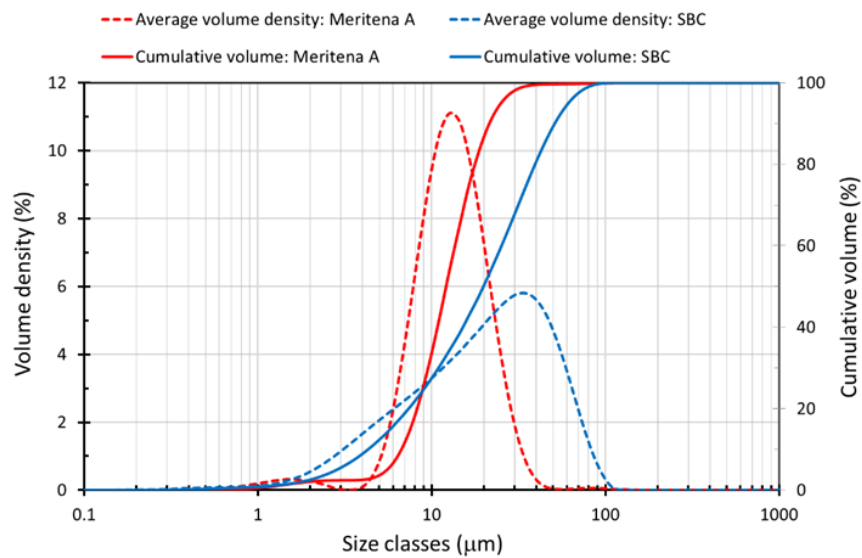


Figure 3.8: Average volume density and cumulative volume for Meritena A and SBC.

Table 3.3 summarised selected physical and chemical properties of the inert diluents used in the present study.

Table 3.3: Selected properties of the inert diluents used in the present study.

Property	Nitrogen	Carbon dioxide	Sodium bicarbonate (SBC)
State at ambient conditions	Gas	Gas	Solid (crystalline powder)
Flammability	Non-combustible	Non-combustible	Non-combustible
Chemical formula	N ₂	CO ₂	NaHCO ₃
Molecular structure	N=N	O=C=O	Salt: Na ⁺ HCO ₃ ⁻
Molecular weight	28.02 g/mol	44.01 g/mol	84.006 g/mol
Detectability by senses	Colourless and odourless	Colourless, sharp, acidic odour at high concentrations.	Colourless and odourless
Taste	Tasteless	Tasteless	Slightly alkaline (bitter) taste
Density	1.25 kg/m ³ @20°C, 1 atm.	1.836 kg/m ³ @20°C, 1 atm.	2200 kg/m ³
Molar heat capacity ^a , constant pressure (c _{p,m})	29.12 J/(mol K) @25°C, 1 atm.	36.94 J/(mol K) @25°C, 1 atm.	87.7 J/(mol K) @25°C
Molar heat capacity ^a , constant volume (c _{v,m})	20.80 J/(mol K) @25°C, 1 atm.	28.48 J/(mol K) @25°C, 1 atm.	-
Specific heat capacity ^b , constant pressure (c _p)	1.040 kJ/(kg K) @20°C, 1 atm.	0.844 kJ/(kg K) @20°C, 1 atm.	1.043 kJ/(kg K)
Specific heat capacity ^b , constant volume (c _v)	0.743 kJ/(kg K) @20°C, 1 atm.	0.655 kJ/(kg K) @20°C, 1 atm.	-
Reactivity	Inert	Inert	Inert, starts to decompose at temperatures > 80 °C: 2 NaHCO ₃ → Na ₂ CO ₃ +CO ₂ +H ₂ O

3.2.2. General test procedure

For each test, the general procedure was more or less the same. The required amount of inert solid suppressant (SBC) and/or combustible dust was added to the 0.6-litre dust reservoir, and the reservoir was pressurised to 20 bar overpressure with compressed air from a 50-litre bottle. The vacuum pump evacuated the 20-litre explosion vessel to the desired pressure, typically 0.40 bar absolute for regular dust explosion tests, and down to 0.1 bar absolute for tests with gaseous fuel and/or an inert diluent (e.g. 10 vol.% methane and 20 vol.% inert gas, either N₂ or CO₂). The gaseous fuel and/or inert diluent were added to the 20-litre explosion vessel prior to injection of air from the 0.6-litre reservoir.

All mixing of flammable and inert gases was done by admission of gas controlled by partial pressure, followed by turbulent mixing when air or dust-air was injected into the vessel. The limitation of 0.40 – 0.10 = 0.30 bar pressure range for the mixing of gases by partial pressure implied that not more than 30 vol.% gas (inert and fuel) could be added. *Figure 3.9* illustrates that this implies that it was not possible to determine LOC values for methane and maize starch with this experimental setup. The green triangles (Zlochower & Green, 2007: LOC 10.7-12.0 vol.% O₂) and circles (Krause *et al.*, 2016: LOC 8.0-11.0 vol.% O₂) indicate published LOC values for methane

and starch diluted with nitrogen, respectively. The variations in the published results reflect the use of explosion vessels with different volume, different ignition sources, etc.

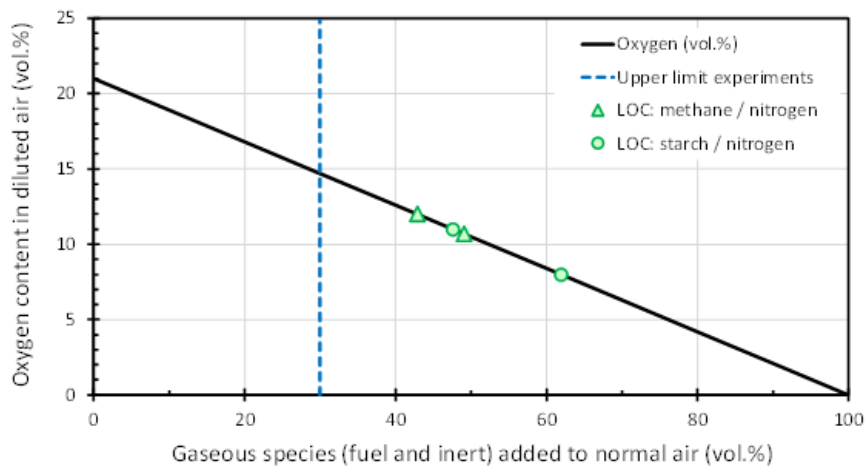


Figure 3.9: Oxygen content in diluted air and represented LOC values for methane and starch.

An inherent limitation for the experiments was the cost of the chemical igniters, and the fact that the spark/ark generator at the dust explosion laboratory was not operational during the project period. This limited the number of repetitions, as well as the number and range of parameters that could be investigated.

The following sections outline the experimental procedure for the various types of tests. Chapter 4 includes tables that summarise the results from each test.

3.2.3. Test procedure for dust explosions

The general procedure for tests with combustible dust entailed:

- Installing the chemical igniter and evacuating the vessel to 0.40 bar absolute.
- Adding the desired amount of dust to the reservoir and pressurising the reservoir to 21 bar absolute.
- Starting the test sequence in the KSEP 6 software. This implied that the dust is injected into the vessel, the ignition source is activated 60 ms after the onset of injection, and the pressure is measured and recorded.
- After each test, the vessel depressurised, opened and cleaned.

The corrected explosion pressure P_m and the rate of pressure rise $(dp/dt)_m$ were determined for a range of nominal dust concentrations: 125, 250, 500, 750 and 1000 g/m³.

3.2.4. Test procedure for gas explosions

The test procedure for gas-air explosions resembles the procedure for dust explosions, but the vessel was evacuated to a lower pressure, e.g. 0.30 bar absolute for a test with 10 vol.% methane, the methane was admitted to reach an initial pressure of 0.40 bar absolute, and the test was initiated as described above. The fact that air was injected into the vessel in the same way as for dust explosions implies that it is not possible to determine K_G values from the results. The corrected explosion pressure P_m and the rate of pressure rise $(dp/dt)_m$ were determined for a range of methane concentrations: 5.0, 7.5, 10.0, 12.5 and 15.0 vol.%.

3.2.5. Test procedure for hybrid explosions

The test procedure for hybrid explosions was similar to the procedure described for dust explosions, except that gaseous fuel was added to the vessel in the same way as for gas-air explosions described above. The corrected explosion pressure P_m and the rate of pressure rise $(dp/dt)_m$ were determined for three sets of nominal dust concentrations and methane concentrations: (125 g/m³ and 7.5 vol.%), (250 g/m³ and 5.0 vol.%), (375 g/m³ and 2.5 vol.%).

3.2.6. Test procedure for tests involving inert gases

For tests with inert gases, either nitrogen (N₂) or carbon dioxide (CO₂), the test procedure was similar as described for tests with dust-air, methane-air or hybrid mixtures above, but the vessel was evacuated to a sufficiently low pressure to allow for the admission of either 10 or 20 vol.% inert gas, in addition to methane for tests with gaseous fuel.

3.2.7. Test procedure for tests involving solid suppressant

For tests with inert dust, the required amount of sodium bicarbonate (NaHCO₃) was added to the dust reservoir, in the same way as for combustible dust described above.

4 Experimental results

This chapter summarises the experimental results.

4.1. Dust explosions

This section summarises the results from tests with maize starch dispersed in air, with or without inert gases or inert dust.

4.1.1. Maize dust explosions in air

Table 4.1 and Figure 4.1 summarise the results from the tests with maize starch dispersed in air.

4.1.2. Influence of nitrogen on dust explosions

Tables 4.2-4.4 and Figures 4.2-4.4 summarise the results from tests with maize dust dispersed in air diluted with 10 or 20 vol.% nitrogen.

4.1.3. Influence of carbon dioxide on dust explosions

Tables 4.5-4.7 and Figures 4.5-4.7 summarise the results from tests with maize dust dispersed in air diluted with 10 or 20 vol.% carbon dioxide.

4.1.4. Influence of sodium bicarbonate on dust explosions

Tables 4.8-4.10 and Figures 4.8-4.10 summarise the results from tests with maize dust and sodium bicarbonate (NaHCO_3) dispersed in air.

Table 4.1: Summary of results for maize dust dispersed in air.

Maize dust with air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Dust concentration(g/m ³)	Series I	Series II	Average	Series I	Series II	Average
1 kJ	125	2.6	0.2	1.4	24	10	17
1 kJ	250	5.0	5.6	5.3	124	205	165
1 kJ	500	7.9	7.4	7.7	469	345	407
1 kJ	750	8.4	8.6	8.5	536	534	535
1 kJ	1000	8.4	8.4	8.4	531	454	493

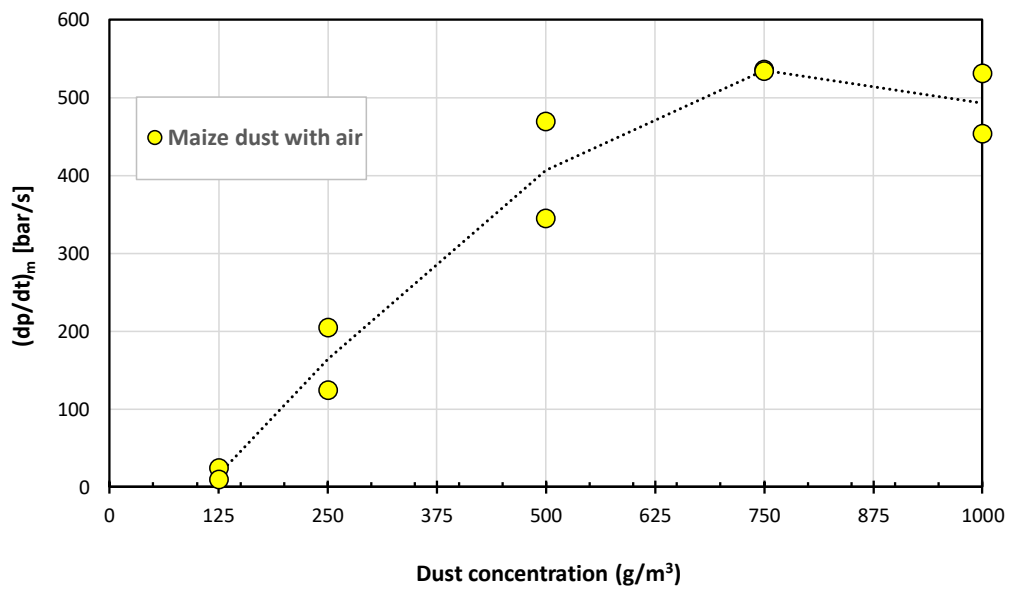
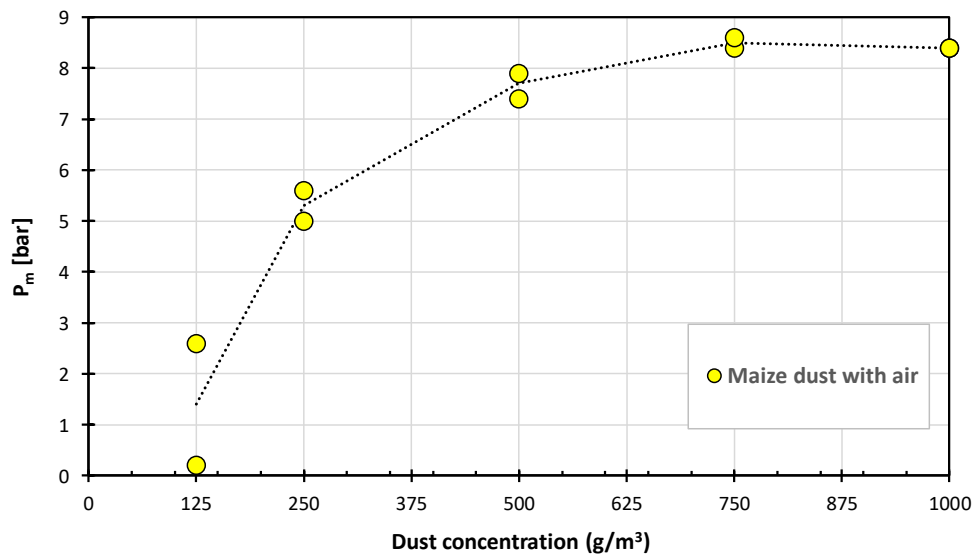


Figure 4.1: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for maize dust dispersed in air. The dotted line represents the average value of the two series.

Table 4.2: Summary of results for maize dust dispersed in air diluted by 10 vol.% nitrogen, including average values for the two series.

Maize dust with 10 vol.% N ₂ in air		<i>P_m</i> [bar]			<i>(dp/dt)_m</i> [bar/s]		
IE	Dust concentration (g/m ³)	Series I	Series II	Average	Series I	Series II	Average
1 kJ	125	1.5	1.5	1.5	11	15	13
1 kJ	250	6.4	5.7	6.1	244	173	209
1 kJ	500	7.8	7.5	7.7	380	368	374
1 kJ	750	7.4	7.5	7.5	346	327	337
1 kJ	1000	7.2	7.1	7.2	291	328	310

Table 4.3: Summary of results for maize dust dispersed in air diluted by 20 vol.% nitrogen, including average values for the two series.

Maize dust with 20 vol.% N ₂ in air		<i>P_m</i> [bar]			<i>(dp/dt)_m</i> [bar/s]		
IE	Dust concentration (g/m ³)	Series I	Series II	Average	Series I	Series II	Average
1 kJ	125	0.2	0.1	0.2	8	12	10
1 kJ	250	5.3	4.7	5.0	121	69	95
1 kJ	500	7.2	7.0	7.1	305	246	276
1 kJ	750	7.2	7.1	7.2	309	290	300
1 kJ	1000	6.6	6.1	6.4	238	176	207

Table 4.4: Overall average results for maize dust dispersed in air, including tests with air diluted by 10 and 20 vol.% of nitrogen.

Maize dust with 10 & 20 vol.% N ₂ in air		<i>P_m</i> [bar]			<i>(dp/dt)_m</i> [bar/s]		
IE	Dust concentration (g/m ³)	Dust with air	with 10% N ₂	with 20% N ₂	Dust with air	With 10% N ₂	with 20% N ₂
1 kJ	125	1.4	1.5	0.2	17	13	10
1 kJ	250	5.3	6.1	5.0	165	209	95
1 kJ	500	7.7	7.7	7.1	407	374	276
1 kJ	750	8.5	7.5	7.2	535	337	300
1 kJ	1000	8.4	7.2	6.4	493	310	207

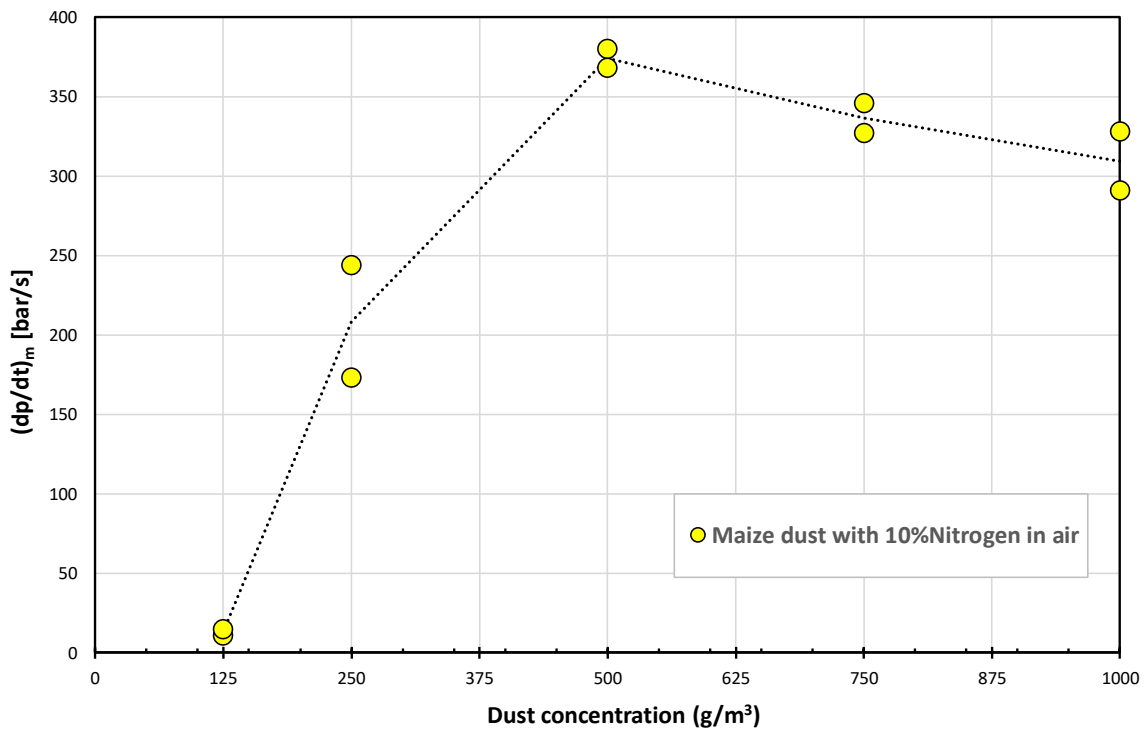
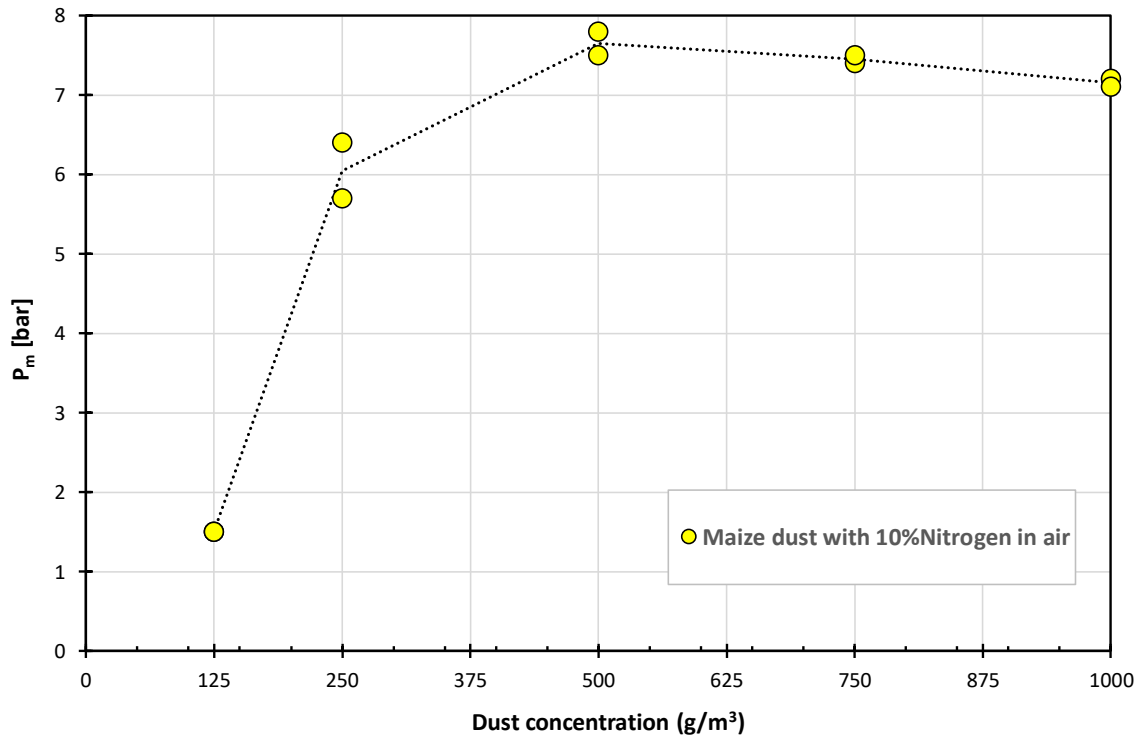


Figure 4.2: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for maize dust dispersed in air diluted by 10 vol.% nitrogen. The dotted line represents the average value of the two series.

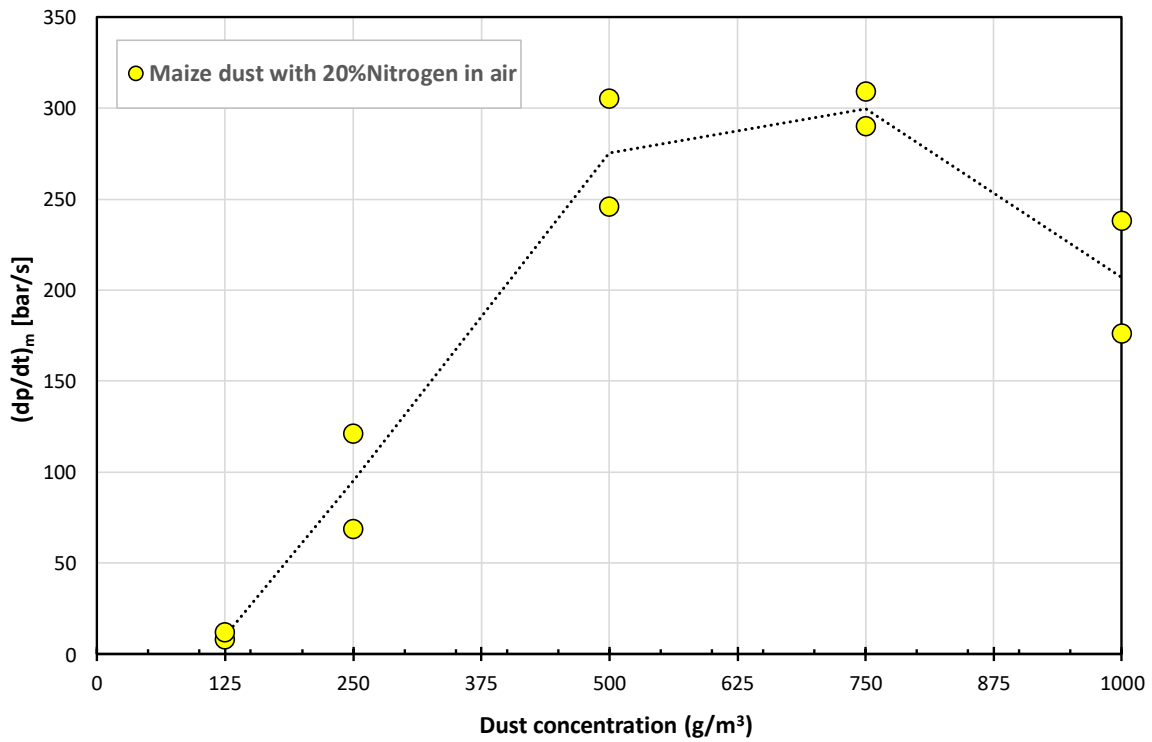
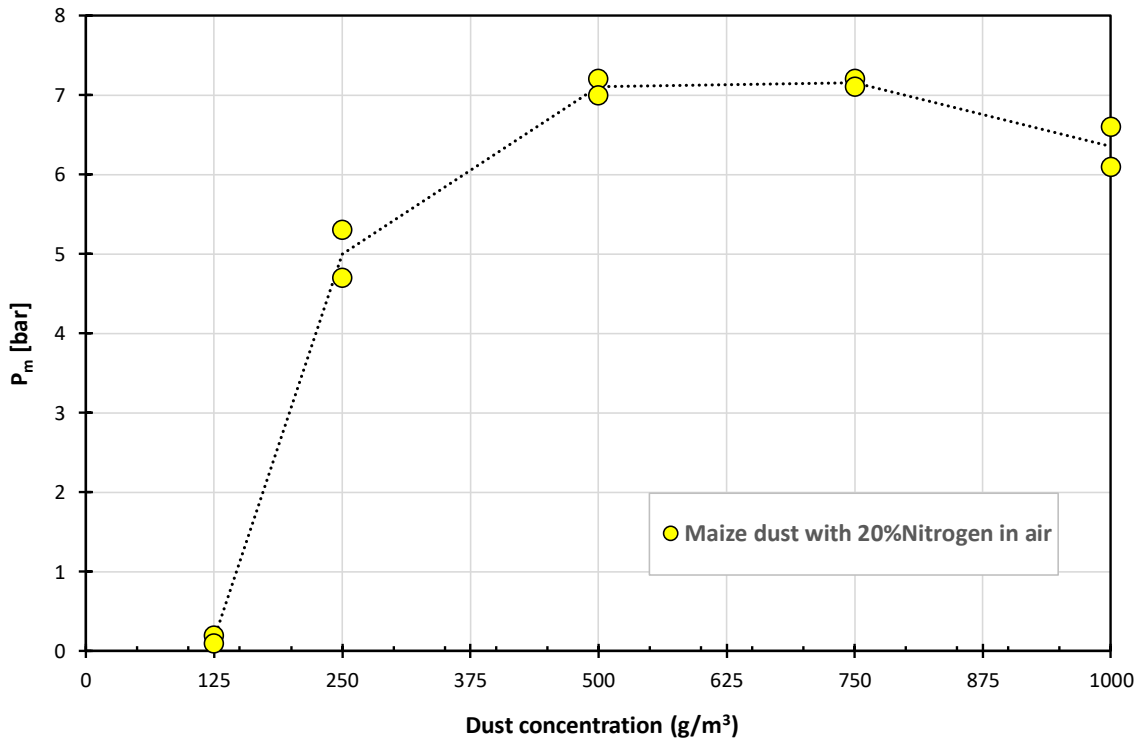


Figure 4.3: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for maize dust dispersed in air diluted by 20 vol.% nitrogen. The dotted line represents the average value of the two series.

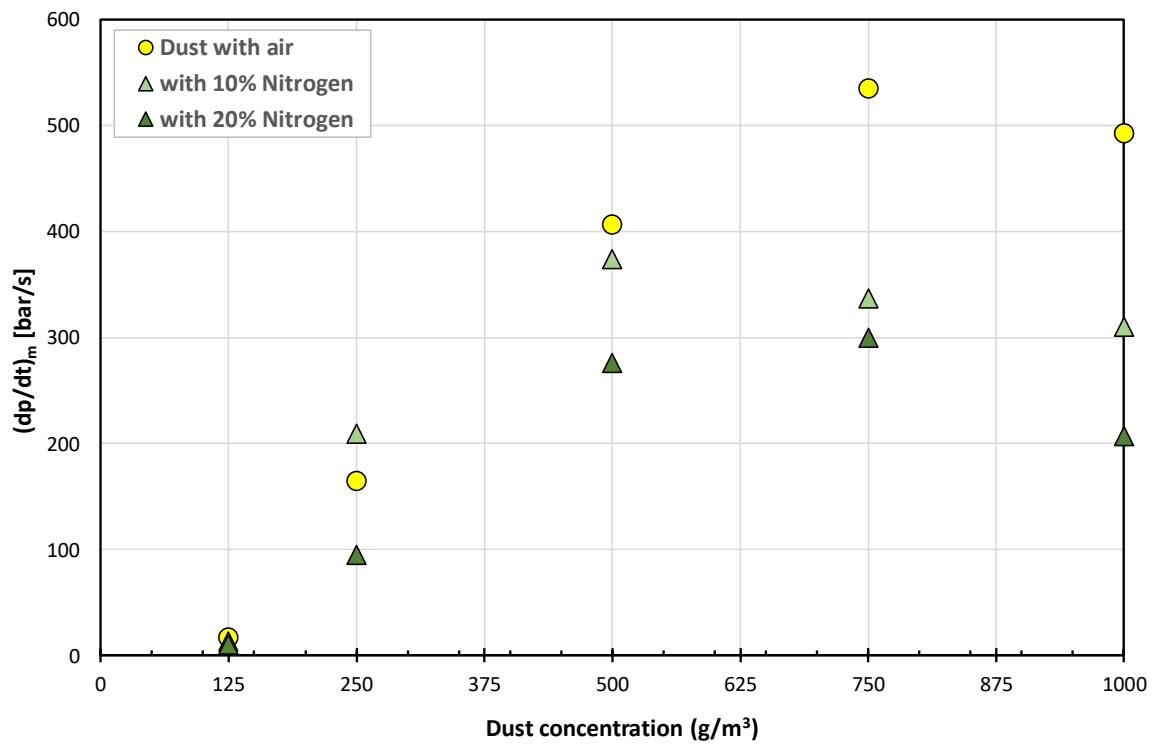
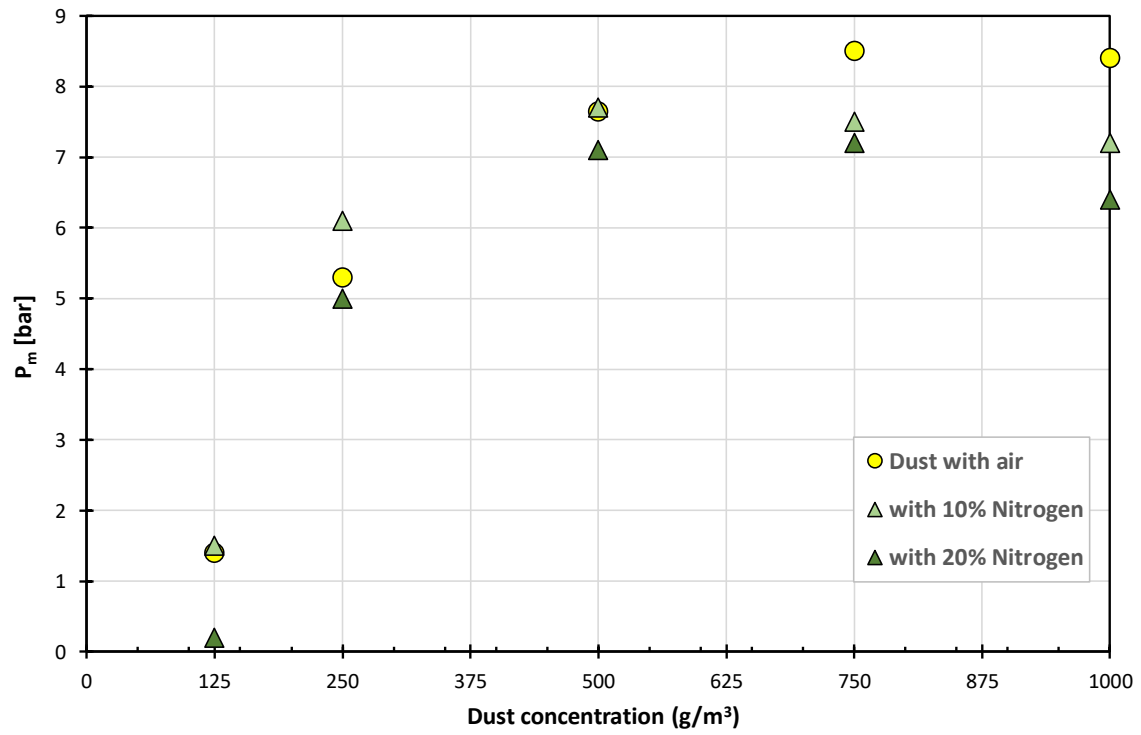


Figure 4.4: Average values for the maximum explosion pressure (above) and maximum rate of pressure rise (below) for maize dust dispersed in air, air diluted by 10 and 20 vol.% nitrogen.

Table 4.5: Summary of results for maize dust dispersed in air diluted by 10 vol.% carbon dioxide, including average values for the two series.

Maize dust with 10 vol.% CO ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Dust concentration (g/m ³)	Series I	Series II	Average	Series I	Series II	Average
1 kJ	125	0.1	0	0.1	0	0	0
1 kJ	250	4.7	4.7	4.7	83	77	80
1 kJ	500	7	6.8	6.9	249	229	239
1 kJ	750	7.2	7.3	7.3	267	293	280
1 kJ	1000	6.8	6.8	6.8	269	205	237

Table 4.6: Summary of results for maize dust dispersed in air diluted by 20 vol.% carbon dioxide, including average values for the two series.

Maize dust with 20 vol.% CO ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Dust concentration (g/m ³)	Series I	Series II	Average	Series I	Series II	Average
1 kJ	125	0	0	0	0	0	0
1 kJ	250	3.3	3.7	3.5	27	33	30
1 kJ	500	5.8	6	5.9	106	136	121
1 kJ	750	6.2	6.3	6.3	143	180	162
1 kJ	1000	5.7	5.8	5.8	110	111	111

Table 4.7: Overall average results for maize dust dispersed in air, including tests with air diluted by 10 and 20 vol.% of carbon dioxide.

Maize dust with 10 & 20 vol.% CO ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Dust concentration (g/m ³)	Dust with air	with 10% CO ₂	with 20% CO ₂	Dust with air	with 10% CO ₂	with 20% CO ₂
1 kJ	125	1.4	0.1	0	17	0	0
1 kJ	250	5.3	4.7	3.5	165	80	30
1 kJ	500	7.7	6.9	5.9	407	239	121
1 kJ	750	8.5	7.3	6.3	535	280	162
1 kJ	1000	8.4	6.8	5.8	493	237	111

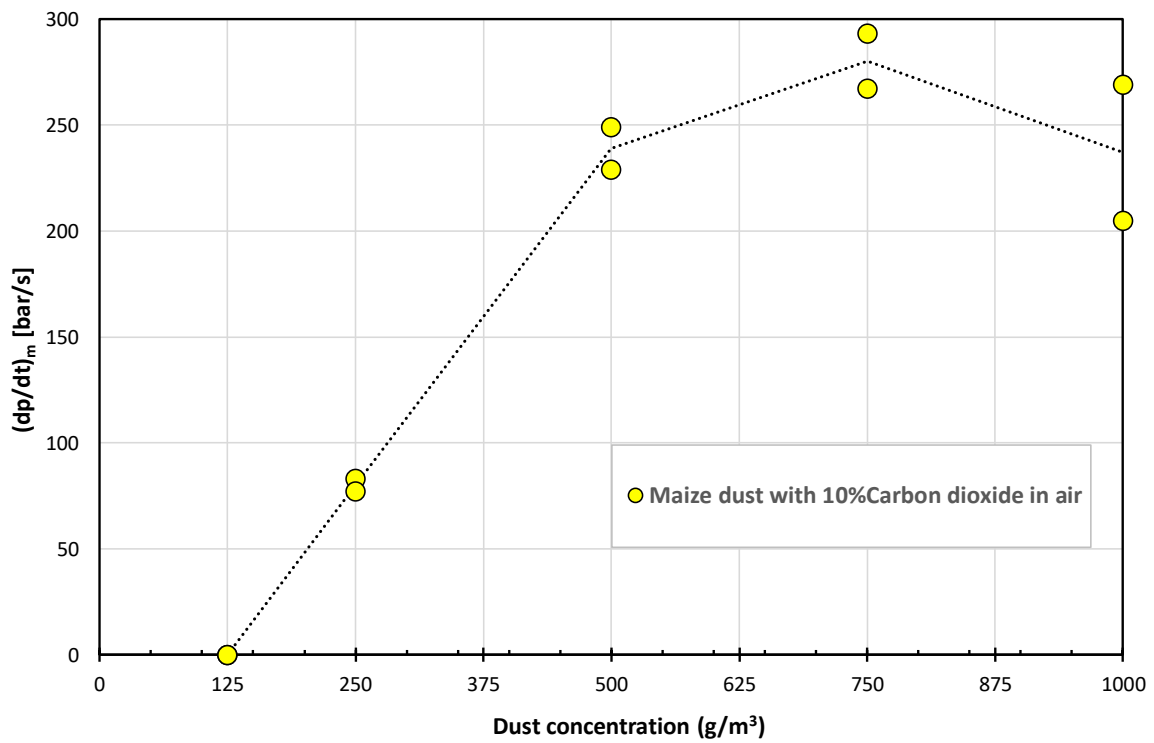
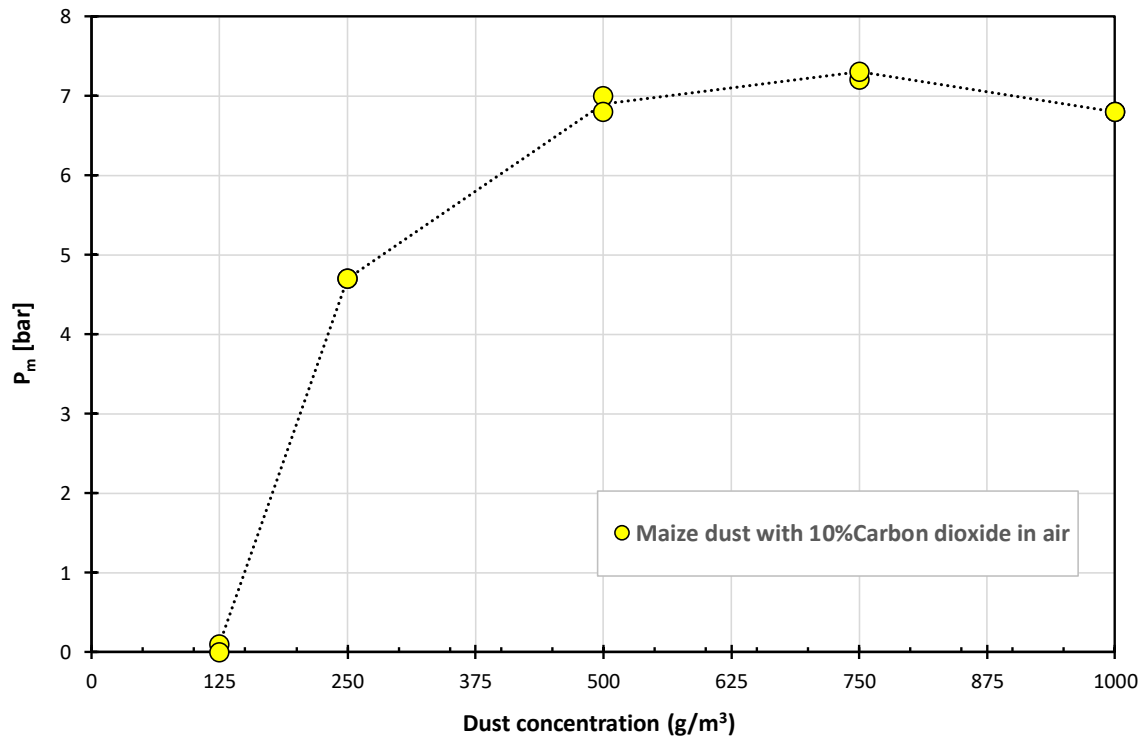


Figure 4.5: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for maize dust dispersed in air diluted by 10 vol.% carbon dioxide. The dotted line represents the average value of the two series.

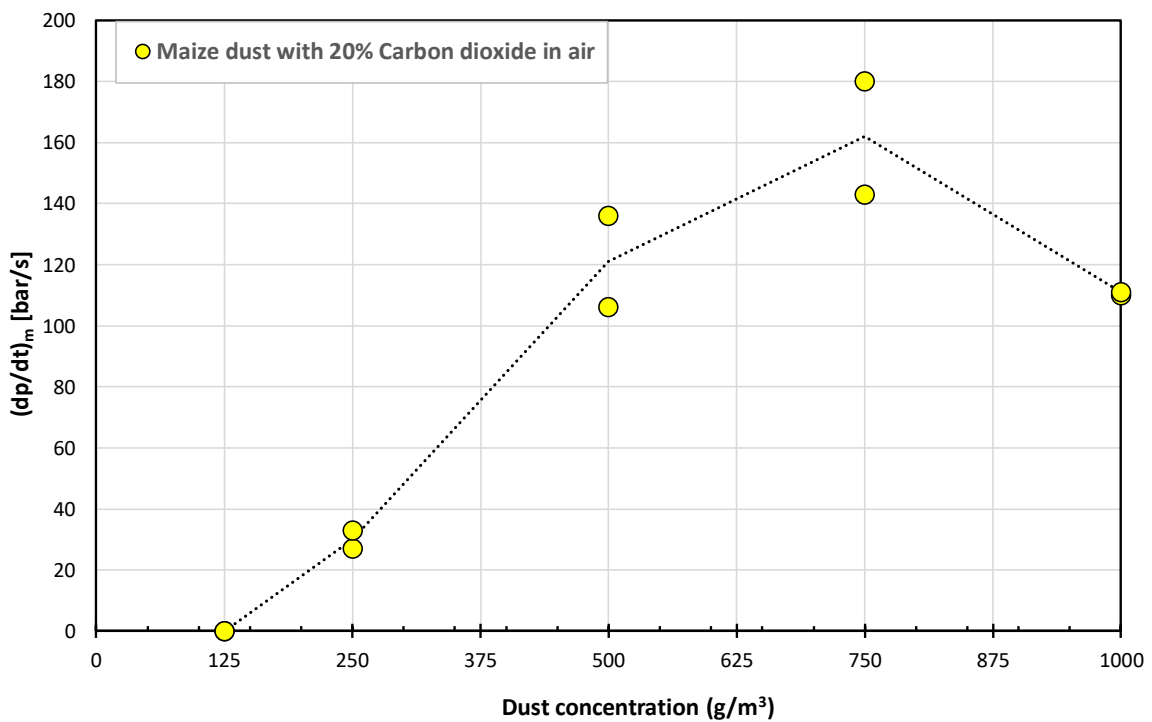
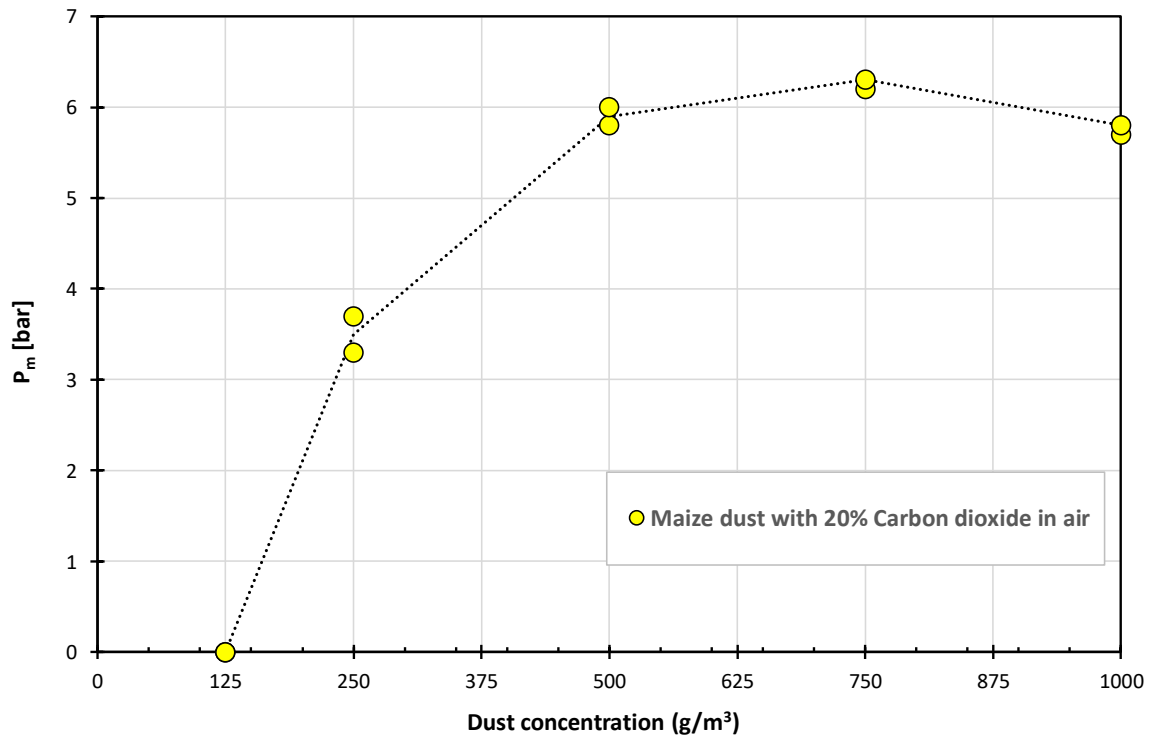


Figure 4.6: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for maize dust dispersed in air diluted by 20 vol.% carbon dioxide. The dotted line represents the average value of the two series.

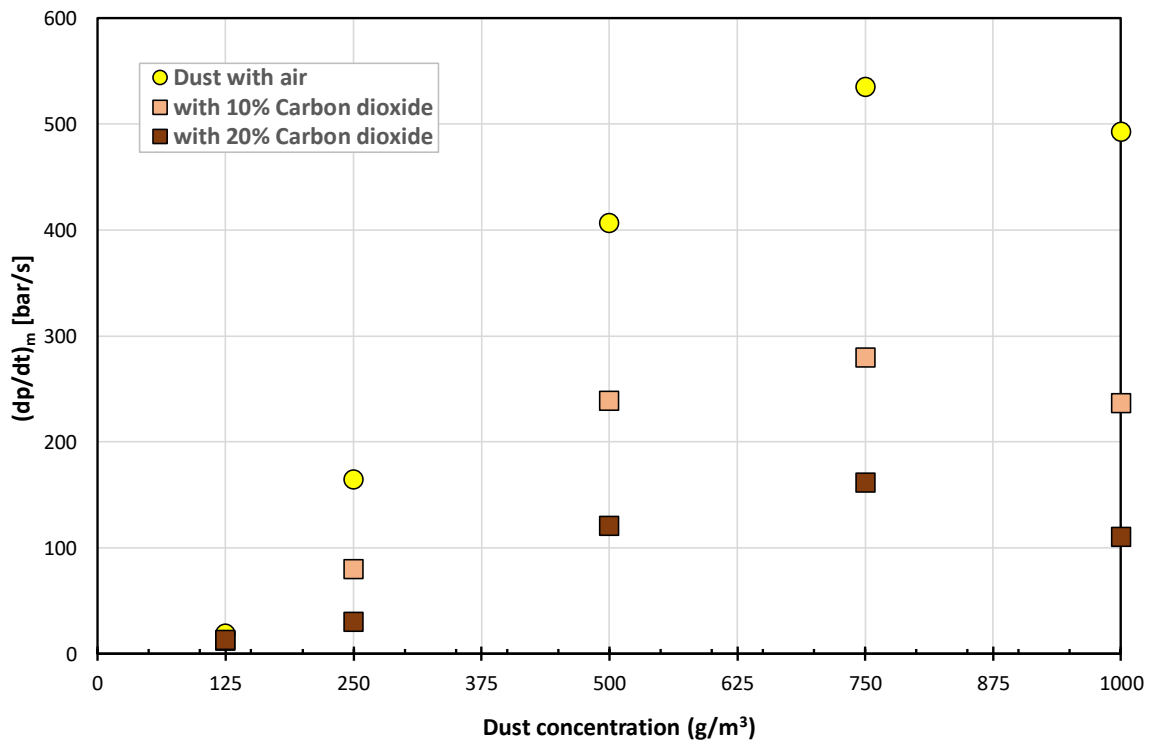
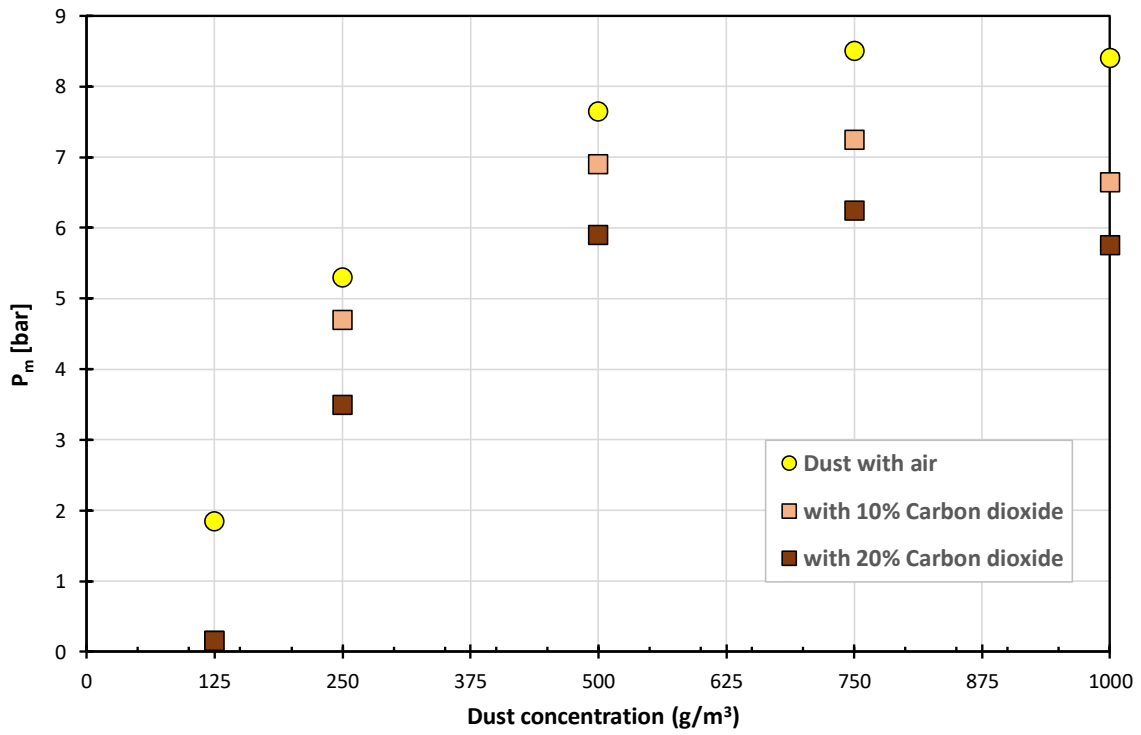


Figure 4.7: Average values for the maximum explosion pressure (above) and maximum rate of pressure rise (below) for maize dust dispersed in air, air diluted by 10 and 20 vol.% carbon dioxide.

Table 4.8: Summary of results for 500 g/m³ of maize dust and various amounts of sodium bicarbonate dispersed in air.

NaHCO ₃ with 500 g/m ³ maize dust & air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	NaHCO ₃ concentration (g/m ³)	Series I	Series II	Average	Series I	Series II	Average
1 kJ	0	7.9	7.4	7.7	469	345	407
1 kJ	50	8.4	8.0	8.2	230	206	218
1 kJ	100	7.9	-	7.9	182	-	182
1 kJ	125	7.9	6.8	7.4	184	106	145
1 kJ	250	7.2	6.4	6.8	146	89	118
1 kJ	375	5.3	6.3	5.8	57	85	71
1 kJ	500	5.9	4.2	5.1	67	24	46
1 kJ	625	5.5	4.6	5.1	33	31	32
1 kJ	750	0.3	0.3	0.3	8	13	11

Table 4.9: Summary of results for various amounts of maize dust and 125 g/m³ sodium bicarbonate dispersed in air.

Maize dust & air with 125 g/m ³ NaHCO ₃		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Dust concentration (g/m ³)	Series I	Series II	Average	Series I	Series II	Average
1 kJ	125	0	0	0	0	0	0
1 kJ	250	3.0	0.2	1.6	16	11	14
1 kJ	375	6.2	6.2	6.2	78	105	92
1 kJ	500	7.9	6.8	7.4	184	106	145
1 kJ	625	7.8	7.7	7.8	146	155	151
1 kJ	750	7.7	7.7	7.7	155	162	159

Table 4.10: Overall average results for various amounts of maize dust and 125 g/m³ of sodium bicarbonate dispersed in air.

Maize dust & air with 125 g/m ³ NaHCO ₃		P_m [bar]		$(dp/dt)_m$ [bar/s]	
IE	Dust concentration(g/m ³)	Dust with air	with NaHCO ₃	Dust with air	with NaHCO ₃
1 kJ	125	1.4	0	17	0
1 kJ	250	5.3	1.6	165	14
1 kJ	375	7.4	6.2	242	92
1 kJ	500	7.7	7.4	407	145
1 kJ	625	8.6	7.8	521	151
1 kJ	750	8.5	7.7	535	159

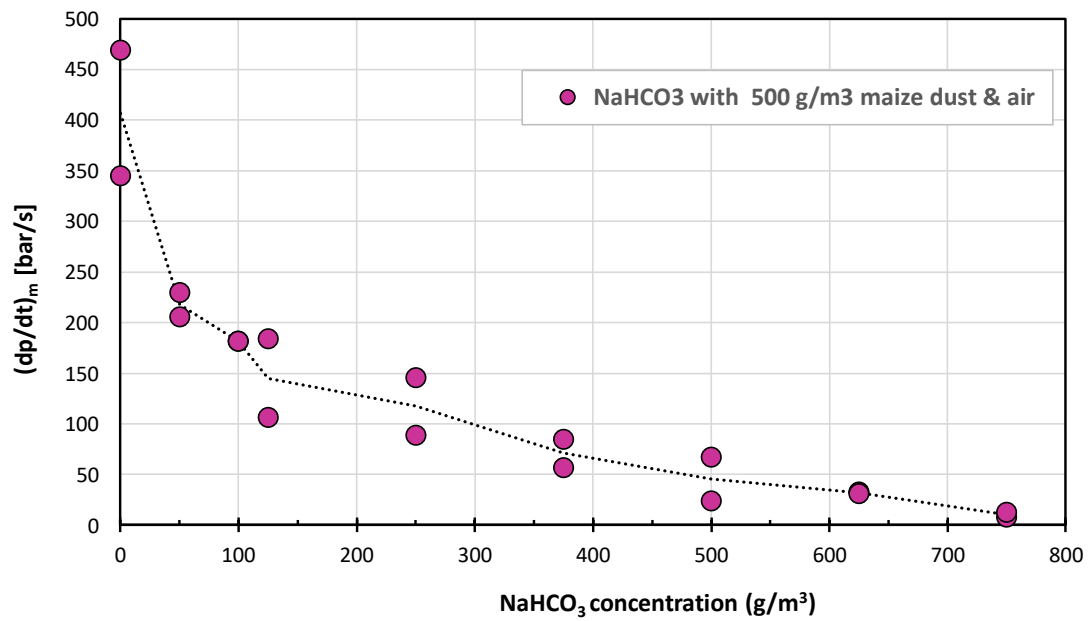
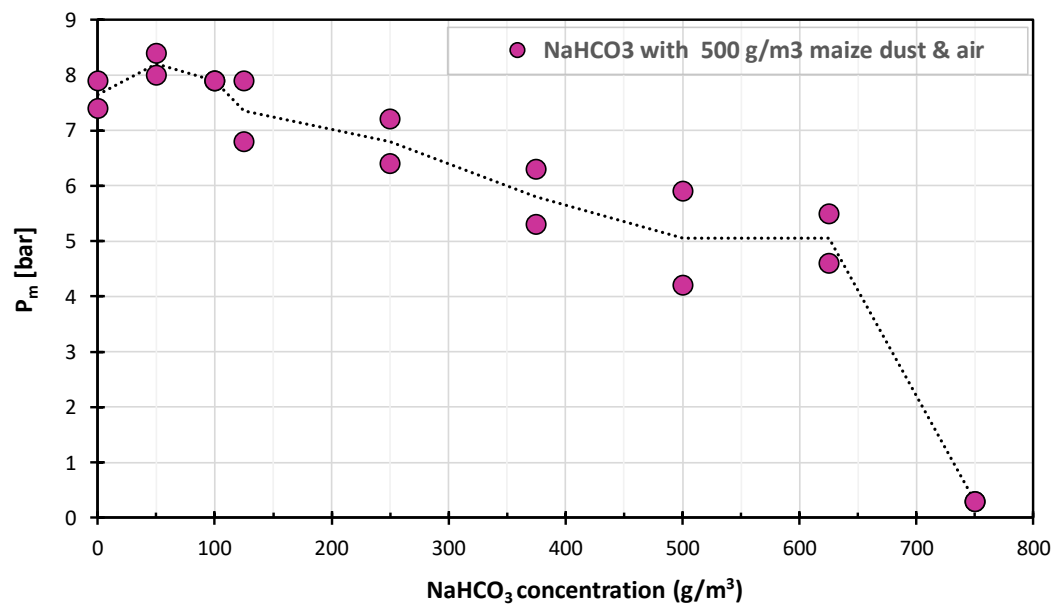


Figure 4.8: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for 500 g/m³ of maize dust and various amounts of sodium bicarbonate dispersed in air. The dotted line represents the average value of the two series.

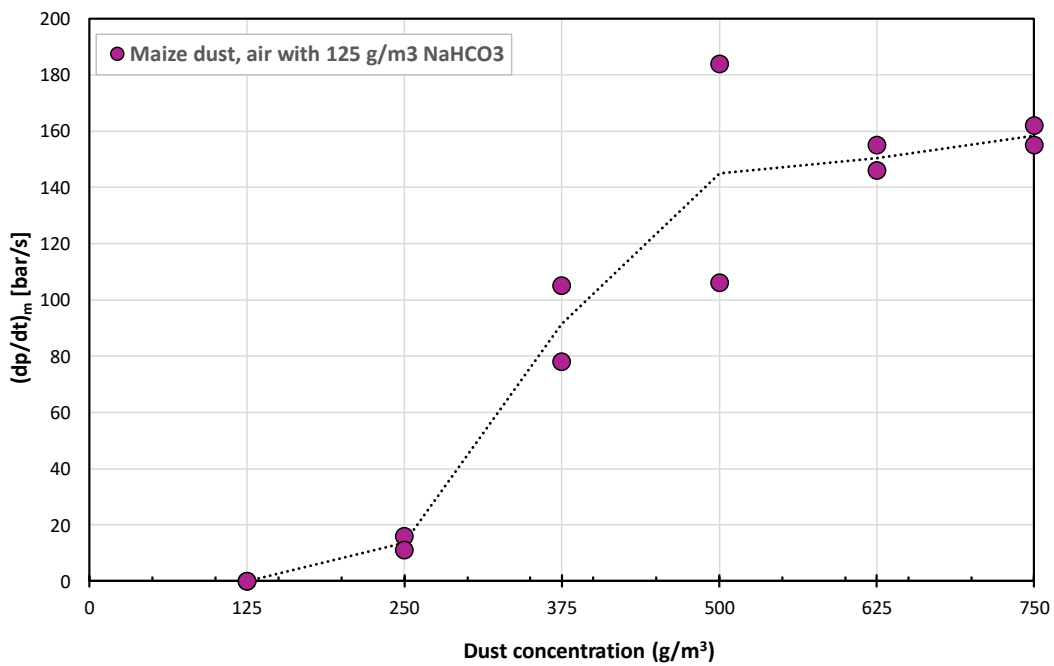
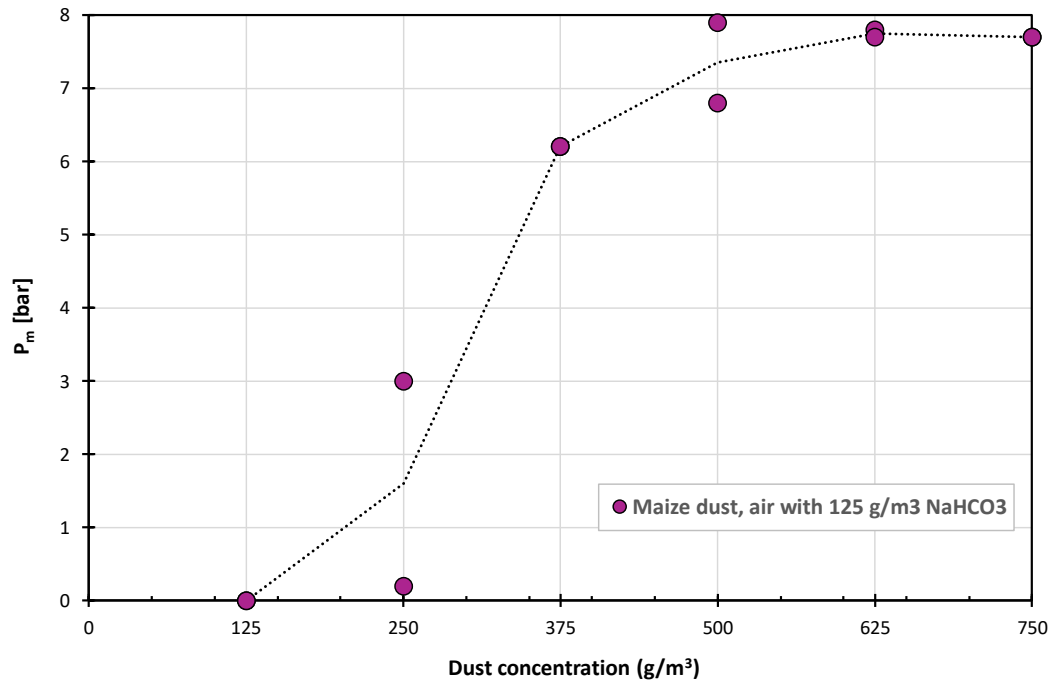


Figure 4.9: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for various amounts of maize dust with 125 g/m³ of sodium bicarbonate dispersed in air. The dotted line represents the average value of the two series.

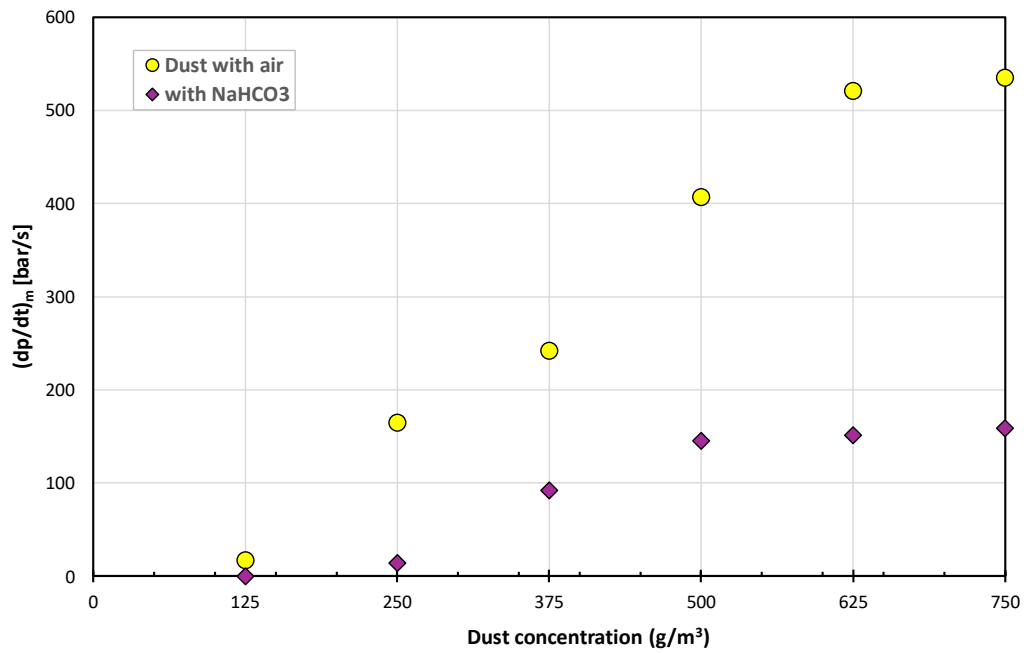
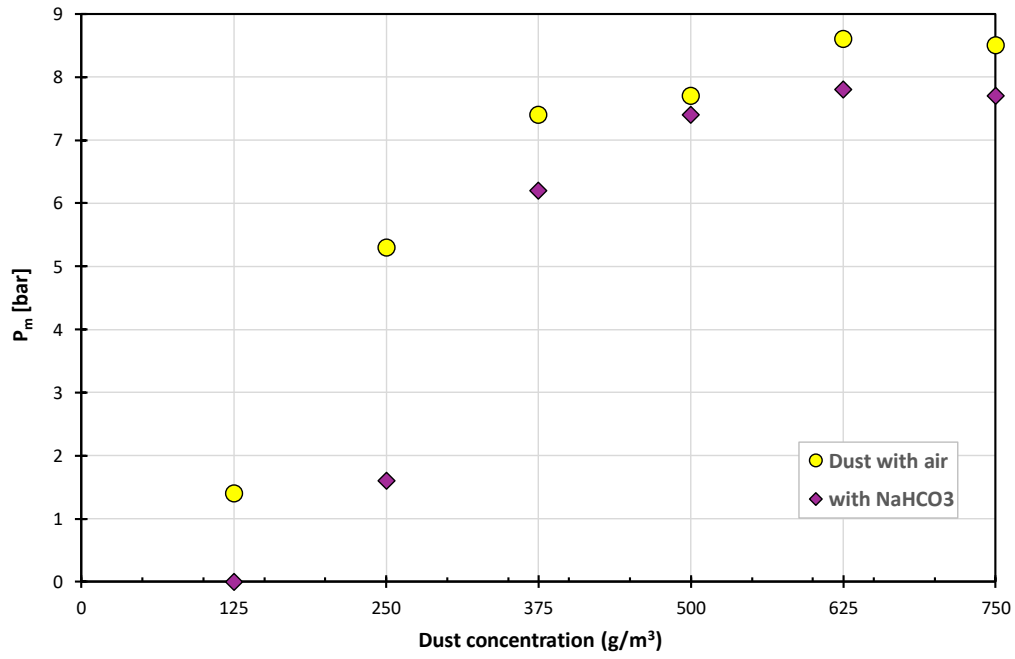


Figure 4.10: Average values for the maximum explosion pressure (above) and maximum rate of pressure rise (below) for various amounts of maize dust and 125 g/m³ of sodium bicarbonate dispersed in air.

4.2. Gas explosions

This section summarises the results from tests with methane-air mixtures, with or without inert gases or inert dust.

4.2.1. Methane explosions in air

Table 4.11 and Figure 4.11 summarise the results from the tests with methane dispersed in air.

4.2.2. Influence of nitrogen on gas explosions

Tables 4.12-4.14 and Figures 4.12-4.14 summarise the results from tests with methane-air mixtures diluted with 10 or 20 vol.% nitrogen.

4.2.3. Influence of carbon dioxide on gas explosions

Tables 4.15-4.17 and Figures 4.15-4.17 summarise the results from tests with methane-air mixtures diluted with 10 or 20 vol.% carbon dioxide.

4.2.4. Influence of sodium bicarbonate on gas explosions

Tables 4.18-4.20 and Figures 4.18-4.20 summarise the results from tests with methane-air mixtures and dispersed sodium bicarbonate (NaHCO₃).

Table 4.11: Summary of results for methane gas dispersed in air.

Methane with air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Series I	Series II	Average	Series I	Series II	Average
1 kJ	2.5	0	-	0	0	-	0
1 kJ	5	4.7	4.6	4.7	96	115	106
1 kJ	7.5	6.8	6.8	6.8	873	672	773
1 kJ	10	8.3	8.2	8.3	1393	1201	1297
1 kJ	12.5	7.9	7.6	7.8	720	509	615
1 kJ	15	7.0	6.7	6.9	279	166	223

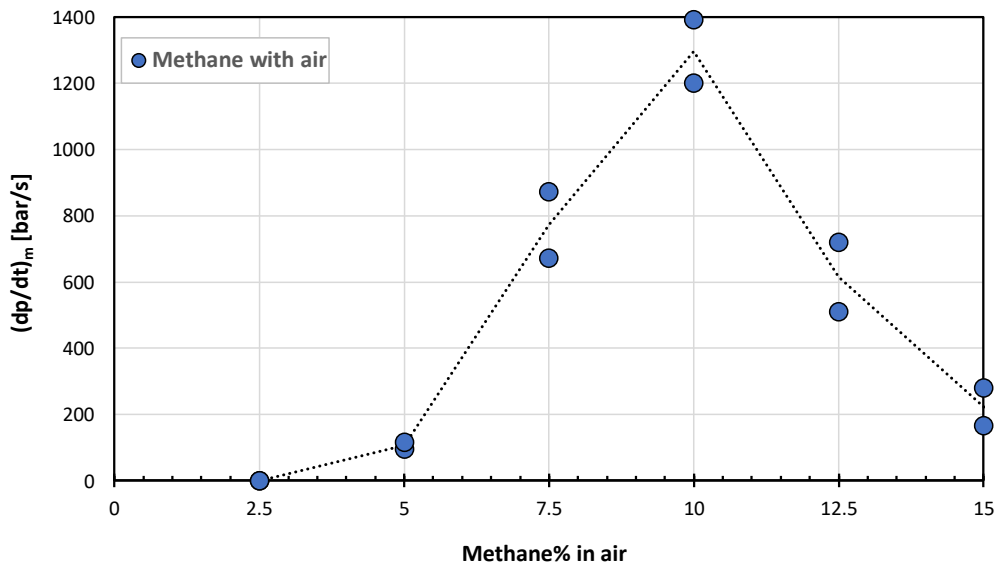
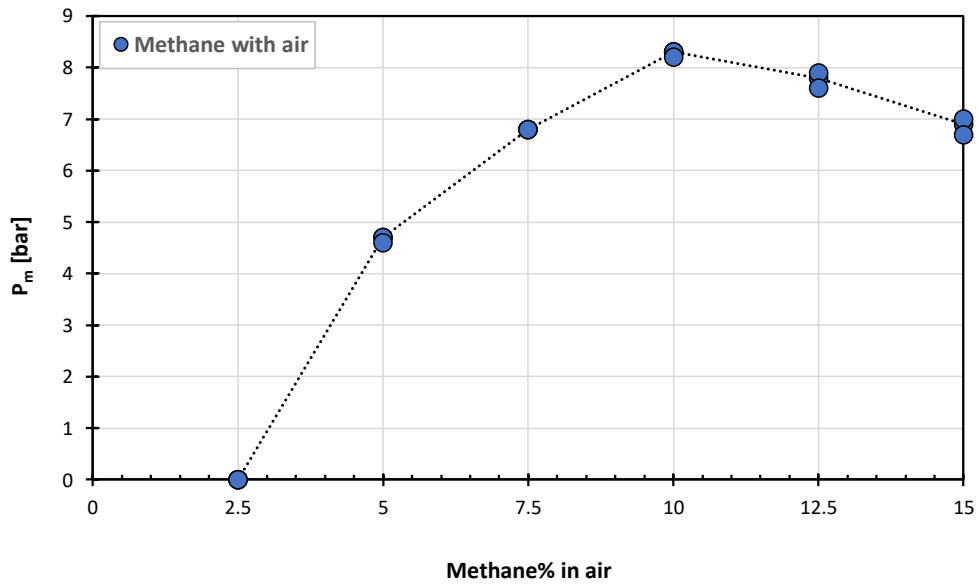


Figure 4.11: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for methane dispersed in air. The dotted line represents the average value of the two series.

Table 4.12: Summary of results for methane dispersed in air diluted by 10 vol.% nitrogen, including average values for the two series.

Methane with 10 vol.% N ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Series I	Series II	Average	Series I	Series II	Average
1 kJ	5	4.7	0.1	2.4	119	17	68
1 kJ	7.5	7.0	6.9	7.0	718	910	814
1 kJ	10	7.3	7.5	7.4	672	630	651
1 kJ	12.5	5.6	5.3	5.5	83	46	65
1 kJ	15	5.7	0.2	3.0	85	10	48

Table 4.13: Summary of results for methane dispersed in air diluted by 20 vol.% nitrogen, including average values for the two series.

Methane with 20 vol.% N ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Series I	Series II	Average	Series I	Series II	Average
1 kJ	5	0.1	0.2	0.2	15	12	14
1 kJ	7.5	6.8	6.7	6.8	808	593	701
1 kJ	10	5.3	6.0	5.7	42	129	86

Table 4.14: Overall average results for methane dispersed in air, including tests with air diluted by 10 and 20 vol.% of nitrogen.

Methane with 10 & 20 vol.% N ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Methane with air	with 10% N ₂	With 20% N ₂	Methane with air	with 10% N ₂	with 20% N ₂
1 kJ	5	4.7	2.4	0.2	106	68	14
1 kJ	7.5	6.8	7.0	6.8	773	814	701
1 kJ	10	8.3	7.4	5.7	1297	651	86
1 kJ	12.5	7.8	5.5	-	615	65	-
1 kJ	15	6.9	3.0	-	223	48	-

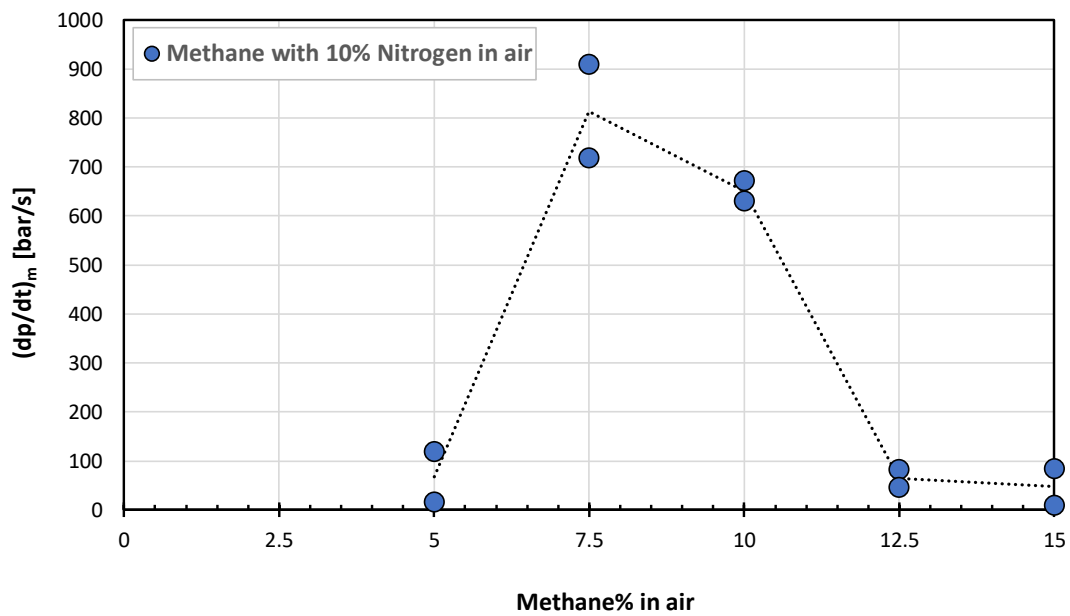
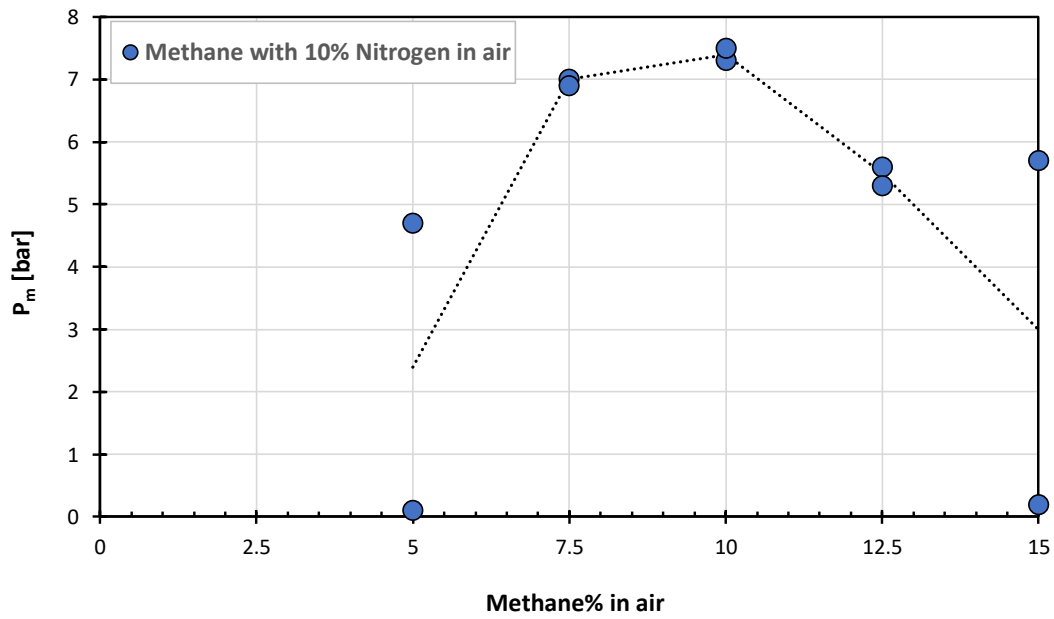


Figure 4.12: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for methane dispersed in air diluted by 10 vol.% nitrogen. The dotted line represents the average value of the two series.

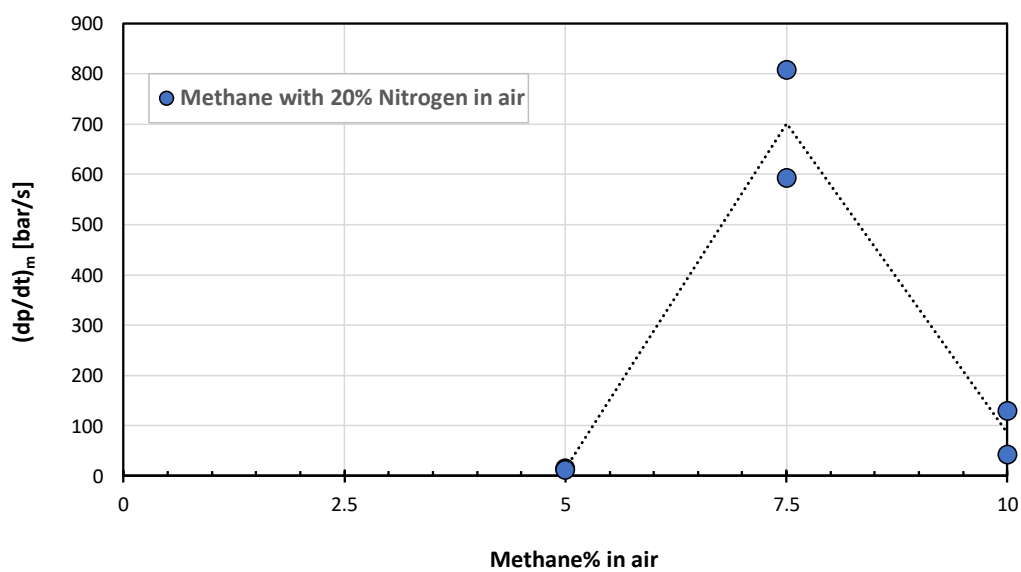
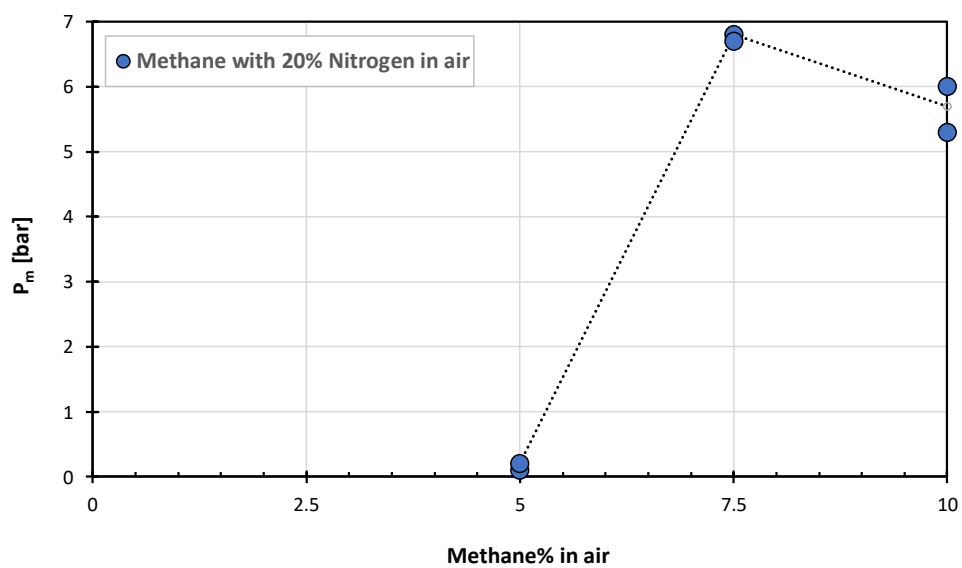


Figure 4.13: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for methane dispersed in air diluted by 20 vol.% nitrogen. The dotted line represents the average value of the two series.

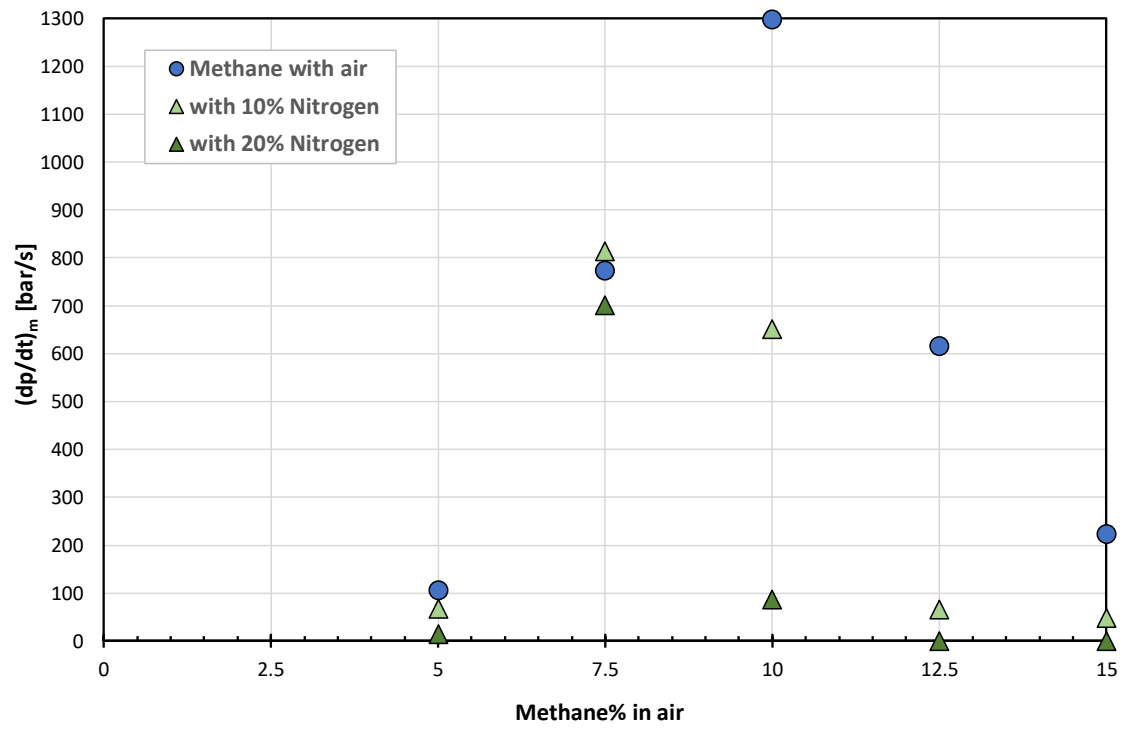
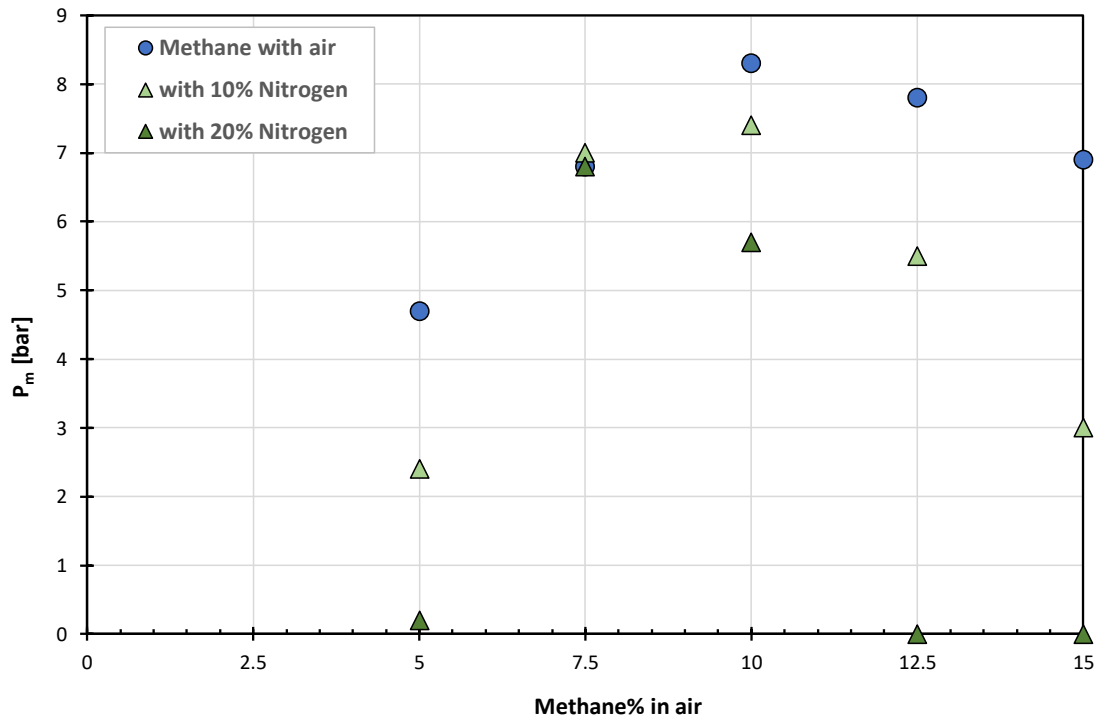


Figure 4.14: Average values for the maximum explosion pressure (above) and maximum rate of pressure rise (below) for methane dispersed in air, air diluted by 10 and 20 vol.% nitrogen.

Table 4.15: Summary of results for methane dispersed in air diluted by 10 vol.% carbon dioxide, including average values for the two series.

Methane with 10 vol.% CO ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Series I	Series II	Average	Series I	Series II	Average
1 kJ	5	0.1	0.4	0.3	9	9	9
1 kJ	7.5	6.7	6.4	6.6	594	598	596
1 kJ	10	6.6	6.7	6.7	429	405	417
1 kJ	12.5	7.2	7.2	7.2	408	520	464
1 kJ	15	6.2	6.4	6.3	96	184	140

Table 4.16: Summary of results for methane dispersed in air diluted by 20 vol.% carbon dioxide, including average values for the two series.

Methane with 20 vol.% CO ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Series I	Series II	Average	Series I	Series II	Average
1 kJ	5	0.1	-	0.1	0	-	0
1 kJ	7.5	5.4	5.1	5.3	134	113	124
1 kJ	10	0.1	0.1	0.1	0	0	0

Table 4.17: Overall average results for methane dispersed in air, including tests with air diluted by 10 and 20 vol.% of carbon dioxide.

Methane with 10 & 20 vol.% CO ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Methane with air	With 10% CO ₂	with 20% CO ₂	Methane with air	with 10% CO ₂	with 20% CO ₂
1 kJ	5	4.7	0.3	0.1	106	9	0
1 kJ	7.5	6.8	6.6	5.3	773	596	124
1 kJ	10	8.3	6.7	0.1	1297	417	0
1 kJ	12.5	7.8	7.2	-	615	464	-
1 kJ	15	6.9	6.3	-	223	140	-

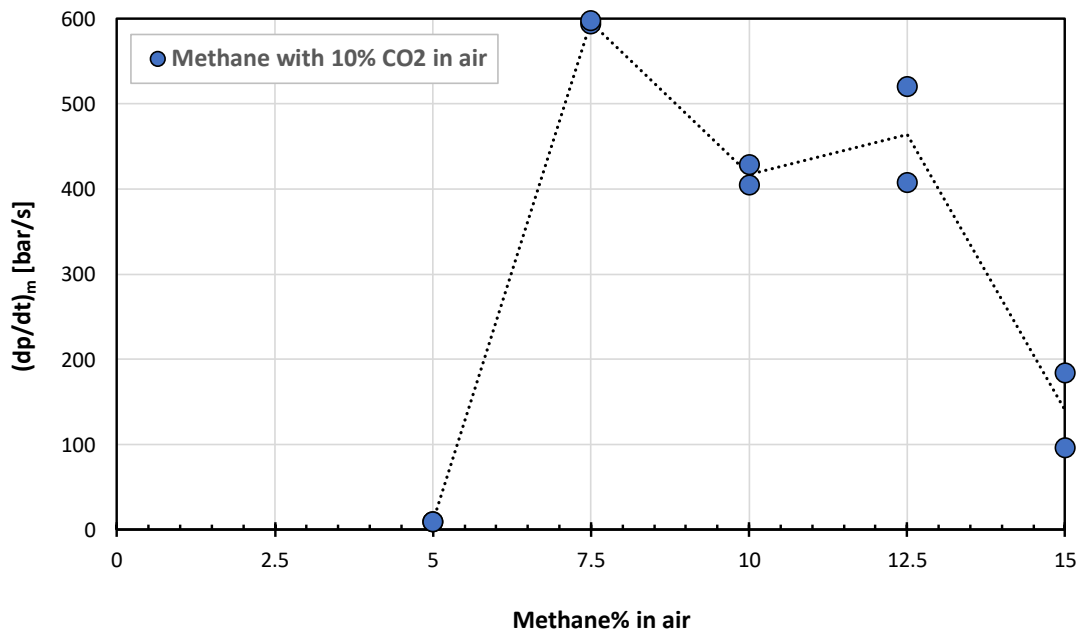
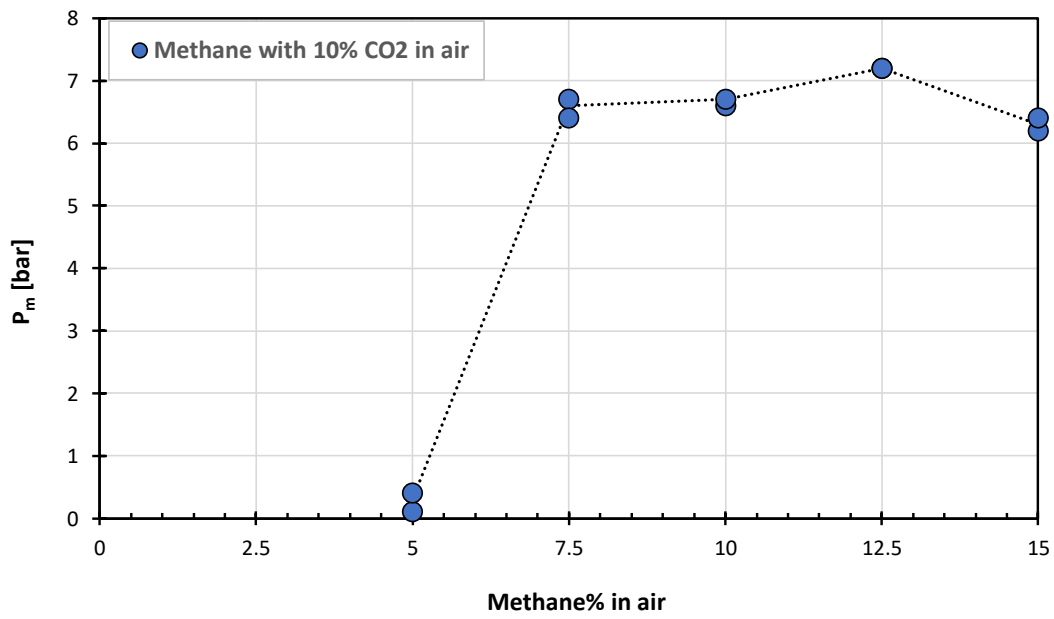


Figure 4.15: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for methane dispersed in air diluted by 10 vol.% carbon dioxide. The dotted line represents the average value of the two series.

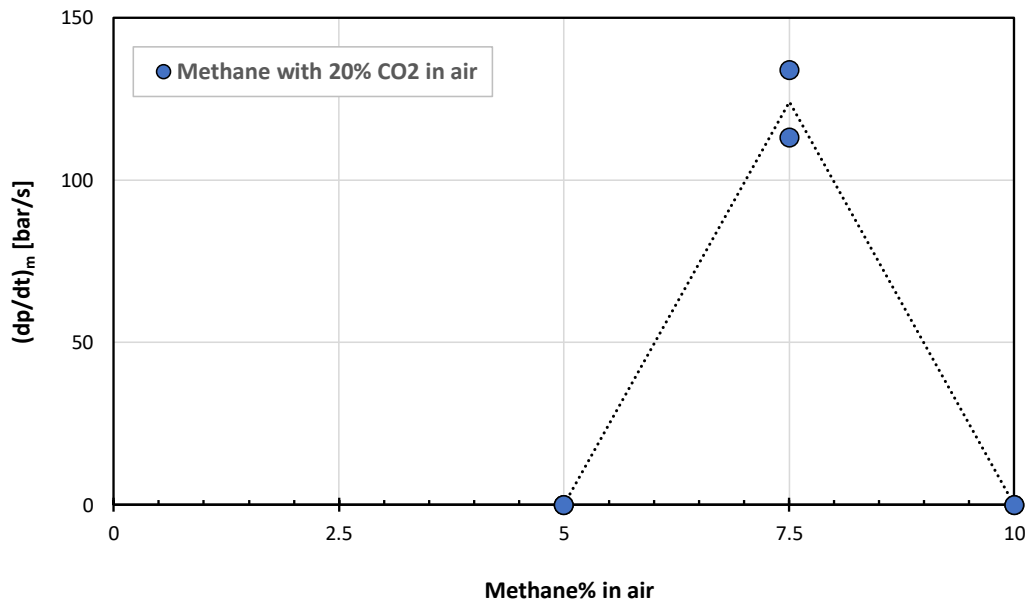
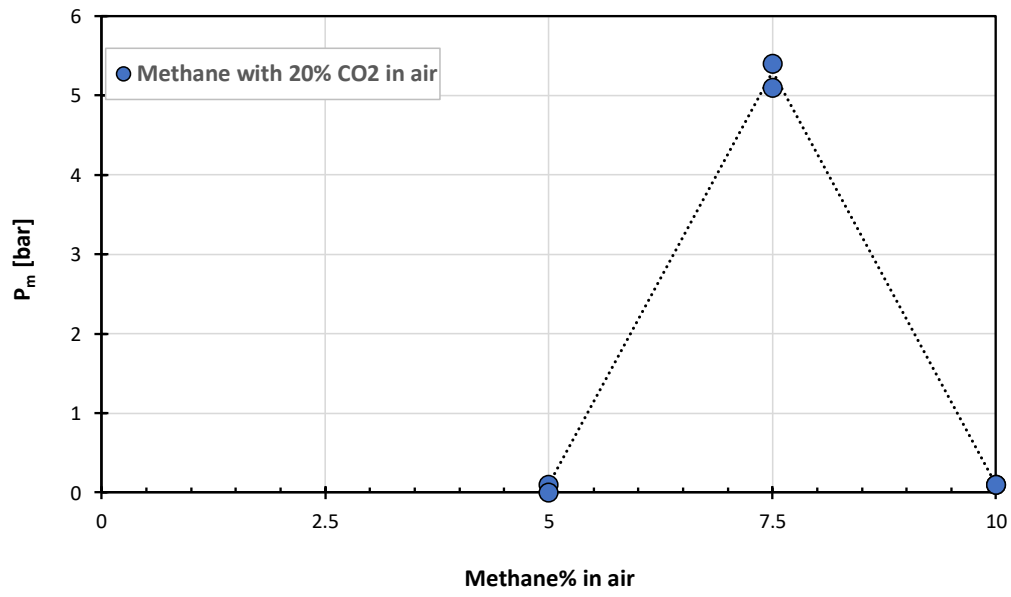


Figure 4.16: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for methane dispersed in air diluted by 20 vol.% carbon dioxide. The dotted line represents the average value of the two series.

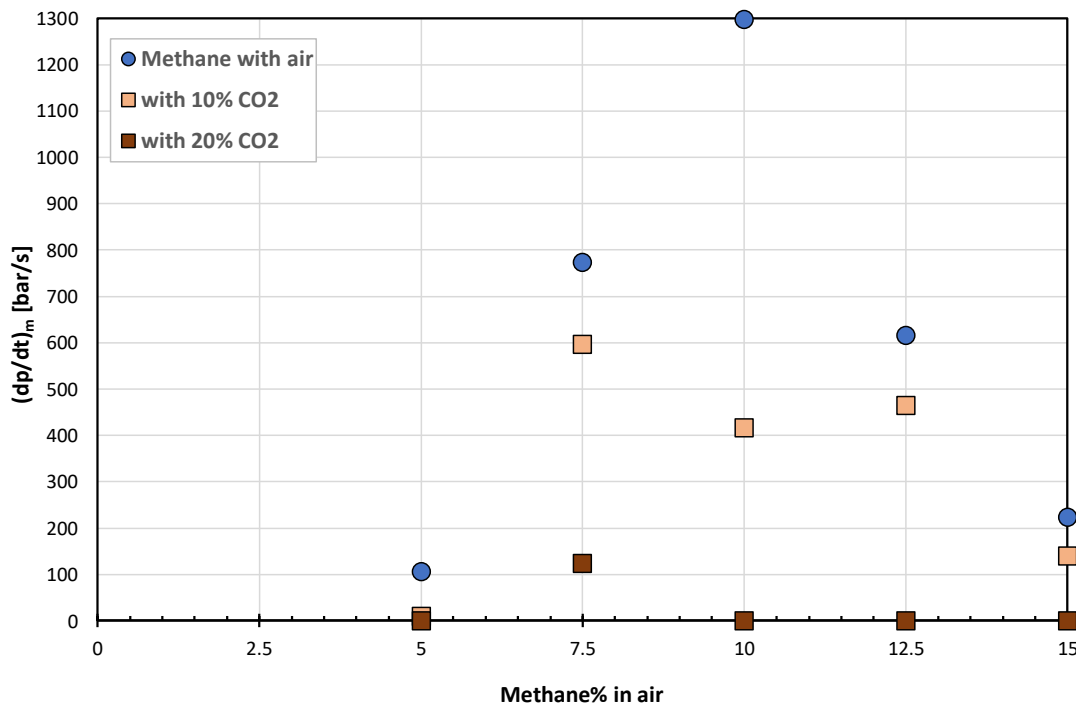
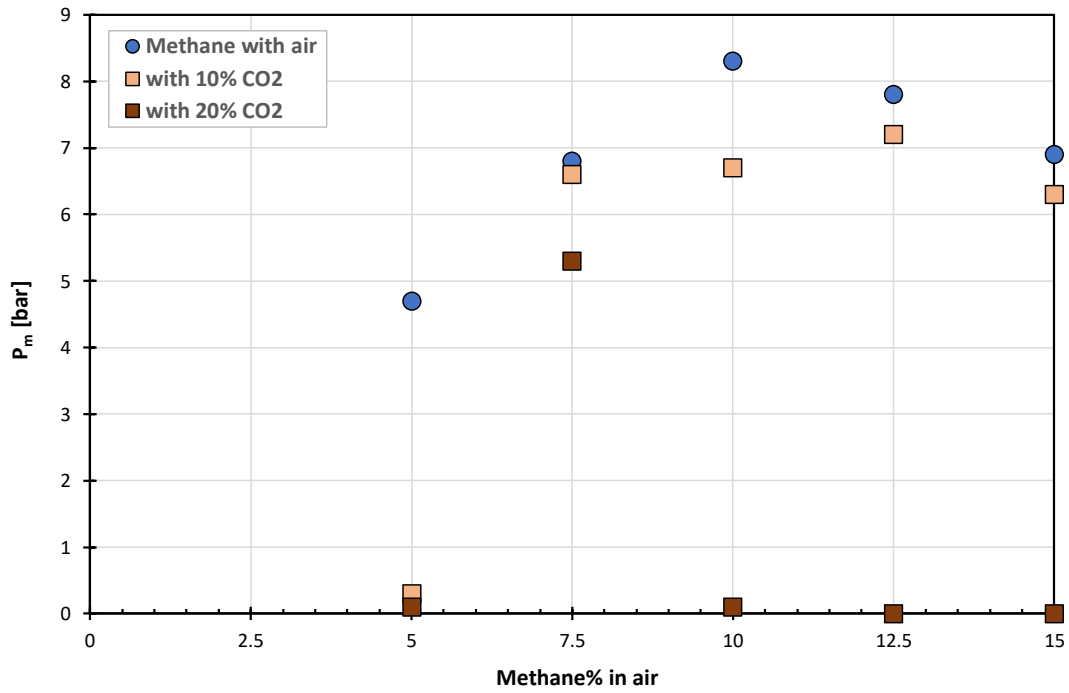


Figure 4.17: Average values for the maximum explosion pressure (above) and maximum rate of pressure rise (below) for methane dispersed in air, air diluted by 10 and 20 vol.% carbon dioxide.

Table 4.18: Summary of results for 10 vol.% of methane and various amounts of sodium bicarbonate dispersed in air.

NaHCO ₃ with 10 vol.% methane in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	NaHCO ₃ concentration (g/m ³)	Series I	Series II	Average	Series I	Series II	Average
1 kJ	0	8.3	8.2	8.3	1393	1201	1297
1 kJ	25	7.6	-	7.6	659	-	659
1 kJ	50	7.4	7.3	7.4	553	416	485
1 kJ	75	7.2	-	7.2	382	-	382
1 kJ	100	7.0	-	7.0	327	-	327
1 kJ	125	7.0	6.9	7.0	264	320	292
1 kJ	250	6.4	6.5	6.5	232	213	223
1 kJ	375	6.1	6.0	6.1	167	156	162
1 kJ	500	5.7	6.1	5.9	89	120	105
1 kJ	625	5.3	5.6	5.5	78	100	89
1 kJ	750	5.1	5.5	5.3	69	107	88
1 kJ	875	0	0.1	0.1	0	0	0
1 kJ	1000	0	-	0	0	-	0

Table 4.19: Summary of results for various amounts of methane with 125 g/m³ of sodium bicarbonate dispersed in air.

Methane with 125 g/m ³ NaHCO ₃		P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Series I	Series II	Average	Series I	Series II	Average
1 kJ	5	0.1	0	0.1	0	0	0
1 kJ	7.5	5.3	5.2	5.3	110	90	100
1 kJ	10	7.0	6.9	7.0	264	320	292
1 kJ	12.5	6.2	6.1	6.2	193	236	215
1 kJ	15	5.7	5.5	5.6	171	150	161

Table 4.20: Overall average results for various amounts of methane and 125 g/m³ of sodium bicarbonate dispersed in air.

Methane, air with 125 g/m ³ NaHCO ₃		P_m [bar]		$(dp/dt)_m$ [bar/s]	
IE	Methane% in air	Methane with air	with 125 g/m ³ NaHCO ₃	Methane with air	with 125 g/m ³ NaHCO ₃
1 kJ	5	4.7	0.1	106	0
1 kJ	7.5	6.8	5.3	773	100
1 kJ	10	8.3	7.0	1297	292
1 kJ	12.5	7.8	6.2	615	193
1 kJ	15	6.9	5.7	223	171

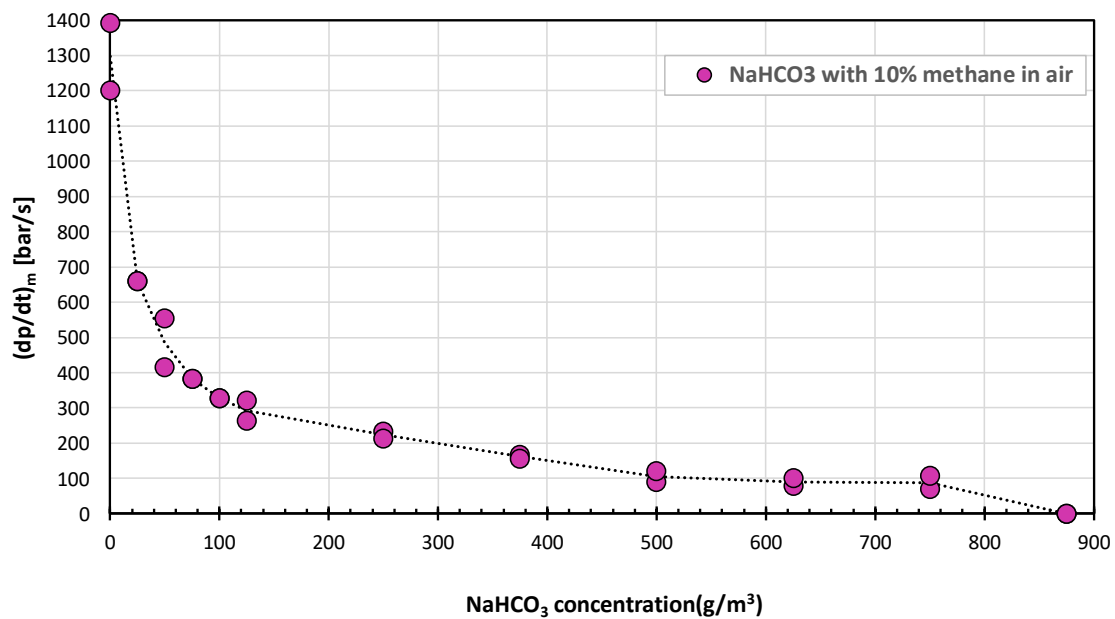
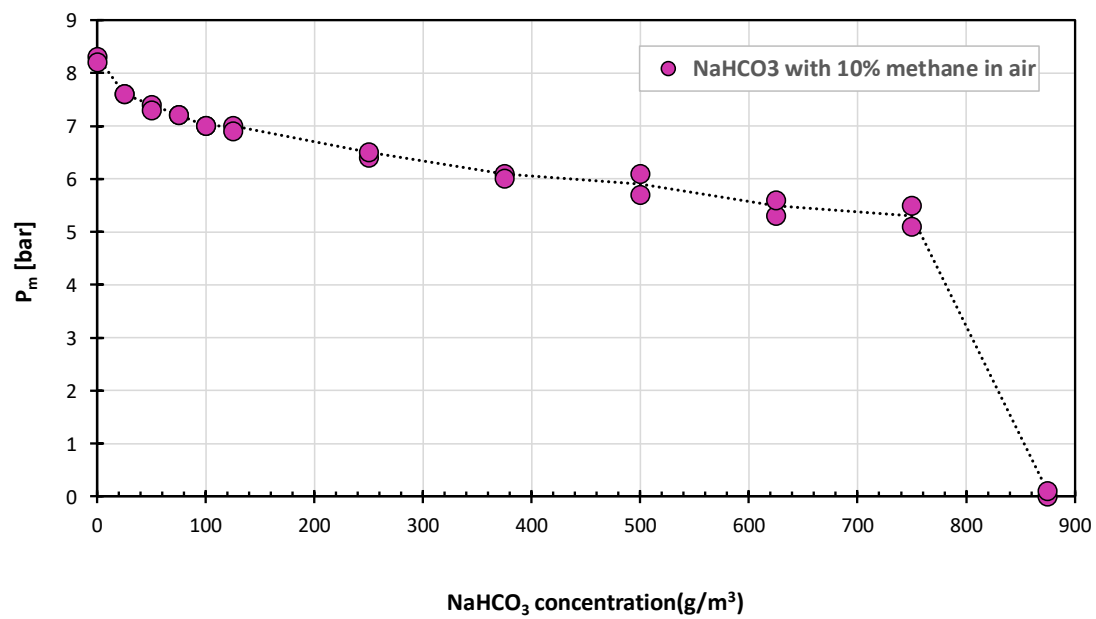


Figure 4.18: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for 10 vol.% of methane and various amounts of sodium bicarbonate dispersed in air. The dotted line represents the average value of the two series.

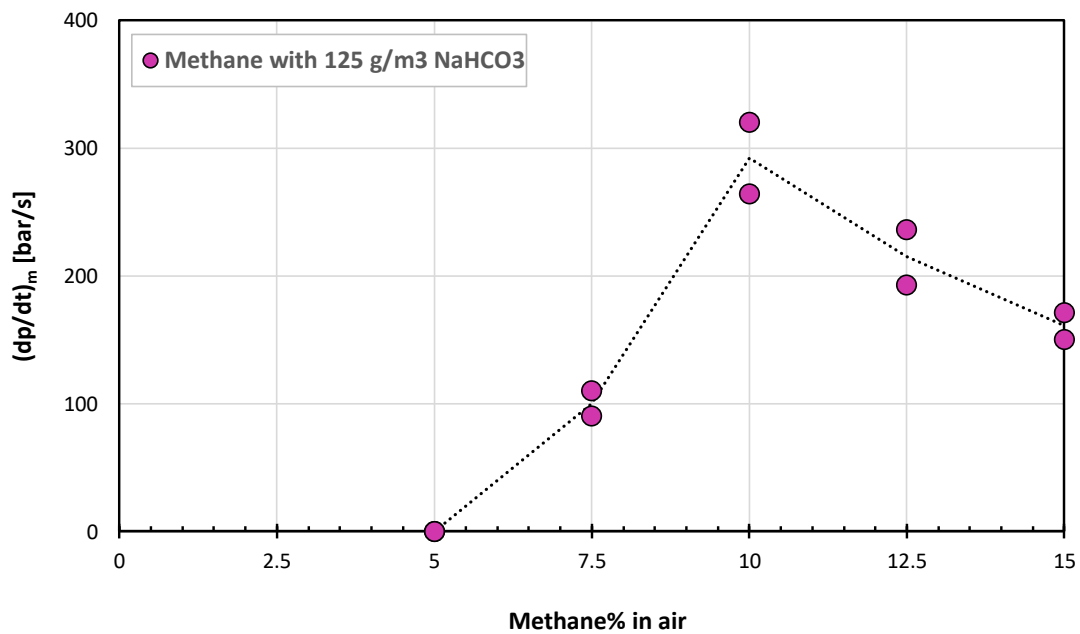
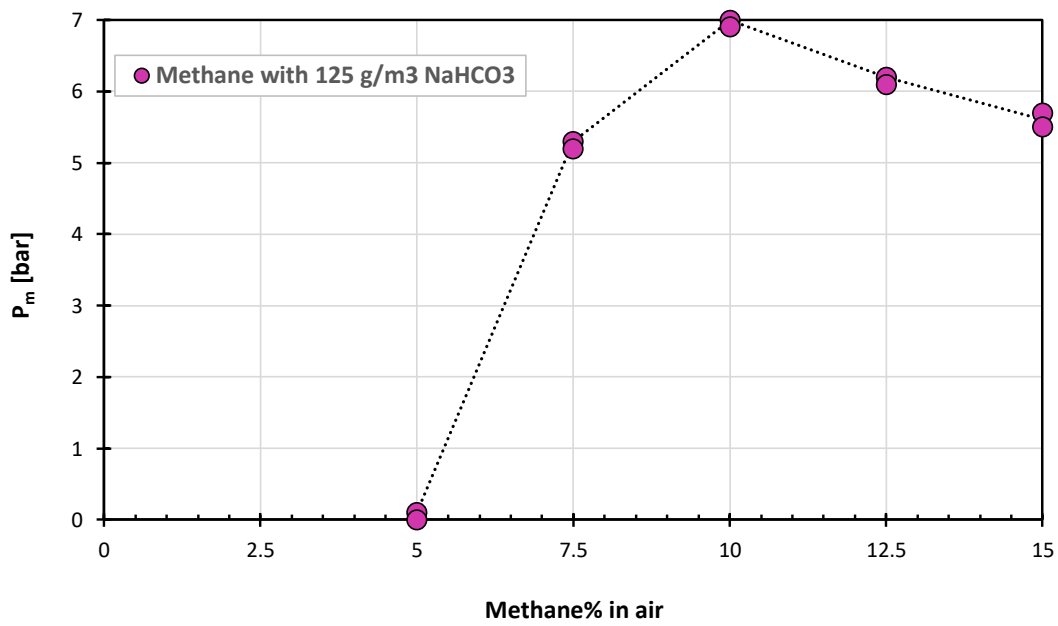


Figure 4.19: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for various amounts of methane with 125 g/m³ of sodium bicarbonate dispersed in air. The dotted line represents the average value of the two series.

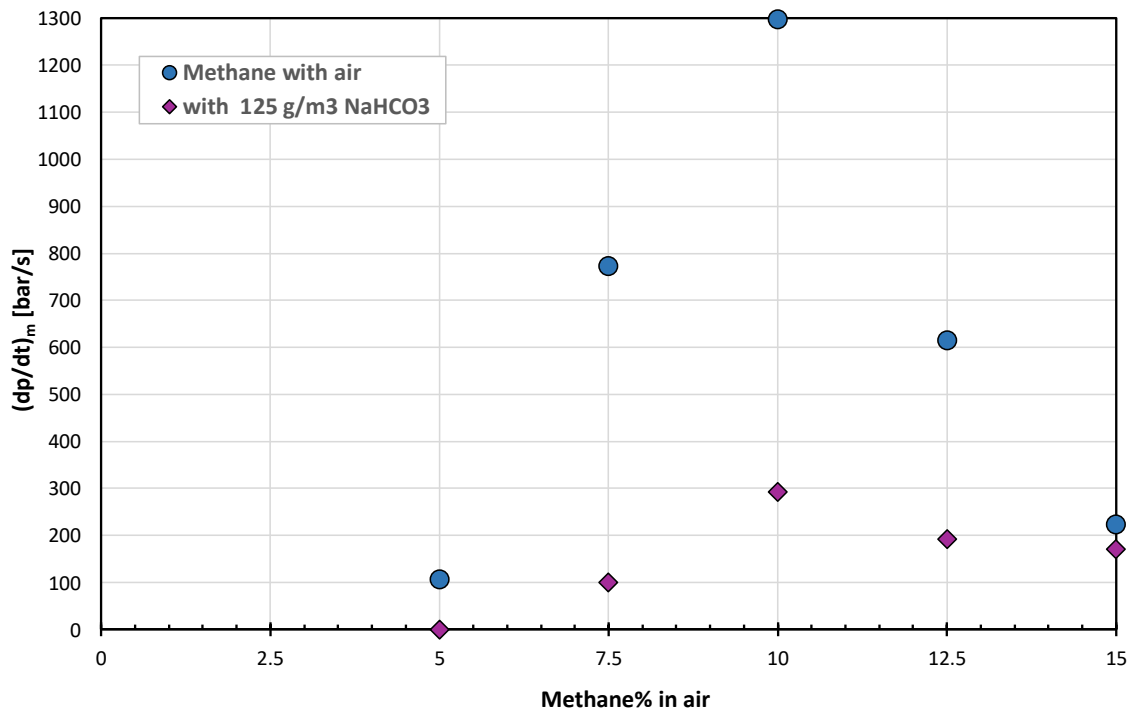
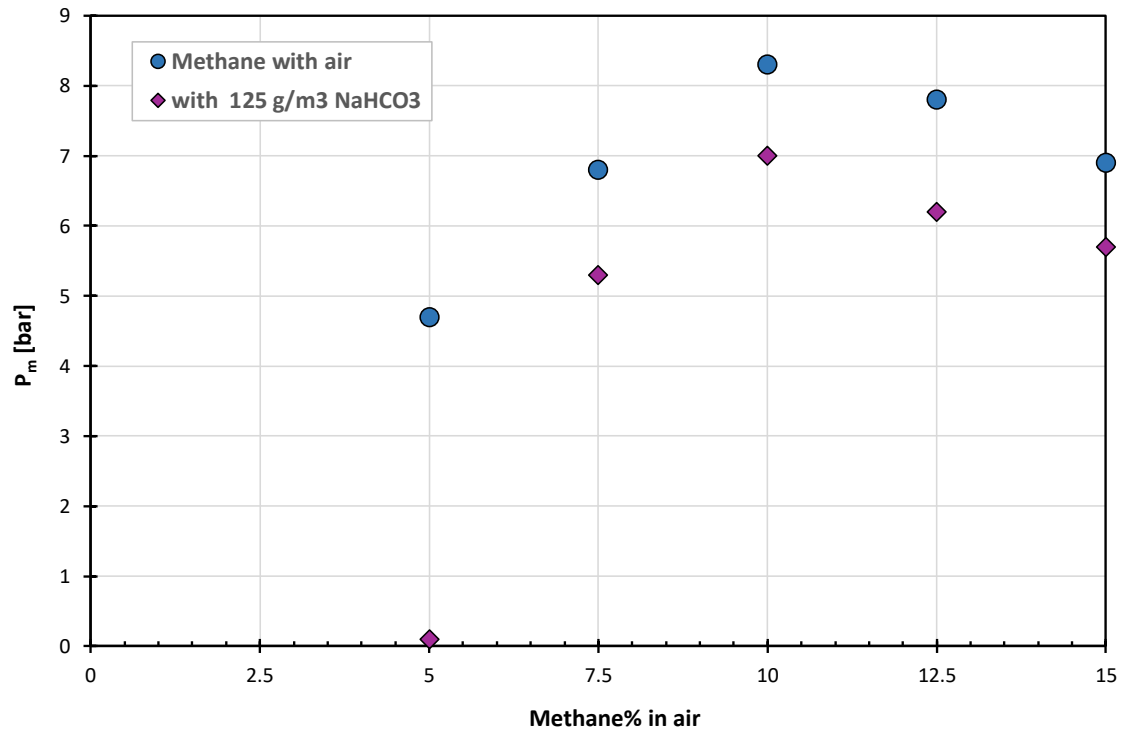


Figure 4.20: Average values for the maximum explosion pressure (above) and maximum rate of pressure rise (below) for various amounts of methane and with 125 g/m³ of sodium bicarbonate dispersed in air.

4.3. Hybrid explosions

This section summarises the results from tests with hybrid mixtures, with or without inert gases or inert dust.

4.3.1. Hybrid methane-maize dust explosions in air

Table 4.21 and Figure 4.21 summarise the results from the tests with hybrid mixtures in air.

4.3.2. Influence of nitrogen on hybrid explosions

Tables 4.22-4.24 and Figures 4.22-4.24 summarise the results from tests with hybrid mixtures diluted with 10 or 20 vol.% nitrogen.

4.3.3. Influence of carbon dioxide on hybrid explosions

Tables 4.25-4.29 and Figures 4.25-4.27 summarise the results from tests with hybrid mixtures diluted with 10 or 20 vol.% carbon dioxide.

4.3.4. Influence of sodium bicarbonate on hybrid explosions

Tables 4.30-4.31 and Figures 4.28-4.29 summarise the results from tests with hybrid mixtures and 125 g/m³ dispersed sodium bicarbonate (NaHCO₃).

Table 4.21: Summary of results for hybrid mixtures dispersed in air.

Hybrid methane-maize with air			P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Dust concentration (g/m ³)	I	II	Average	I	II	Average
1 kJ	10	0	8.3	8.2	8.3	1393	1201	1297
1 kJ	7.5	125	8.2	8.2	8.2	1121	1076	1099
1 kJ	5	250	8.1	8.8	8.5	805	1131	968
1 kJ	2.5	375	8.3	8.3	8.3	613	570	592
1 kJ	0	500	7.9	7.4	7.7	469	345	407

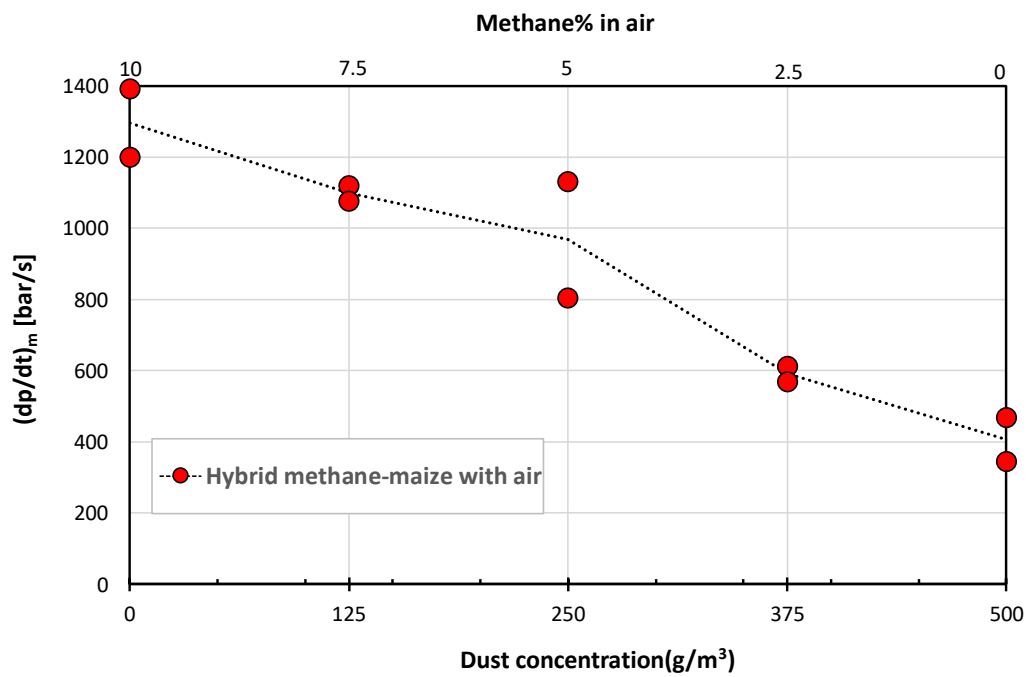
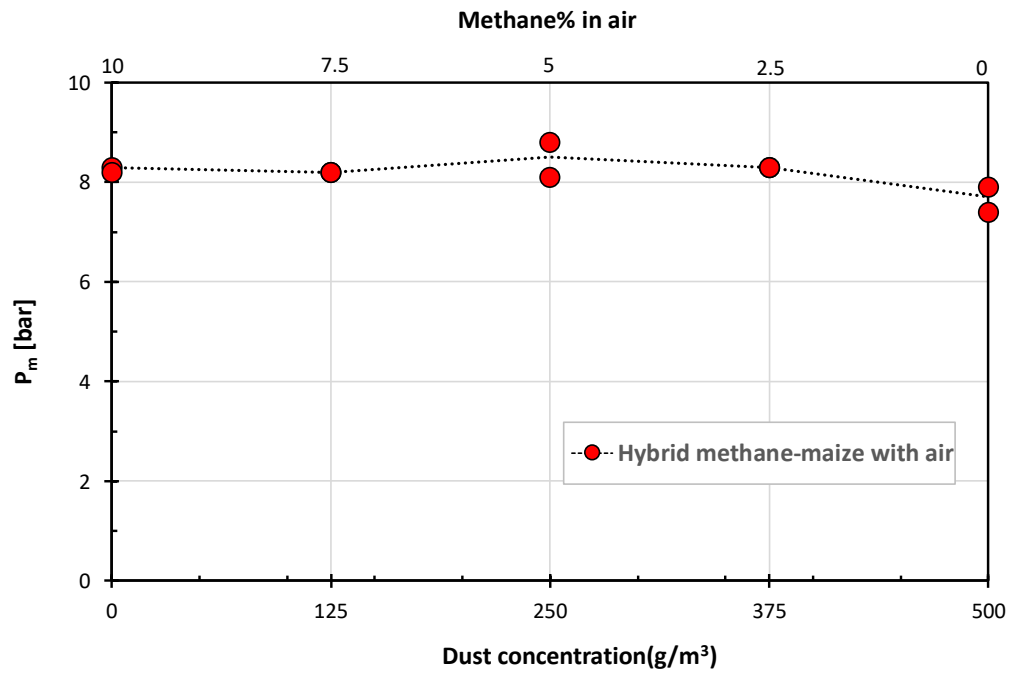


Figure 4.21: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for hybrid mixtures dispersed in air. The dotted line represents the average value of the two series.

Table 4.22: Summary of results for hybrid mixtures dispersed in air diluted by 10 vol.% nitrogen, including average values for the two series.

Hybrid methane-maize with 10 vol.% N ₂ in air			P _m [bar]			(dp/dt) _m [bar/s]		
IE	Methane% in air	Dust concentration (g/m ³)	I	II	Average	I	II	Average
1 kJ	10	0	7.2	7.1	7.2	503	614	559
1 kJ	7.5	125	7.5	7.4	7.5	800	783	792
1 kJ	5	250	7.7	7.6	7.7	622	663	643
1 kJ	2.5	375	7.4	7.4	7.4	396	600	498
1 kJ	0	500	7.8	7.5	7.7	380	368	374

Table 4.23: Summary of results for hybrid mixtures dispersed in air diluted by 20 vol.% nitrogen, including average values for the two series.

Hybrid methane-maize with 20 vol.% N ₂ in air			P _m [bar]			(dp/dt) _m [bar/s]		
IE	Methane% in air	Dust concentration (g/m ³)	I	II	Average	I	II	Average
1 kJ	10	0	5.2	5.5	5.4	219	141	180
1 kJ	7.5	125	6.4	7.0	6.7	270	316	293
1 kJ	5	250	7.3	6.8	7.1	412	474	443
1 kJ	2.5	375	7.4	8.1	7.8	346	602	474
1 kJ	0	500	7.2	7.0	7.1	305	246	276

Table 4.24: Overall average results for hybrid mixtures dispersed in air, including tests with air diluted by 10 and 20 vol.% of nitrogen.

Hybrid (methane-maize-air) with 10 and 20 vol.% N ₂ in air			P _m [bar]			(dp/dt) _m [bar/s]		
IE	Methane% in air	Dust concentration (g/m ³)	Hybrid with air	with 10% N ₂	with 20% N ₂	Hybrid with air	with 10% N ₂	With 20% N ₂
1 kJ	10	0	8.3	7.2	5.4	1297	559	180
1 kJ	7.5	125	8.2	7.5	6.7	1099	792	293
1 kJ	5	250	8.5	7.7	7.1	968	643	443
1 kJ	2.5	375	8.3	7.4	7.8	592	498	474
1 kJ	0	500	7.7	7.7	7.1	407	374	276

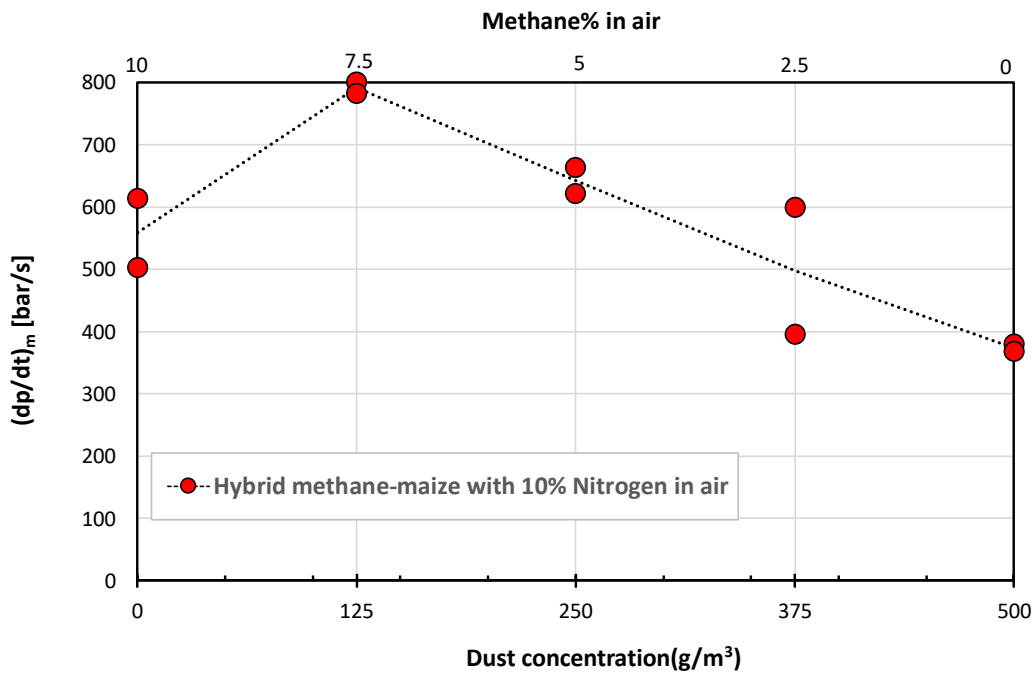
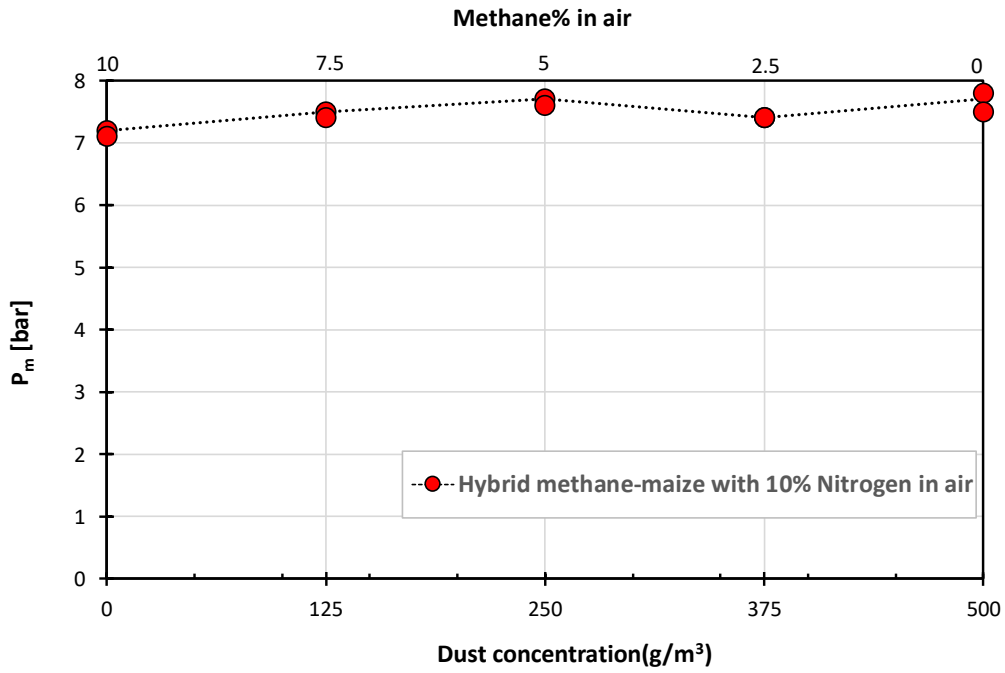


Figure 4.22: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for hybrid mixtures dispersed in air diluted by 10 vol.% nitrogen. The dotted line represents the average value of the two series.

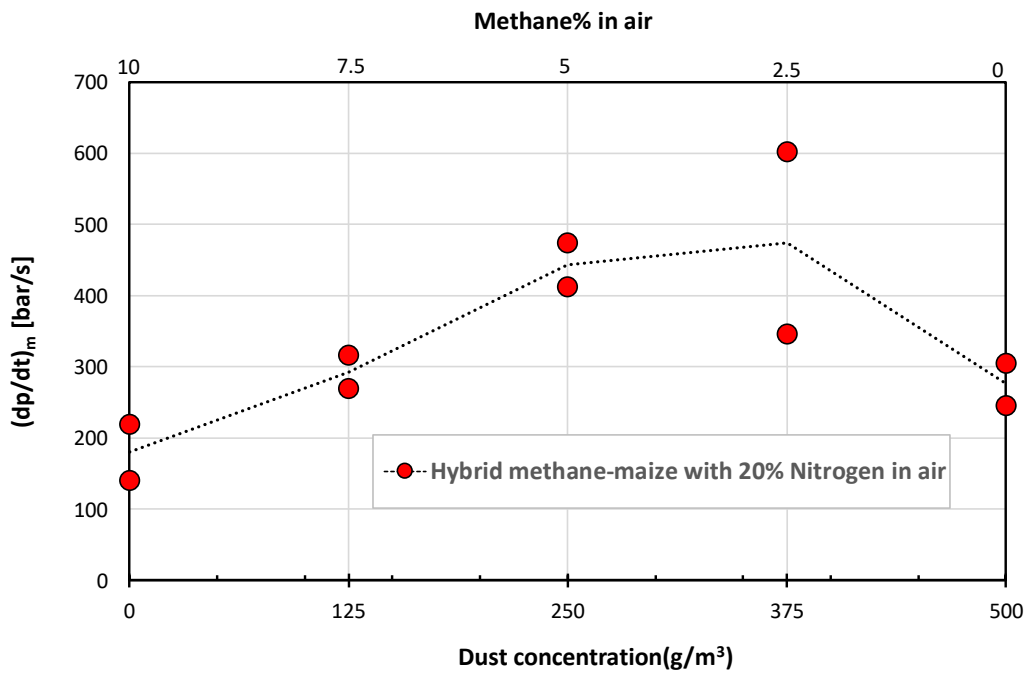
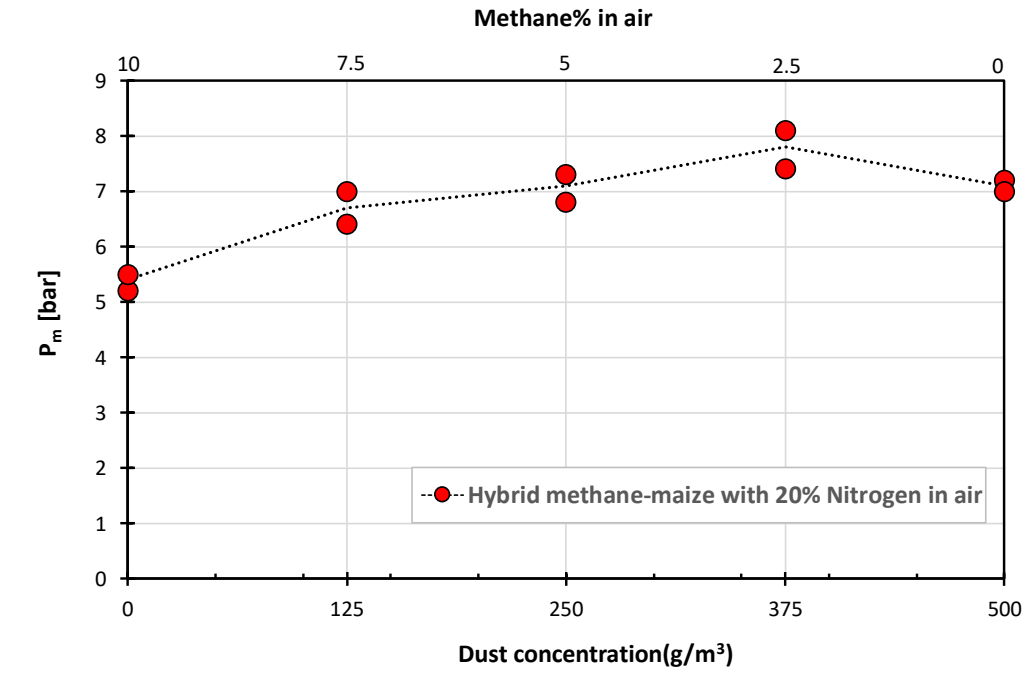


Figure 4.23: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for hybrid mixtures dispersed in air diluted by 20 vol.% nitrogen. The dotted line represents the average value of the two series.

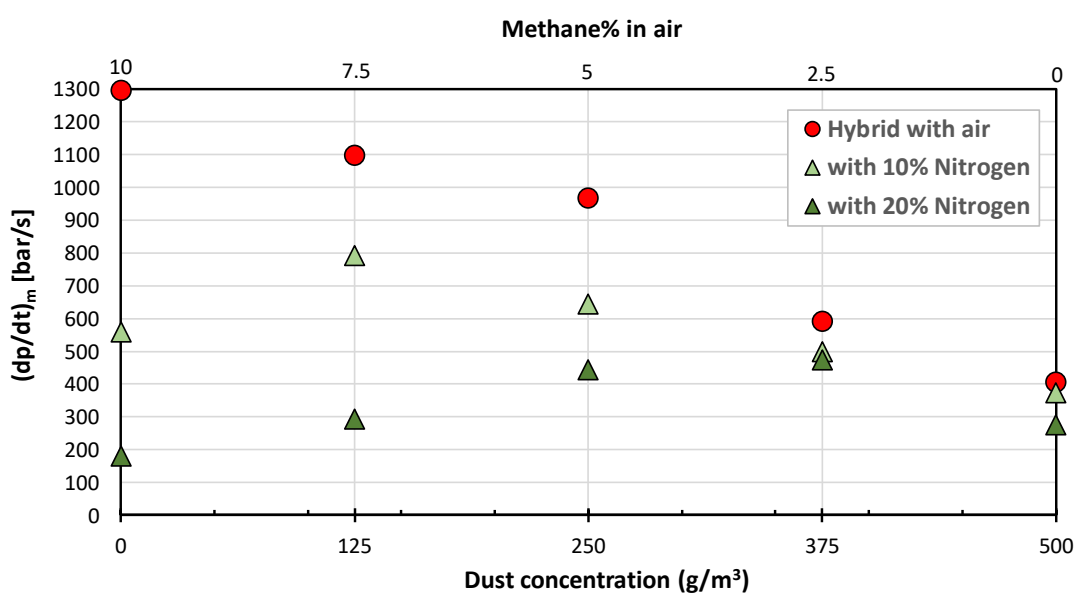
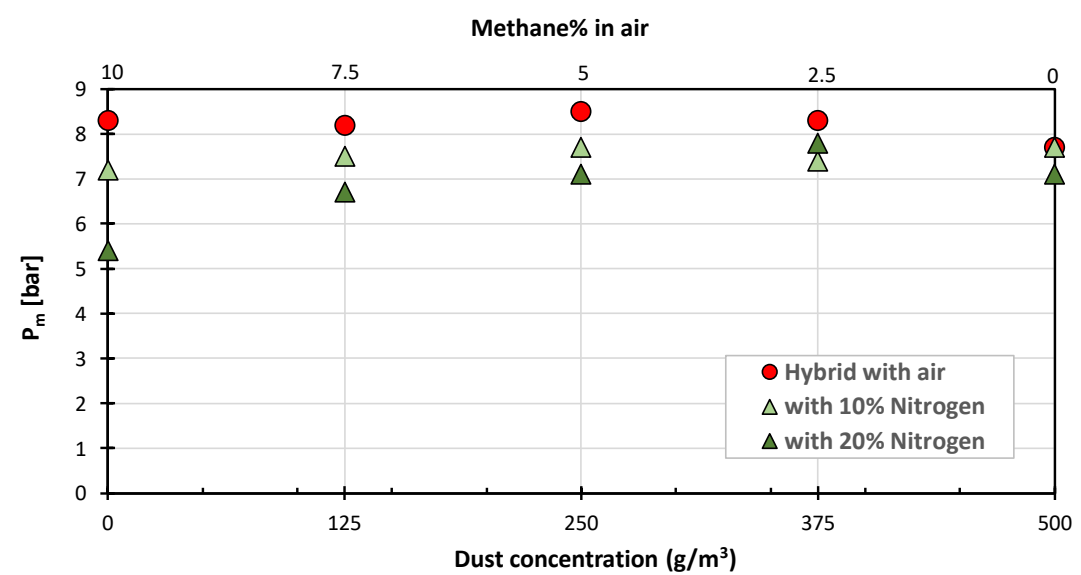


Figure 4.24: Average values for the maximum explosion pressure (above) and maximum rate of pressure rise (below) for hybrid mixtures dispersed in air, air diluted by 10 and 20 vol.% nitrogen.

Table 4.25: Summary of results for hybrid mixtures dispersed in air diluted by 10 vol.% carbon dioxide, including average values for the two series.

Hybrid methane-maize with 10 vol.% CO ₂ in air			P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Dust concentration (g/m ³)	I	II	Average	I	II	Average
1 kJ	10	0	6.7	6.2	6.5	410	231	321
1 kJ	7.5	125	7.2	7.2	7.2	782	793	788
1 kJ	5	250	7.4	7.1	7.3	560	475	518
1 kJ	2.5	375	7.6	7.2	7.4	594	342	468
1 kJ	0	500	7.0	6.8	6.9	249	229	239

Table 4.26: Summary of results for hybrid mixtures dispersed in air diluted by 20 vol.% carbon dioxide, including average values for the two series.

Hybrid methane-maize with 20 vol.% CO ₂ in air			P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Dust concentration (g/m ³)	I	II	Average	I	II	Average
2 kJ	10	0	0.3	0.1	0.2	22	15	19
2 kJ	8	100	4.8	6.4	5.6	58	225	142
2 kJ	7.5	125	5.1	5.1	5.1	58	95	77
1 kJ	6	200	5.8	6.1	6.0	172	181	177
1 kJ	5	250	5.9	5.9	5.9	148	116	132
1 kJ	2.5	375	6.3	6.1	6.2	184	129	157
1 kJ	0	500	5.8	6.0	5.9	106	136	121

Table 4.27: Overall average results for hybrid mixtures dispersed in air, including tests with air diluted by 10 and 20 vol.% of carbon dioxide.

Hybrid methane-maize with 10 & 20 vol.% CO ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
Methane% in air	Dust concentration (g/m ³)	Hybrid with air	with 10% CO ₂	with 20% CO ₂	Hybrid with air	with 10% CO ₂	with 20% CO ₂
10	0	8.3	6.5	0.2	1297	321	19
7.5	125	8.2	7.2	5.1	1099	788	77
5	250	8.5	7.3	5.9	968	518	132
2.5	375	8.3	7.4	6.2	592	468	157
0	500	7.7	6.9	5.9	407	239	121

Table 4.28: Comparison of average results for hybrid mixtures dispersed in air, including tests with air diluted by 10 vol.% of nitrogen and carbon dioxide.

Hybrid methane-maize with 10 vol.% N ₂ & CO ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
Methane% in air	Dust concentration (g/m ³)	Hybrid with air	with 10% N ₂	with 10% CO ₂	Hybrid with air	With 10% N ₂	with 10% CO ₂
10	0	8.3	7.2	6.5	1297	559	321
7.5	125	8.2	7.5	7.2	1099	792	788
5	250	8.5	7.7	7.3	968	643	518
2.5	375	8.3	7.4	7.4	592	498	468
0	500	7.7	7.7	6.9	407	374	239

Table 4.29: Comparison of average results for hybrid mixtures dispersed in air, including tests with air diluted by 20 vol.% of nitrogen and carbon dioxide.

Hybrid methane-maize with 20 vol.% N ₂ & CO ₂ in air		P_m [bar]			$(dp/dt)_m$ [bar/s]		
Methane% in air	Dust concentration (g/m ³)	Hybrid with air	with 20% N ₂	with 20% CO ₂	Hybrid with air	with 20% N ₂	With 20% CO ₂
10	0	8.3	5.4	0.2	1297	180	19
7.5	125	8.2	6.7	5.1	1099	293	77
5	250	8.5	7.1	5.9	968	443	132
2.5	375	8.3	7.8	6.2	592	474	157
0	500	7.7	7.1	5.9	407	276	121

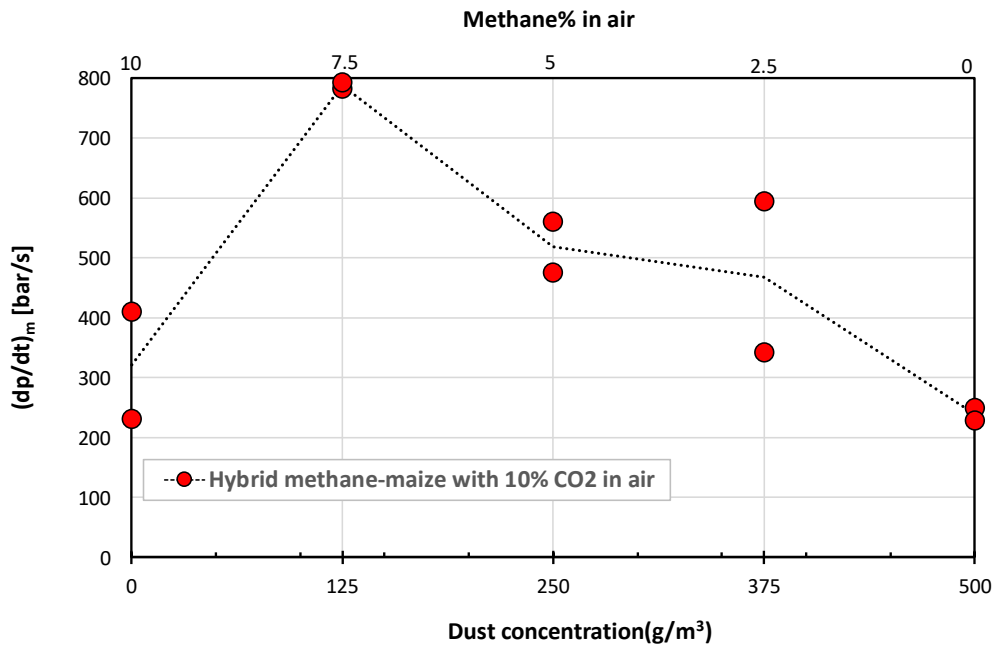
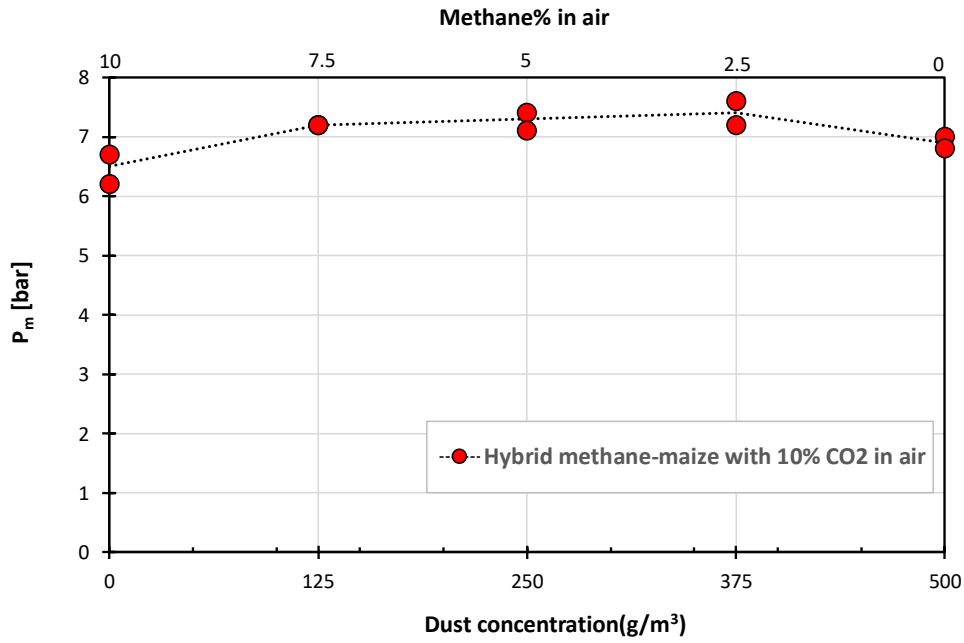


Figure 4.25: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for hybrid mixtures dispersed in air diluted by 10 vol.% carbon dioxide. The dotted line represents the average value of the two series.

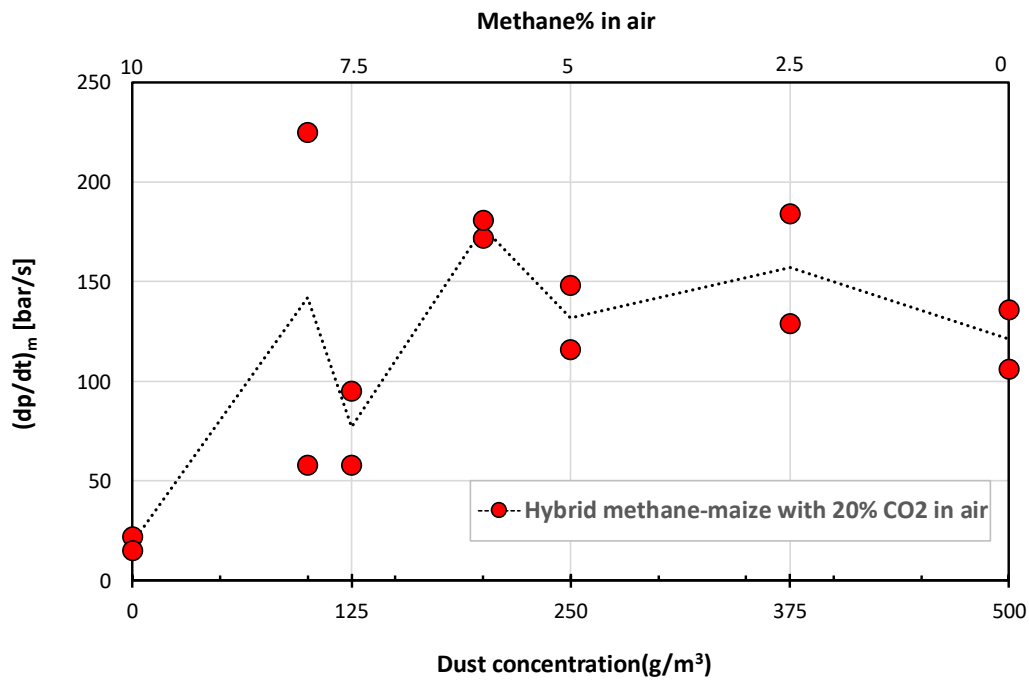
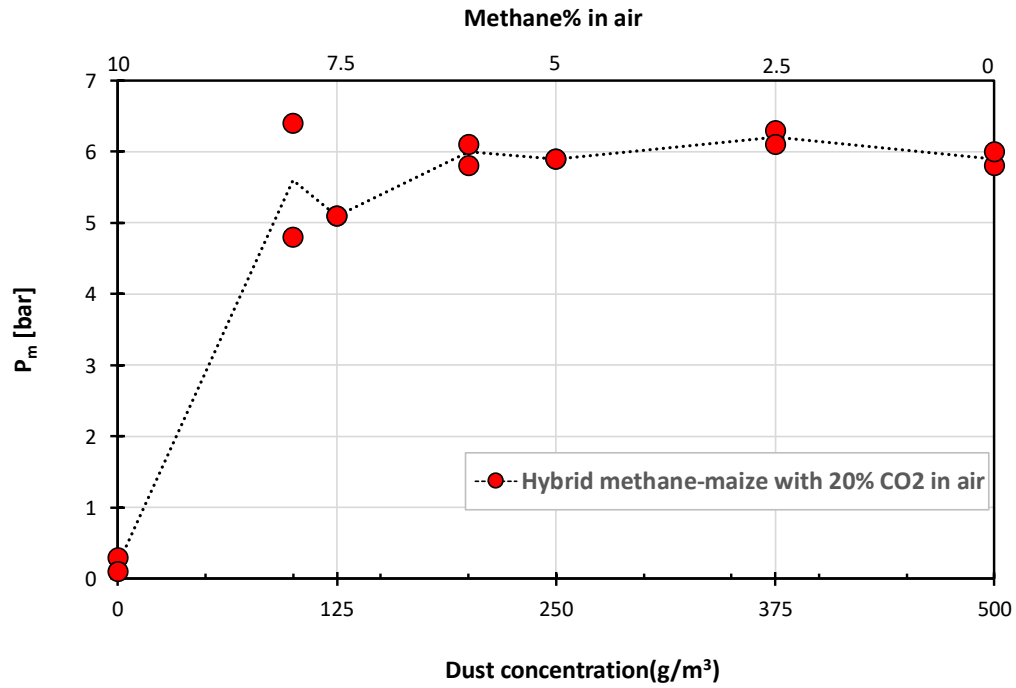


Figure 4.26: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for hybrid mixtures dispersed in air diluted by 20 vol.% carbon dioxide. The dotted line represents the average value of the two series.

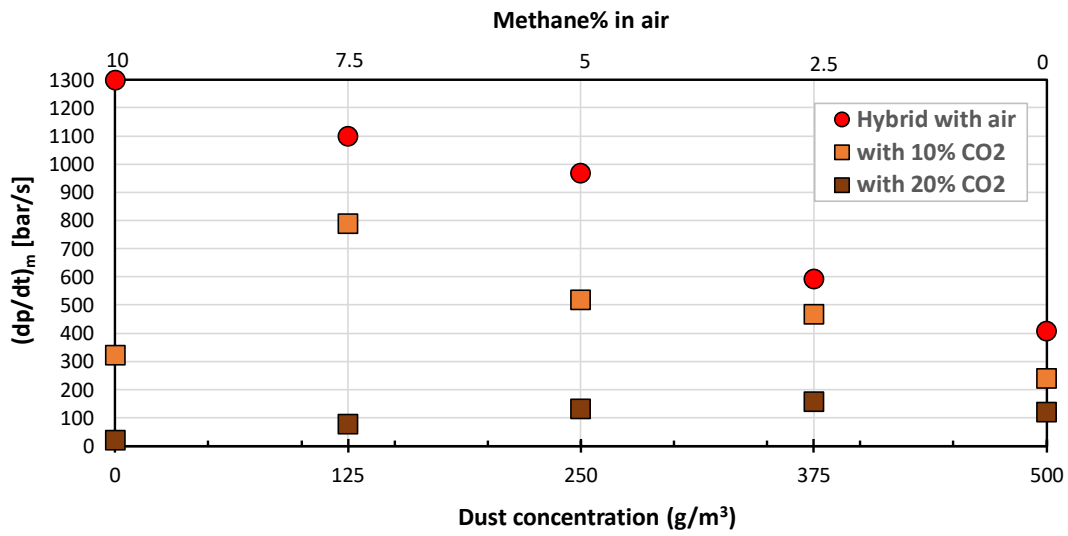
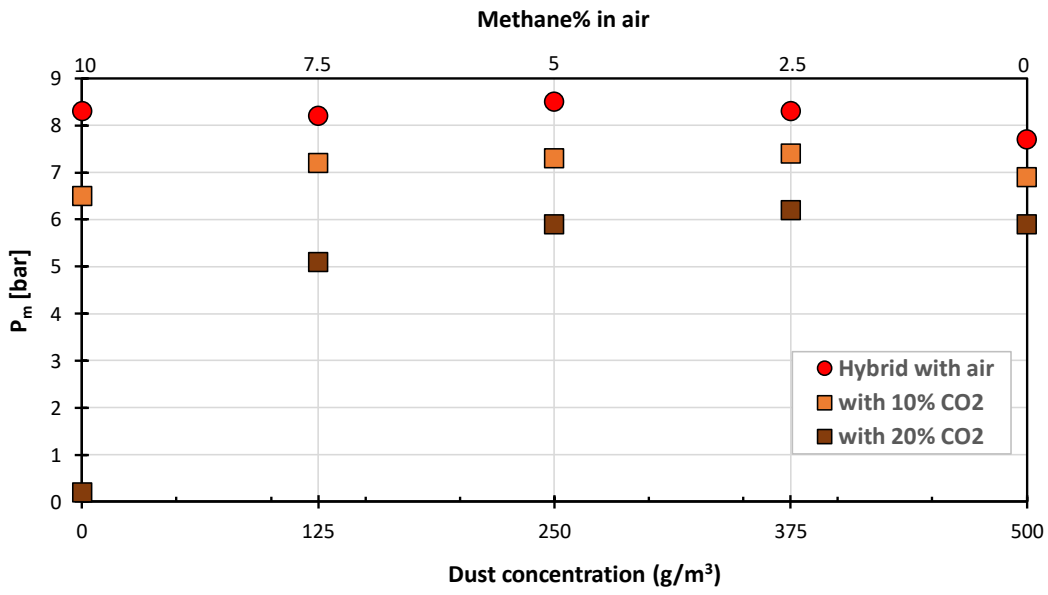


Figure 4.27: Average values for the maximum explosion pressure (above) and maximum rate of pressure rise (below) for hybrid mixtures dispersed in air, air diluted by 10 and 20 vol.% carbon dioxide.

Table 4.30: Summary of results for hybrid mixtures and 125 g/m³ of sodium bicarbonate dispersed in air.

Hybrid methane-maize dust-air with 125 g/m ³ NaHCO ₃			P_m [bar]			$(dp/dt)_m$ [bar/s]		
IE	Methane% in air	Dust concentration (g/m ³)	I	II	Average	I	II	Average
1 kJ	10	0	7.0	6.9	7.0	264	320	292
1 kJ	7.5	125	7.1	7.2	7.2	243	275	259
1 kJ	5	250	7.3	7.4	7.4	241	244	243
1 kJ	2.5	375	7.2	7.5	7.4	156	213	185
1 kJ	0	500	7.9	6.8	7.4	184	106	145

Table 4.31: Overall average results for hybrid mixtures and 125 g/m³ of sodium bicarbonate dispersed in air.

Hybrid methane-maize dust-air with 125 g/m ³ NaHCO ₃			P_m [bar]		$(dp/dt)_m$ [bar/s]	
IE	Methane% in air	Dust concentration (g/m ³)	Hybrid with air	with NaHCO ₃	Hybrid with air	with NaHCO ₃
1 kJ	10	0	8.3	7.0	1297	292
1 kJ	7.5	125	8.2	7.2	1099	259
1 kJ	5	250	8.5	7.4	968	243
1 kJ	2.5	375	8.3	7.4	592	185
1 kJ	0	500	7.7	7.4	407	145

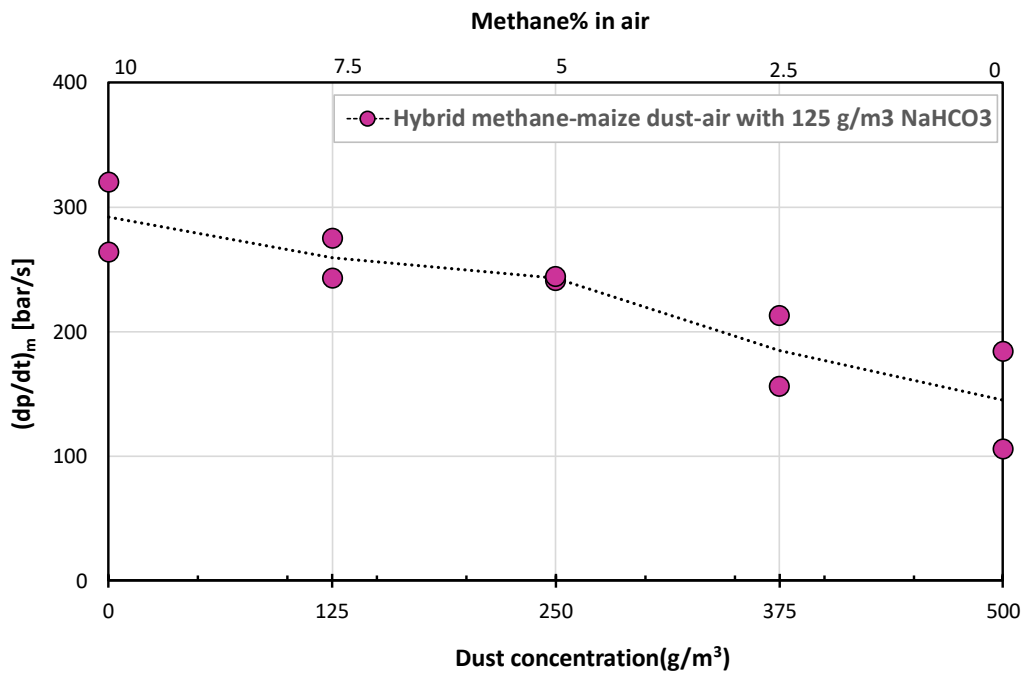
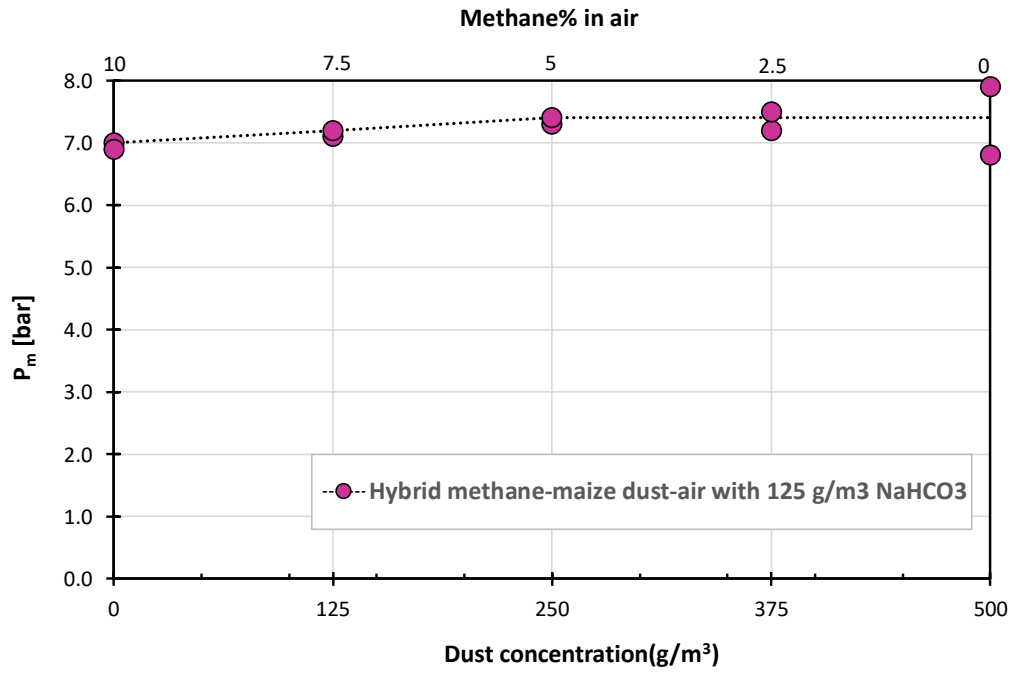


Figure 4.28: Maximum explosion pressure (above) and maximum rate of pressure rise (below) for hybrid mixtures with 125 g/m³ of sodium bicarbonate dispersed in air. The dotted line represents the average value of the two series.

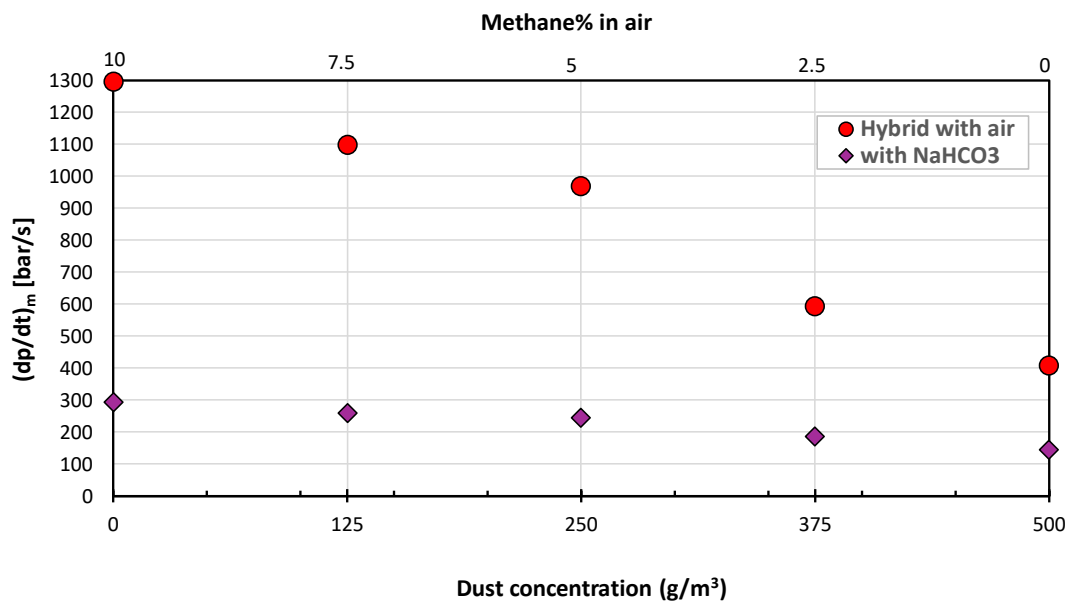
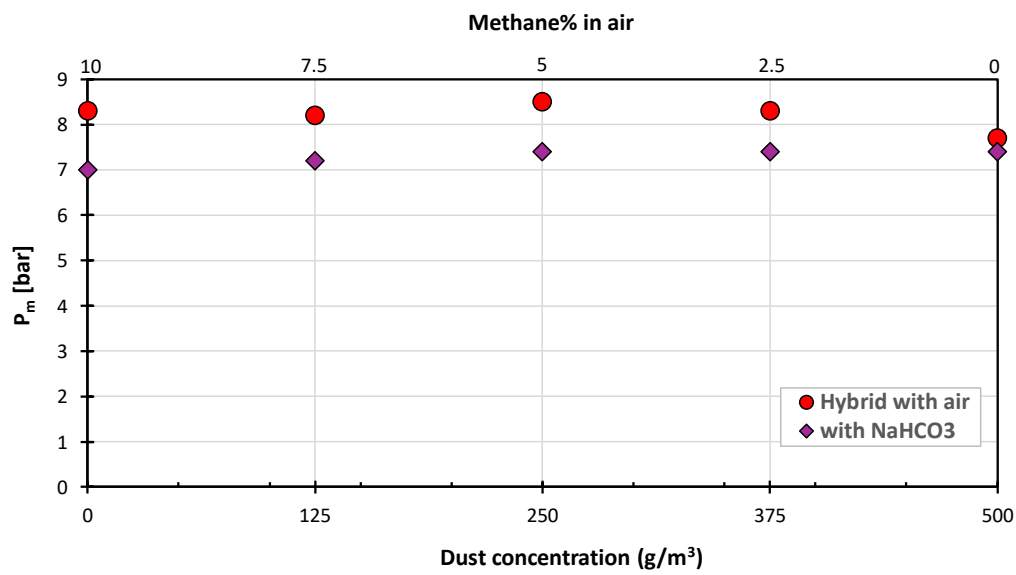


Figure 4.29: Average values for the maximum explosion pressure (above) and maximum rate of pressure rise (below) for hybrid mixtures and with 125 g/m³ of sodium bicarbonate dispersed in air.

5 Discussion

This chapter discusses the results presented in Chapter 4. The analysis includes a comparison with results from previous work and a systematic comparison of the effect of different inert diluents on the explosion severity parameters corrected explosion pressure P_m and rate of pressure rise $(dp/dt)_m$ for the dust, gas and hybrid explosions investigated.

The primary objective of the present study was to study the relative effect of different inert diluents on various flammable mixtures. Due to the limited number of chemical igniters available, the use of only one 1 kJ igniter per test, and the limited number of tests that could be performed with the igniters available, the results are not suitable for deriving 'standard' values for safety-related parameters such as the lower flammability limit (LFL), P_{max} or K_{St} . Furthermore, as outlined in Section 3.2.2, *Figure 3.9* that illustrates that the inherent limitations of the experimental procedure did not allow for the determination of the limiting oxygen concentration (LOC). To this end, the discussion will focus on the effect of different inert diluents towards partial inerting of various flammable mixtures.

5.1. Dust explosions

Section 4.1 summarised the results from the experiments with maize starch in the 20-litre vessel, including the inerting effect of nitrogen, carbon dioxide and sodium bicarbonate. All tests were ignited by a single 1 kJ chemical igniter at a fixed ignition delay time of 60 milliseconds relative to the onset of injection of dust and air from the 0.6-litre reservoir.

Figure 4.1 summarises the results for dust explosions with maize starch without inert diluents. The maximum average values for P_m and $(dp/dt)_m$ of 8.5 bar and 535 bar/s occur for a nominal dust concentration of 750 g/m³. The maximum rate of pressure rise indicates a K_{St} value of 145 bar m/s in a 20-litre vessel, which is reasonably consistent with results reported by other researchers. The maize starch used in the present work originated from the same batch of *Meritena A* used by Eckhoff *et al.* (1987) and Skjold *et al.* (2006). The results reported by Skjold *et al.* (2006) for dust explosion experiments in the 20-litre USBM vessel at UiB indicated a maximum explosion pressure of 8.6-8.7 bar, and K_{St} values of about 150 and 160 bar m/s for ignition with a 6 J arc discharge and two 5 kJ chemical igniters, respectively. Similar to the present study, the maximum values for both P_{max} and $(dp/dt)_{max}$ were found for nominal dust concentrations in the range 750-800 g/m³. An increased number of repeated tests in the present study would likely have resulted in a somewhat higher estimate for P_{max} and K_{St} , but further testing was prohibited by the limited number of chemical igniters available.

Skjold *et al.* (2006) reported standard percentile readings from the particle size distribution for *Meritena A* of 6, 13 and 20 μm for the 10, 50 and 90 percentiles, respectively, measured with a Malvern Mastersizer X and dispersion in water. These results are reasonably consistent with the results summarised in *Table 3.2* ($Dv_{10} = 7.6 \mu\text{m}$, $Dv_{50} = 13.7 \mu\text{m}$, $Dv_{90} = 24.4 \mu\text{m}$). The particle size measurements in the present study involved dispersion in air, since SBC is soluble in water, which is likely to be somewhat less effective compared to dispersion in water.

Table 5.1 summarises literature values for the LFL of maize starch from Addai *et al.* (2016).

Table 5.1: Comparison between experimental data for the LFL of four types of dust, from Addai *et al.* (2016)

Dust LFL (g/m ³)	Addai <i>et al.</i> (2016)	Shevchuk <i>et al.</i> (1979)	Schonewald (1971)	Buksowicz <i>et al.</i> (1983)
Starch	150	84.6	77.8	133.9
Lycopodium	100	51.0	41.4	62.2
Toner	60	42.5	32.7	47.9
HDPE	120	41.4	24.3	33.8

5.1.1. Inerting effect of nitrogen and carbon dioxide

Figure 4.4 summarises the effect of inerting maize starch explosions with 10 or 20 vol.% nitrogen. The apparent increase in both P_m and $(dp/dt)_m$ observed for a nominal dust concentration of 250 g/m³ when 10 vol.% nitrogen is added to the air is presumably a result of the limited effect of modest amounts of inert diluents for lean mixtures (excess oxygen still available), combined with the relatively low molar heat capacity of nitrogen and significant spread in the results for repeated tests. The results for higher dust concentrations show a consistent mitigative effect of adding increasing amounts of inert diluent. The effect of partial inerting is especially pronounced for $(dp/dt)_m$ at higher fuel concentrations. Figure 4.7 shows the corresponding results for carbon dioxide, where the mitigating effect of the inert diluent is consistent through the range of fuel concentrations investigated.

Figure 5.1 and Figure 5.2 summarise the results for nitrogen and carbon dioxide for normalised explosion pressures and normalised rates of pressure rise. The measured values of P_m and $(dp/dt)_m$ are normalised by the maximum values measured for dust-air mixtures without inert diluents, for all dust concentrations investigated (i.e. 8.50 bar and 535 bar/s, respectively). Apart from the results for 10 vol.% nitrogen and 250 g/m³ maize starch mentioned above, the results are reasonably consistent. Increasing amounts of inert diluents result in lower values of both P_m and $(dp/dt)_m$, and carbon dioxide is more efficient for inerting, compared to nitrogen, because of the higher molecular weight and higher molar heat capacity resulting from the three-atomic molecule.

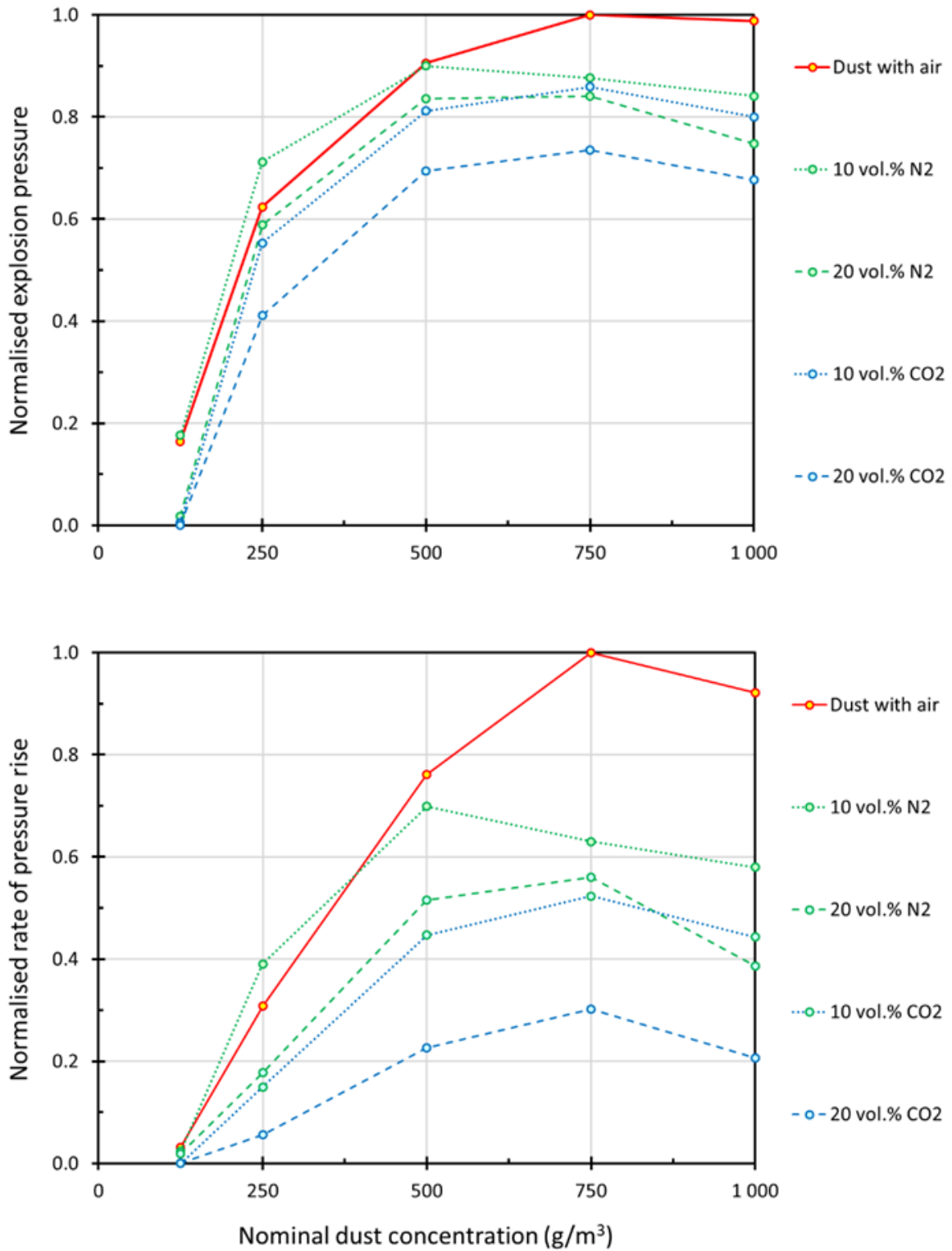


Figure 5.1: The effect of dilution by 10 and 20 vol.% nitrogen (green) or 10 and 20 vol.% carbon dioxide (blue) on the normalised average explosion pressure (above) and normalised average rate of pressure rise (below) for fuel-air explosions with increasing amounts of maize starch.

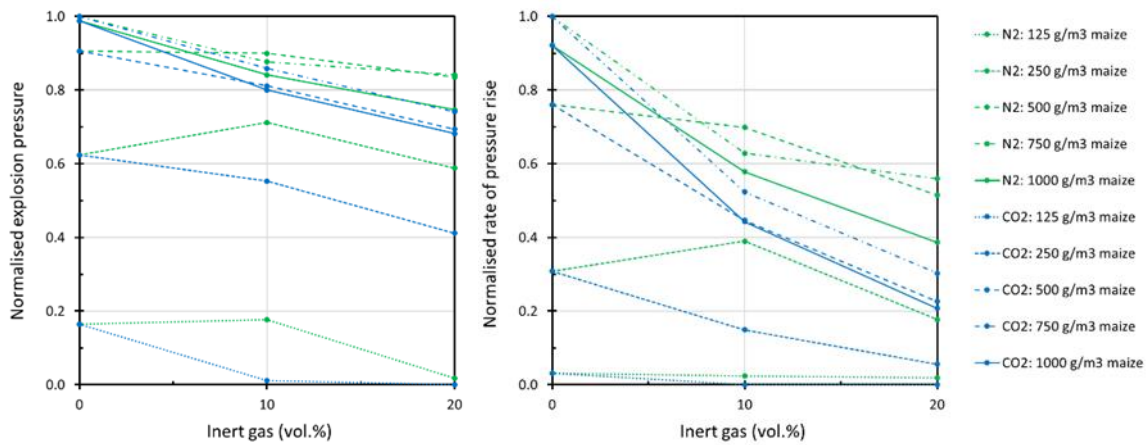


Figure 5.2: Normalised average explosion pressure (left) and normalised average rate of pressure rise (right) for maize-air explosions diluted with 10 and 20 vol.% nitrogen (green) and carbon dioxide (blue).

5.1.2. Inerting effect of sodium bicarbonate

Figure 4.10 summarises the effect of inerting maize starch explosions with 125 g/m³ sodium bicarbonate. The effect is most pronounced for the rate of pressure rise, and especially at higher dust concentrations. Figure 5.3 shows results for the normalised explosion pressure and the normalised rate of pressure rise for fuel-air mixtures of 500 g/m³ maize starch and 10 vol.% methane, for increasing amounts of sodium bicarbonate. The measured values of P_m and $(dp/dt)_m$ are normalised by the maximum values measured for dust-air and methane-air mixtures without inert diluents, for all fuel concentrations investigated (i.e. 8.50 bar and 535 bar/s for maize starch and 8.3 bar and 1297 bar/s for methane, respectively). Note that the normalised values for 500 g/m³ maize starch are less than unity because the highest values for P_m and $(dp/dt)_m$ were obtained for a nominal concentration of 750 g/m³ maize starch in air. The results for the normalised explosion pressure and the normalised rate of pressure rise indicate that the inhibiting/inerting effect of sodium bicarbonate is similar for methane and maize starch. This result will depend on the particle size distribution for both the solid fuel and the solid inert diluent, since the time required for heating and volatising/decomposing the solid particles will depend on particle size.

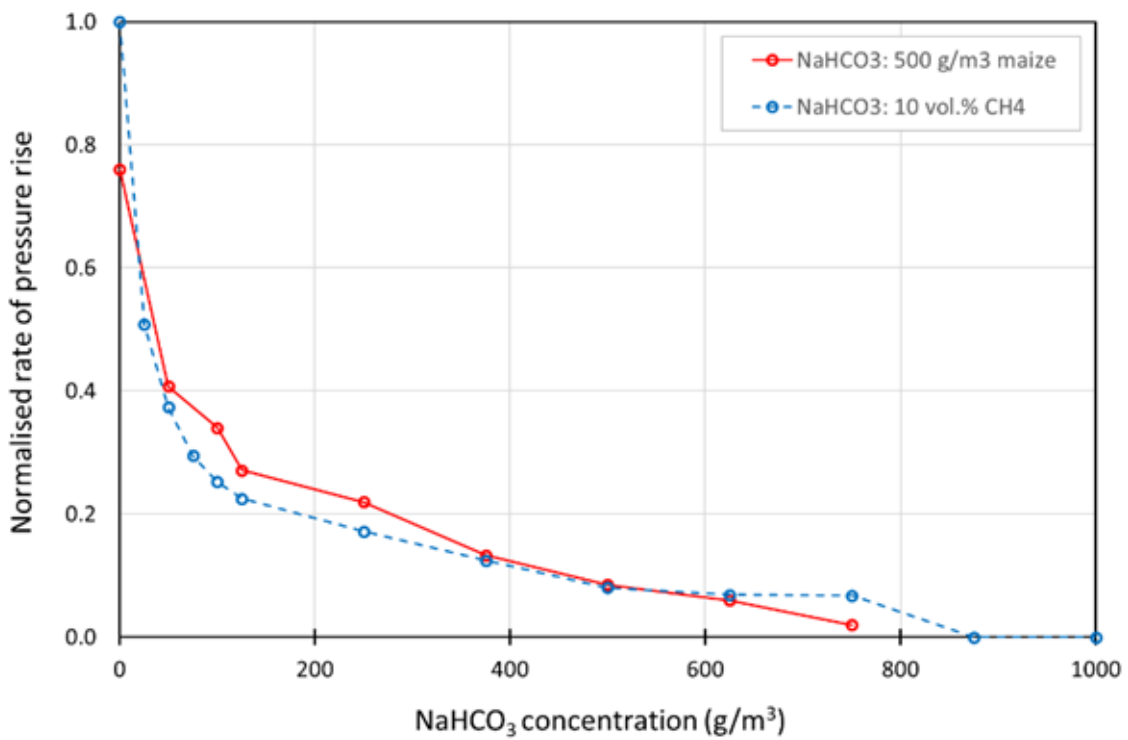
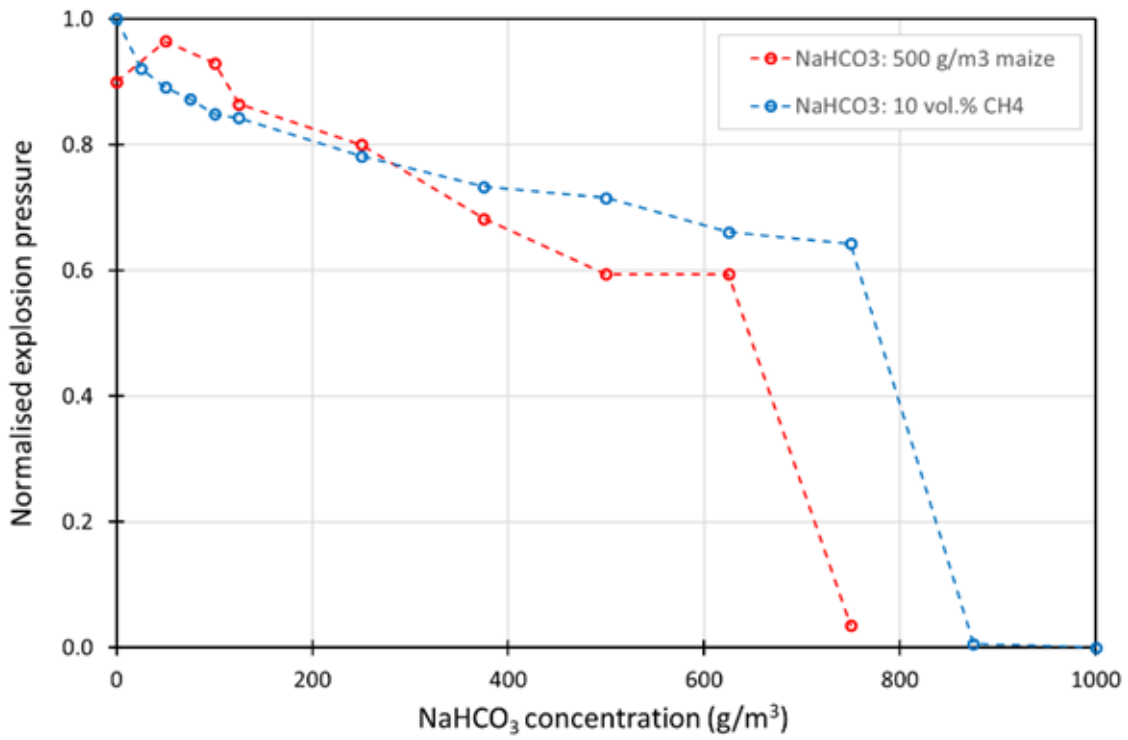


Figure 5.3: Normalised average explosion pressure (above) and normalised average rate of pressure rise (below) for fuel-air explosions with 10 vol.% methane (blue) and 500 g/m³ maize starch (red) diluted by increasing amounts of sodium bicarbonate.

For low concentrations of sodium bicarbonate (50-100 g/m³), the explosion pressures for 500 g/m³ maize starch are somewhat higher than for the tests without inert diluent. This effect can be attributed to the decomposition of inert particles. Dastidar *et al.* (1999) introduced the term Suppressant Enhanced Explosion Parameter (SEEP) for this phenomenon. *Figure 5.4* illustrates the SEEP phenomenon for tests conducted in the 1-m³ vessel with aluminium as fuel and different amounts of sodium bicarbonate (SBC).

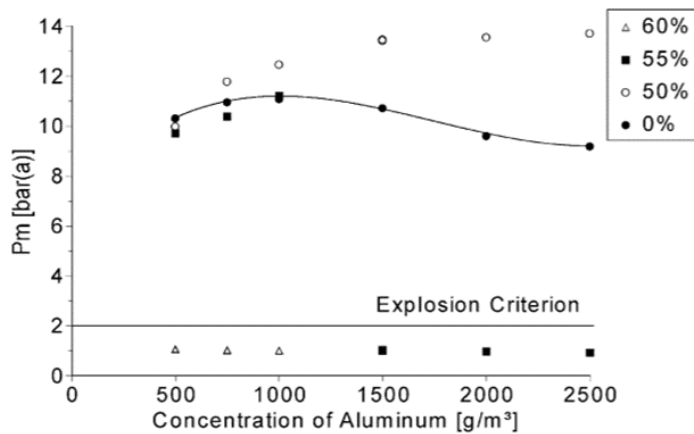


Figure 5.4: Explosion overpressure plotted against aluminium concentration for different amounts of SBC in the mixture, from Dastidar *et al.* (1999).

Figure 5.3 indicated that about 800 g/m³ of sodium bicarbonate is required for preventing flame propagation in dust clouds with 500 g/m³ maize starch dispersed in air. This result is reasonably consistent with the results from Dastidar *et al.* (2002) summarised in *Figure 5.5*, where the amount of sodium bicarbonate required for preventing flame propagation in clouds of maize starch is somewhere between 500 and 1000 g/m³. *Figure 5.5* illustrates that the results from this type of experiments depend on parameters such as the size of the explosion vessel, the ignition source used, and the particle size distributions for the inert diluent and fuel. *Figure 5.5* also illustrates that decreasing the ignition energy in the 20-litre vessel from 5 kJ to 1 kJ lowered the minimum inerting concentration (MIC) from 1500 to 500 g/m³.

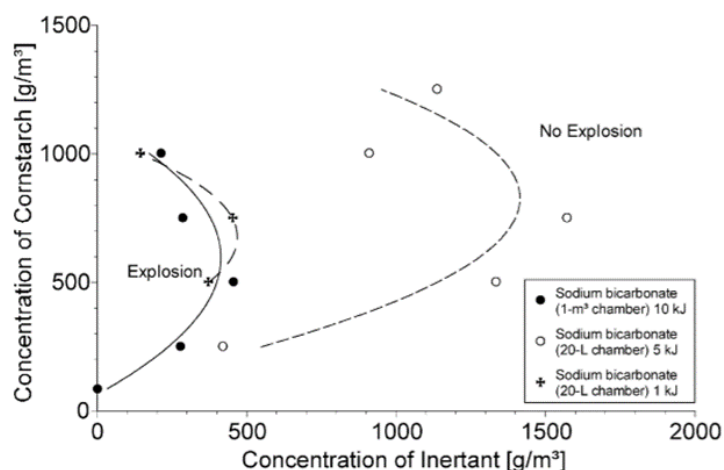


Figure 5.5: Inerting requirements of maize starch inerted with sodium bicarbonate (SBC) in different explosion vessels with various chemical igniters as ignition source, from Dastidar *et al.* (2002).

5.2. Gas explosions

Section 4.2 summarised the results from the experiments with methane in the 20-litre vessel, including the inerting effect of nitrogen, carbon dioxide and sodium bicarbonate. All tests were ignited by a single 1 kJ chemical igniter at a fixed ignition delay time of 60 milliseconds relative to the onset of injection of air from the 0.6-litre reservoir.

Table 5.2 summarised experimentally determined LFL values from a study by Addai *et al.* (2016), indicating a lower flammability limit in the range of 4.7 to 5.2 vol.% methane in air. Figure 5.6 summarises the results from an experimental study by Vanderstraeten *et al.* (1997), as well as selected values from other researchers. This study concluded that LFL and UFL for methane-air mixtures at ambient temperature and pressure are 4.6 ± 0.3 vol.% and 15.8 ± 0.4 vol.%, respectively. The possibility of igniting mixtures at concentrations below 5.0 vol.% methane in air, combined with the inherent uncertainty in the experimental approach used in the present study (i.e. injection of 60 vol.% of the air present at the time of ignition, and highly turbulent flow conditions), may explain the relatively high explosion pressure recorded for the 5.0 vol.% mixture. It is also possible that the relatively strong ignition source (1 kJ) may have influenced the results in the present study, but a relatively weak ignition source should normally not have this strong effect on the flammability limits for a gaseous fuel such as methane.

Table 5.2: Experimental data for the LEL of three gases, from Addai *et al.* (2016).

Gas LEL (vol.%)	Addai <i>et al.</i> (2016)	Spakowski (1952)	Zabetakis (1965)	Shebeko <i>et al.</i> (2002)
Methane	5.0	4.9	5.2	4.7
Acetone	2.5	2.5	2.7	2.1
Isopropanol	2.1	2.4	2.5	1.8

According to Vanderstraeten *et al.* (1997), the UEL for methane increases at elevated initial pressures, and one might speculate whether incomplete mixing during the injection process resulted in a flammable pocket of gas that could be ignited by the chemical igniter. Further experiments with rich mixtures and relatively strong ignition sources might explain the observation. However, this result has limited influence on the overall conclusions from the thesis.

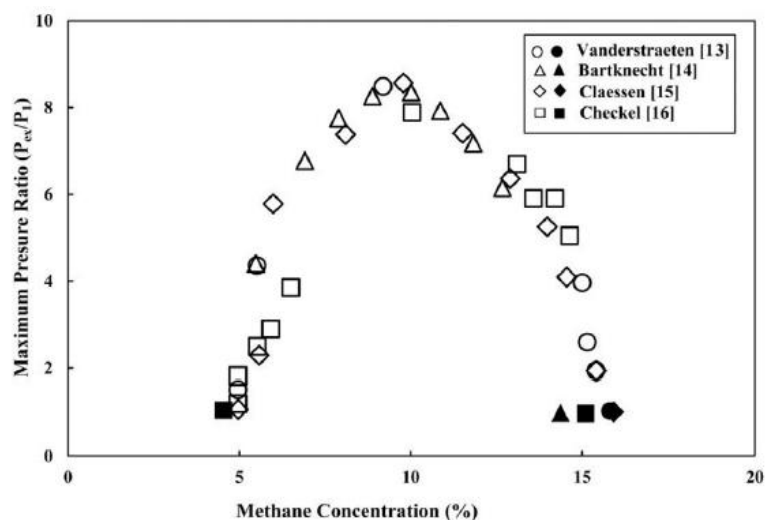


Figure 5.6: LEL, UEL and maximum explosion pressure ratios for methane-air mixtures ignited at ambient pressure and temperature, from Vanderstraeten *et al.* (1997).

The peak values of 8.3 bar and 1297 bar/s for P_m and $(dp/dt)_m$, respectively, occur for the 10 vol.% mixture, i.e. close to the stoichiometric concentration of 9.5 vol.% methane in air (Zanganeh *et al.* 2016; Vanderstraeten *et al.* 1997). The sharp peak in the values for $(dp/dt)_m$ at 10 vol.% is a result of the limited number of tests that could be performed with the available igniters. Additional experiments, both near the flammability limits and near the optimum concentration, should be included in further studies.

5.2.1. Inerting effect of nitrogen and carbon dioxide

Figure 4.14 and Figure 4.17 summarise the effect of inerting methane-air explosions with 10 and 20 vol.% nitrogen and carbon dioxide, respectively. Figure 5.7 summarises the corresponding results for the normalised explosion pressure and the normalised rate of pressure rise. All results are normalised by the peak values of 8.3 bar and 1297 bar/s for P_m and $(dp/dt)_m$, respectively (i.e. the average values found for 10 vol.% methane in air). The results for gaseous mixtures resemble the results presented in Figure 5.2 for maize starch. As expected, the mitigating effect of carbon dioxide is consistently more pronounced than the effect of nitrogen. The gaseous inert diluents, and especially nitrogen, have limited effect on the results for 7.5 vol.% methane in air. For 10 vol.% nitrogen there is a small increase in both P_m and $(dp/dt)_m$ for this mixture, relative to combustion in air, but this can probably be explained by the significant variation in the results between repeated tests. The results obtained for carbon dioxide are in reasonable agreement with data from Gant *et al.* (2011).

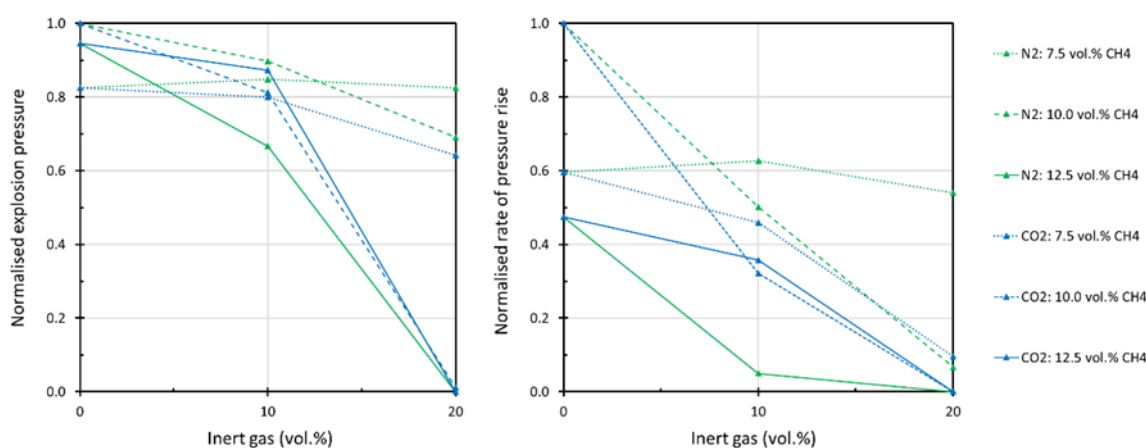


Figure 5.7: Normalised average explosion pressure (left) and normalised average rate of pressure rise (right) for fuel-air explosions with 7.5, 10.0 and 12.5 vol.% methane in air, diluted by 10 or 20 vol.% nitrogen (green) and carbon dioxide (blue).

5.2.2. Inerting effect of sodium bicarbonate

Figure 4.20 summarises the effect on P_m and $(dp/dt)_m$ from adding 125 g/m³ sodium bicarbonate to methane-air mixtures. The effect of the inert diluent is most pronounced for $(dp/dt)_m$ in the concentration range 7.5-12.5 vol.% methane in air. Figure 5.3 shows results for the normalised explosion pressure and the normalised rate of pressure rise for fuel-air mixtures of 500 g/m³ maize starch and 10 vol.% methane, for increasing amounts of sodium bicarbonate. As mentioned in Section 5.1.2, the effect of adding increasing amounts of sodium bicarbonate is similar for the maize starch and methane explosions. A gradual increase in the amount of SBC results in a near-linear reduction in the normalised explosion pressure, up to the point where the flame is quenched. However, the addition of SBC results in an exponential decrease in the normalised rate of pressure rise. The strong effect of relatively small amounts of solid suppressant on the rate of

pressure rise is particularly relevant for risk-reducing measures such as partial inerting and partial suppression.

The results in *Figure 5.3* indicate a minimum inerting concentration (MIC) of about 875 g/m^3 NaHCO_3 for 10 vol.% methane in air. This value is somewhat lower than the MIC of 975 g/m^3 NaHCO_3 for 10 vol.% methane in air reported by Tamanini *et al.* (2000). Tamanini and co-workers used the 20-litre spherical vessel at Factory Mutual Research Corporation (FMRC), with a single 5 kJ chemical igniter and ignition delay time 30 ms. The sodium bicarbonate was of type Ansul Plus 50C, but no particle size measures were provided. The limited number of tests that could be performed in the present study, both concerning the number of repetitions (maximum two) and the number of concentrations that could be tested, implies an inherent uncertainty in the estimation of limiting values such as MIC, LOC, LFL and UFL. Furthermore, factor such as vessel size, ignition source, turbulence level and the particle size distribution of the inert particles will influence the results.

5.3. Hybrid explosions

Figure 4.21 shows a near-linear change in both P_m and $(dp/dt)_m$ when the concentration of methane is reduced from 10 to 0 vol.%, in steps of 2.5 vol.% methane, and the nominal concentration of maize starch is increased from 0 to 500 g/m^3 in steps of 125 g/m^3 . *Figure 5.8* compares the results obtained for the hybrid mixtures the individual values of P_m and $(dp/dt)_m$ obtained for the individual components, i.e. maize starch without methane, and methane without maize starch, for the fuel concentrations indicated on the respective axes. The combined effect of both fuels is most pronounced for the intermediate values, i.e. 5.0 vol.% methane and 250 g/m^3 maize starch in air. Although the explosion pressure of almost 5 bar indicated for 5.0 vol.% methane in air, i.e. close to LFL (see Section 5.2), indicate that the actual gas concentration may be somewhat higher, it is clear that both fuels take part in the combustion reactions.

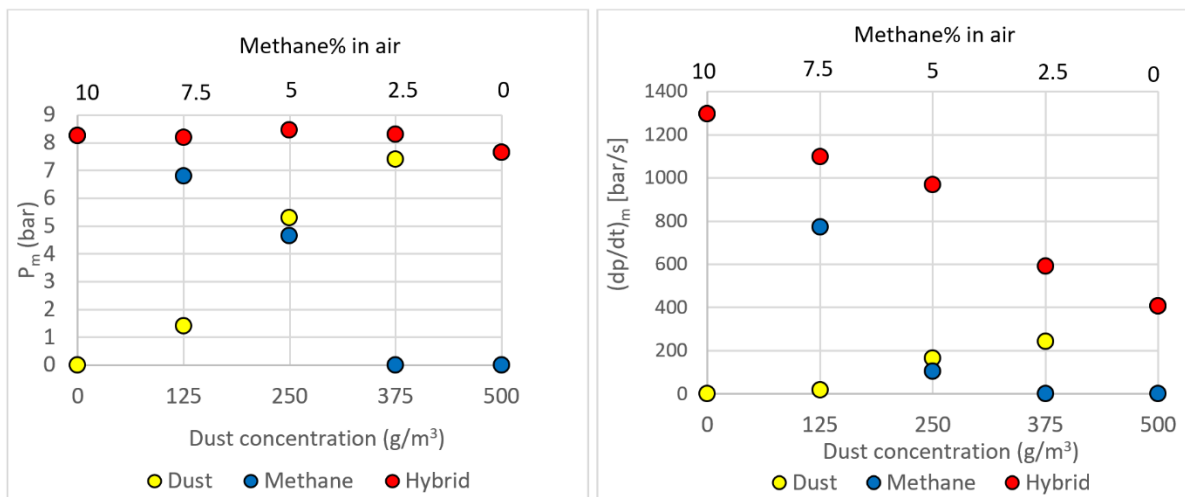


Figure 5.8: Corrected explosion pressure (left) and rate of pressure rise (right) for hybrid mixtures (red), methane only (blue), maize dust only (yellow).

5.3.1. Inerting effect of gaseous and solid inert diluents

Figure 5.9 summarises the results for the normalised explosion pressure and the normalised rate of pressure rise for hybrid mixtures with inert diluents. Since the normalised values of P_m and $(dp/dt)_m$ for dust clouds (Section 5.1) and gaseous mixtures (Section 5.2) were normalised with

the maximum values observed for the individual fuels (i.e. 8.3 bar and 1297 bar/s for methane, and 8.50 bar and 535 bar/s for maize starch, respectively), the results for hybrid mixtures were normalised with values determined by linear interpolation between the values for the respective fuels. This explains how some normalised values can exceed 1.0. Also, the values for 500 g/m³ maize starch and no methane in *Figure 5.9* is less than 1.0, because the maximum values of P_m and $(dp/dt)_m$ used for normalising were obtained for 750 g/m³ maize starch in air. *Figure 5.10* shows the effect of normalising P_m and $(dp/dt)_m$ by the maximum values obtained for 500 g/m³ maize starch in air.

The results summarised in *Figure 5.9* and *Figure 5.10* are consistent with the results obtained for the individual fuels. Increasing the amount of gaseous inert diluent results in lower values of both P_m and $(dp/dt)_m$, and carbon dioxide have a stronger mitigating effect than nitrogen. It is not straightforward to compare the inerting effect of gaseous and solid inert diluents. *Table 5.3* summarises the approximate mass of nitrogen and carbon dioxide present in the mixtures. Although mixtures with 10 vol.% inert diluents include approximately the same mass of inert substance as the suspension with 125 g/m³ sodium bicarbonate, the addition of gaseous diluents implies the combined effect of inert material and reduced oxygen content. The combined effect of added mass, reduced oxygen content and the higher molar heat capacity of CO₂ compared to N₂ explains the strong effect of 20 vol.% carbon dioxide on both P_m and $(dp/dt)_m$. However, for all tests with added maize starch, the mitigating effect of 125 g/m³ sodium bicarbonate is stronger than the mitigating effect of vol.% nitrogen (i.e. about 360 g/m³ nitrogen in air diluted to about 17 vol.% oxygen). This illustrates the significant potential for risk reduction by partial suppression using solid inhibitors such as SBC.

Table 5.3: Mass (g/m³) of gaseous inert diluents in gaseous mixtures at 20 °C and atmospheric pressure.

Diluent	100 vol.%	10 vol.%	20 vol.%
Nitrogen	1150	115	230
Carbon dioxide	1807	181	361

Figure 5.11 and *Figure 5.12* summarise the results for P_m and $(dp/dt)_m$ with 10 and 20 vol.% nitrogen added to hybrid mixtures. *Figure 5.13* and *Figure 5.14* summarise the corresponding results for hybrid mixtures with 10 and 20 vol.% carbon dioxide. The plots include results for maize starch without methane (yellow points) and methane without maize starch (blue points), highlighting the combined effect of both fuels in the hybrid mixture (red points).

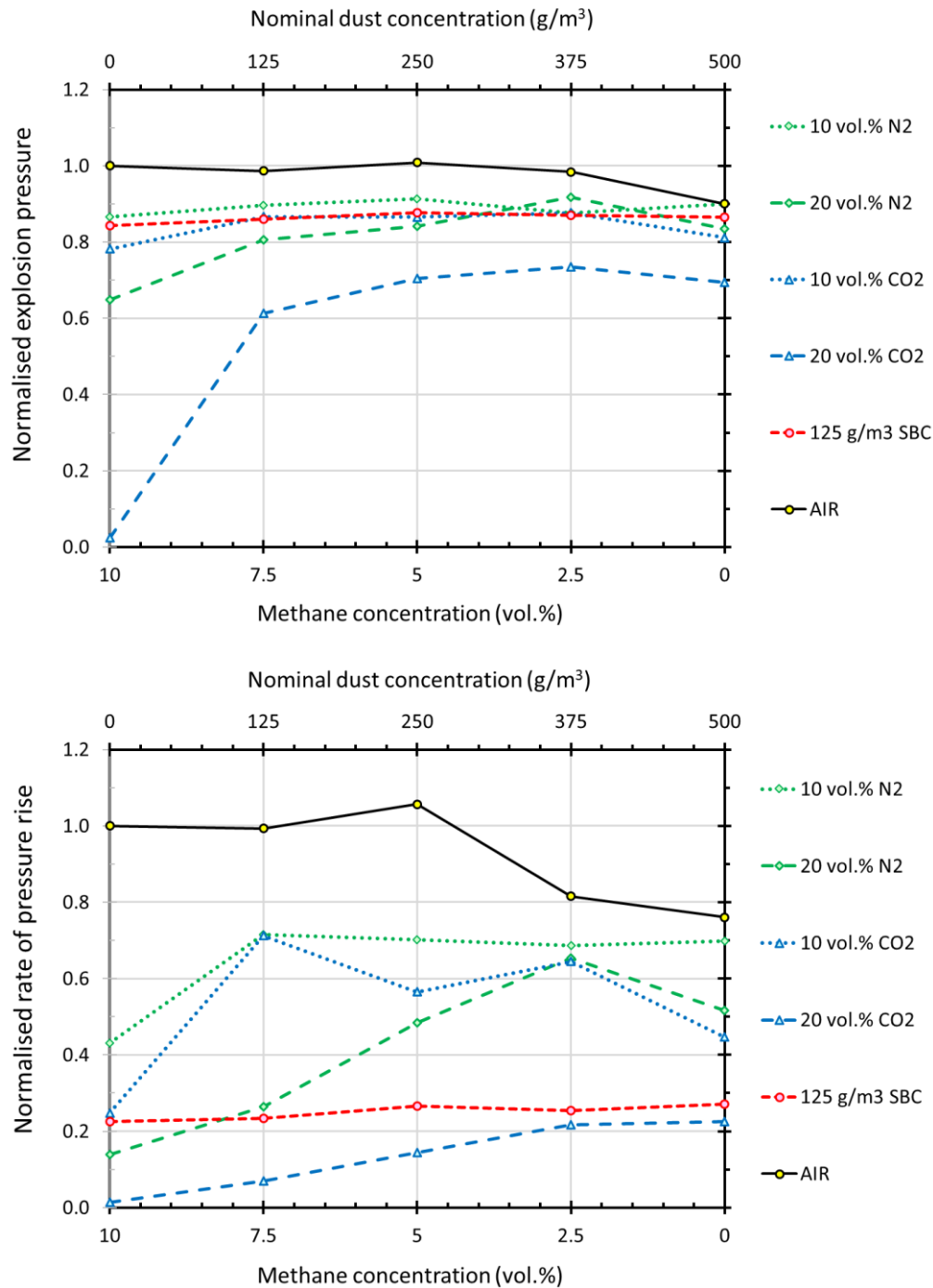


Figure 5.9: Normalised average explosion pressure (above) and normalised average rates of pressure rise (below) for hybrid explosions in air, and explosions in air diluted with 10 or 20 vol.% nitrogen (green), 10 or 20 vol.% carbon dioxide (blue) and 125 g/m³ sodium bicarbonate (red). Values normalised for 10 vol.% methane and 750 g/m³ maize starch in air (i.e. the maximum values obtained for all maize starch concentrations tested).

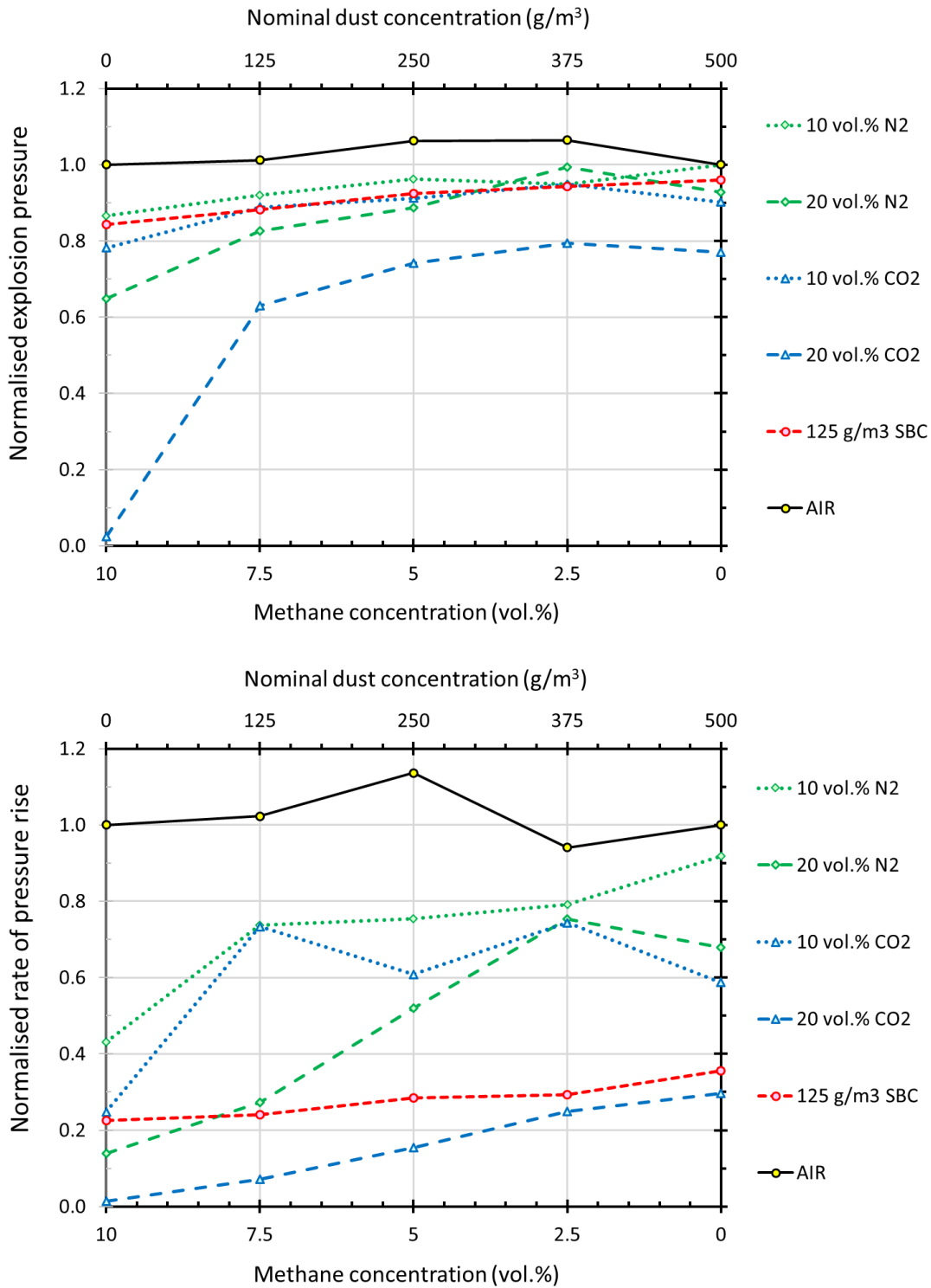


Figure 5.10: Normalised average explosion pressures (above) and normalised average rates of pressure rise (below) for hybrid explosions in air, and explosions in air diluted with 10 or 20 vol.% nitrogen (green), 10 or 20 vol.% carbon dioxide (blue) and 125 g/m³ sodium bicarbonate (red). Values normalised for 10 vol.% methane and 500 g/m³ maize starch in air (i.e. the maximum values obtained for 500 g/m³ maize starch in air).

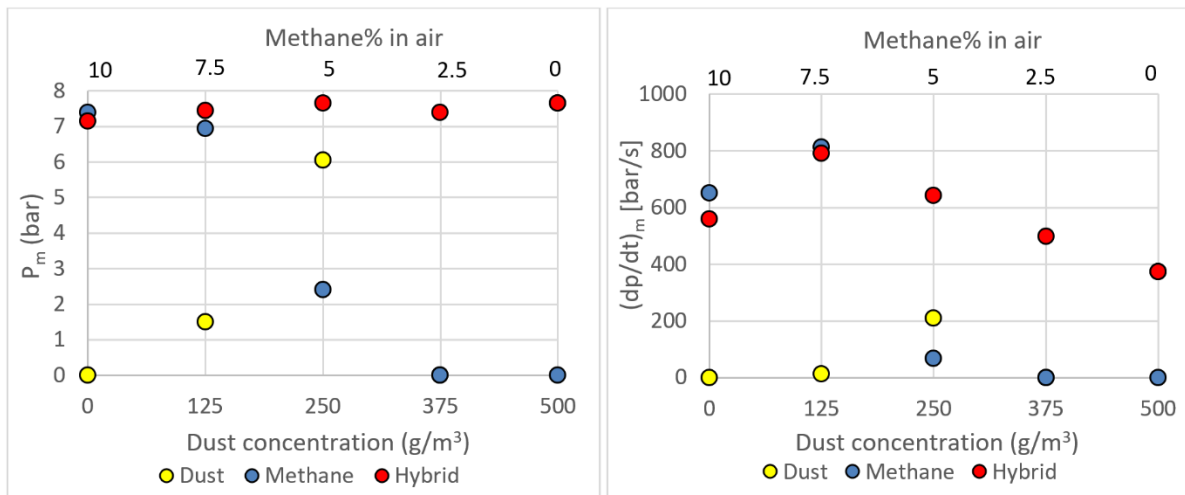


Figure 5.11: Corrected explosion pressure (left) and rate of pressure rise (right) for methane, maize starch and hybrid explosions in air diluted with 10 vol.% nitrogen in a 20-litre vessel.

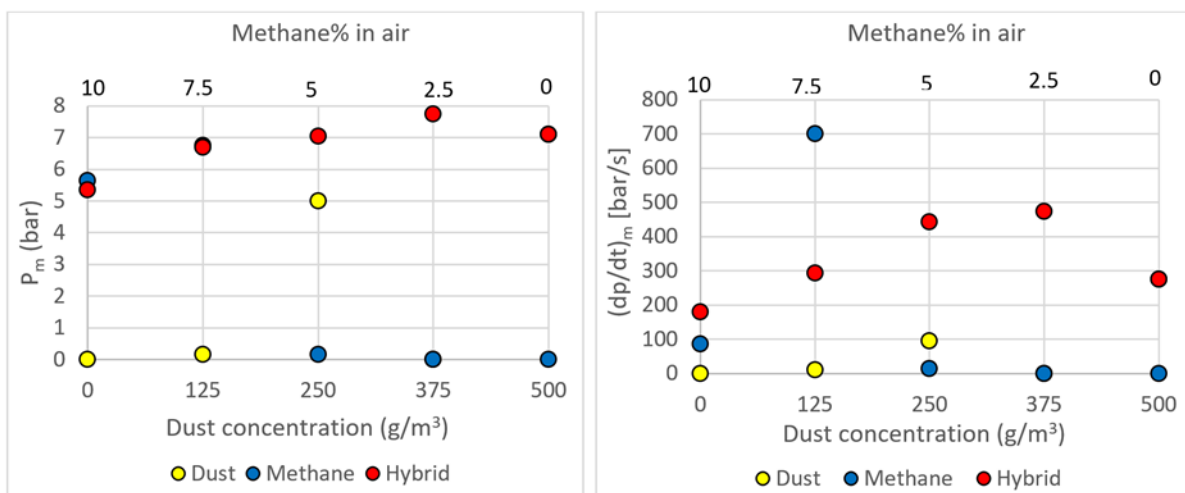


Figure 5.12: Corrected explosion pressure (left) and rate of pressure rise (right) for methane, maize starch and hybrid explosions in air diluted with 20 vol.% nitrogen in a 20-litre vessel.

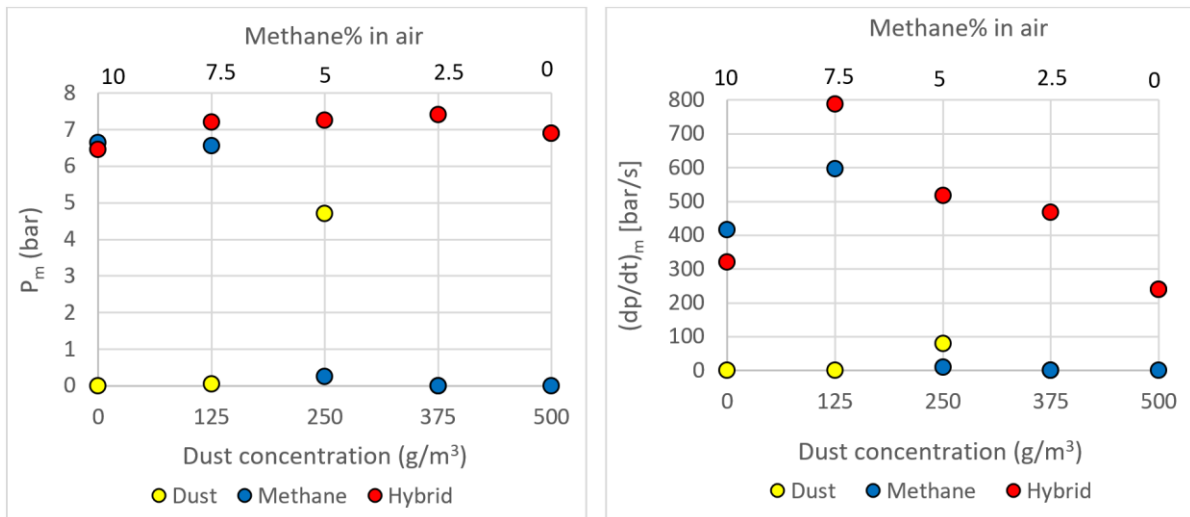


Figure 5.13: Corrected explosion pressure (left) and rate of pressure rise (right) for methane, maize starch and hybrid explosions in air diluted with 10 vol.% carbon dioxide in a 20-litre vessel.

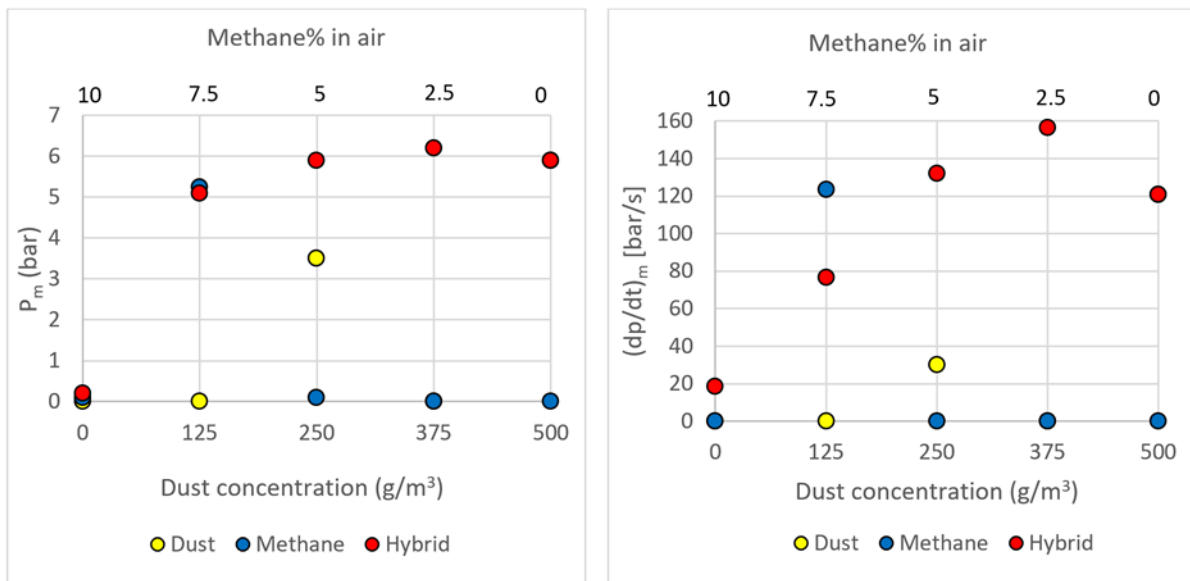


Figure 5.14: Corrected explosion pressure (left) and rate of pressure rise (right) for methane, maize starch and hybrid explosions in air diluted with 20 vol.% carbon dioxide in a 20-litre vessel.

5.4. Overall results for gaseous and solid inert diluents

This section elaborates on the overall results on the effect of gaseous and solid inert diluents on the normalised explosion pressure and the normalised rate of pressure rise for dust, gas and hybrid explosions.

To compare the effect of gaseous and solid diluents, it is convenient to plot the results discussed in sections 5.1 and 5.2 as a function of the total mass of gaseous and solid inert substances added to the vessel. However, direct comparison is still not straightforward, since the addition of gaseous diluents, fuel and inert, reduce the oxygen content of the air. Furthermore, pure air consists of approximately 21 vol.% oxygen and 79 vol.% nitrogen, which implies that there always will be a significant fraction of inert material present.

Figure 5.15 summarises the mitigating effect of various gaseous and solid inert diluents on the normalised explosion pressure and the normalised rate of pressure rise for explosions with 125, 250, 500, 750 and 1000 g/m³ maize starch in air. In general, carbon dioxide has a stronger mitigation effect than nitrogen for most dust concentrations. It is not clear what causes the apparent increase in both pressure and rate of pressure rise for 250 g/m³ maize starch in air. There is also a small increase in pressure for 125 g/m³. However, there is a significant spread in the results from individual tests, and additional repeated tests would likely have resulted in more consistent results. Further work with a significant increase in the number of tests, using a low-energy (and low-cost) ignition source such as an electric spark, may produce more consistent results. Since the addition of sodium bicarbonate (SBC) does not influence the oxygen content in air, a significantly higher mass of inert substance must be added to prevent flame propagation. However, the addition of relatively small amounts of SBC is very effective for reducing the rate of pressure rise.

Figure 5.16 summarises the mitigating effect of various gaseous and solid inert diluents on the normalised explosion pressure and the normalised rate of pressure rise for explosions with 7.5, 10.0 and 12.5 vol.% methane in air. For mitigating the normalised explosion pressure, the gaseous diluents are more efficient than the solid suppressant. This can be explained by the reduction in oxygen content (*Figure 3.9*), which eventually prevents flame propagation. As noted in Section 5.2, nitrogen is not very effective for mitigating P_m and $(dp/dt)_m$ for lean mixtures (e.g. 7.5 vol.% methane in air), but very effective for rich mixtures (e.g. 12.5 vol.% methane in air). This is reasonable since the oxygen concentration in air will be diluted by both gaseous fuel and gaseous inert (*Figure 3.9*). The presence of the gaseous fuel implies that gaseous fuel-air mixtures are more sensitive to the addition of gaseous inert diluents, which probably explains the strong mitigating effect of nitrogen for P_m and $(dp/dt)_m$ in *Figure 5.16*. *Table 3.3* shows that nitrogen has a higher specific heat capacity than carbon dioxide. Similar to the results for maize starch in *Figure 5.15*, the addition of relatively small amounts of SBC is very effective for reducing the rate of pressure rise.

The results summarised in *Figure 5.15* and *Figure 5.16*, as well as *Figure 5.9* and *Figure 5.10* for hybrid mixtures, show that the inhibiting effect of adding modest amounts of SBC to the more reactive methane, maize starch and hybrid fuel-air mixtures is comparable, or even stronger, compared to the mitigating effect of adding the same mass of nitrogen or carbon dioxide to the same mixtures. As mentioned in Section 2.2.2, a theoretical analysis by Omar *et al.* (2018) suggests that the mitigating effect of SBC can be attributed to the thermal decomposition of the particles, combined with the effect of the gaseous species NaOH on the chemical kinetics in the flame.

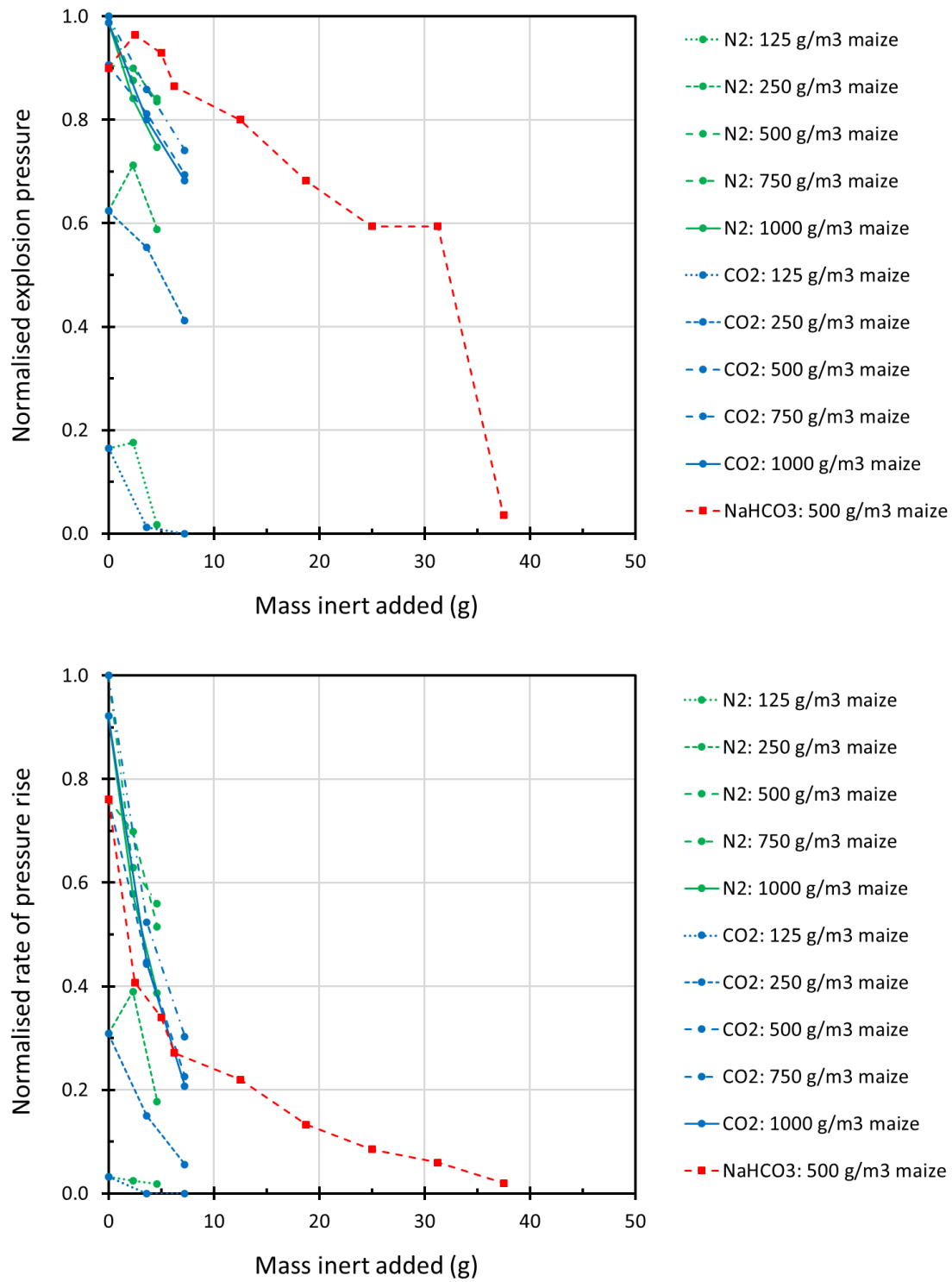


Figure 5.15: Normalised average explosion pressure (above) and normalised average rate of pressure rise (below) for dust explosions with maize starch diluted by nitrogen (green), carbon dioxide (blue) and sodium bicarbonate (red) as a function of the mass of inert substances added to the air inside the 20-litre vessel.

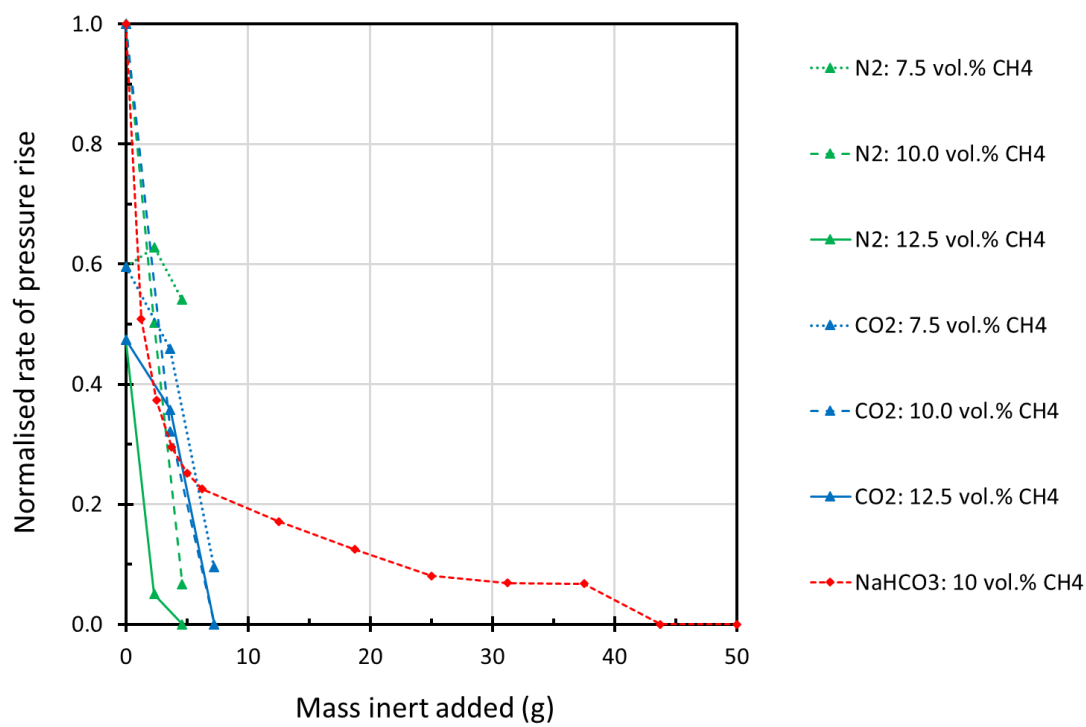
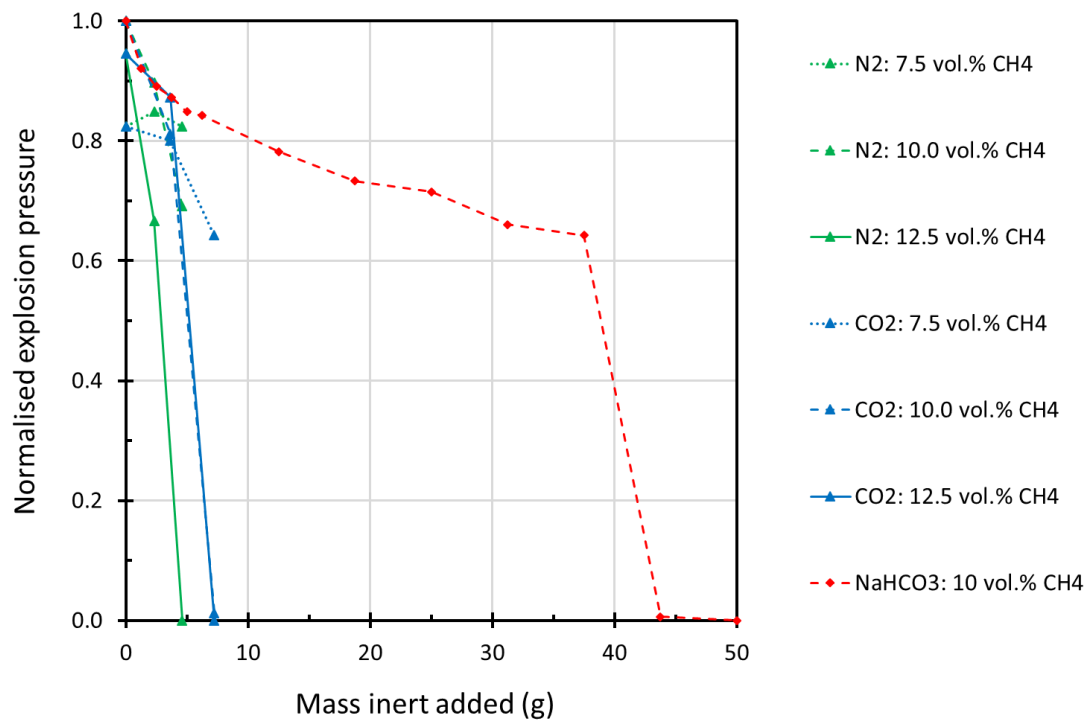


Figure 5.16: Normalised average explosion pressure (above) and normalised average rate of pressure rise (below) for methane-air explosions diluted by nitrogen (green), carbon dioxide (blue) and sodium bicarbonate (red) as a function of the mass of inert substances added to the air inside the 20-litre vessel.

6 Conclusions

The present study aimed to investigate the mitigating effect of inert substances on the severity of fuel-air explosions, quantified by the corrected explosion pressure P_m and the rate of pressure rise $(dp/dt)_m$. Initially, turbulent mixtures of methane (CH₄) and/or maize starch (Meritena A) in air, with or without added inert substances, were investigated in a 20-litre explosion vessel. Compressed air, with or without dust particles, either fuel or suppressant, were injected into the explosion vessel from a 0.6-litre reservoir, and the turbulent mixture was ignited using a 1 kJ chemical igniter triggered at a fixed ignition delay time of 60 milliseconds after the onset of dispersion. Various amounts of the inert substances nitrogen (N₂), carbon dioxide (CO₂) and sodium bicarbonate (NaHCO₃) could be added to the fuel-air mixtures prior to ignition. The results and discussion support the following conclusions:

- The present study confirms observation from previous studies, demonstrating that relatively modest amounts of inert substances can significantly reduce the rate of combustion in fuel-air explosions, quantified by the rate of pressure rise.
- The values estimated for the minimum inerting concentration (MIC) of sodium bicarbonate for maize starch and methane are in reasonable agreement with data from Dastidar *et al.* (2002) and Tamanini *et al.* (2000), respectively.
- The addition of 100-200 g/m³ of the solid inert diluent sodium bicarbonate resulted in a 60-80 % reduction in the rate of pressure rise for methane, maize starch and hybrid methane/maize starch explosions at close to optimal conditions, i.e. the concentrations that produce the highest values of P_m and $(dp/dt)_m$.
- The results indicate that partial inerting or suppression, either as isolated measures or in combination with other preventive or mitigating measures (e.g. deflagration venting or forced ventilation), represent an effective means of reducing the risk of accidental explosions.

The number of chemical igniters available determined the number of tests that could be performed. This inherent limitation, combined with the significant spread in some of the experimental results, implies that there is significant uncertainty associated with some of the results. However, the overall results summarised above are consistent, and not particularly sensitive to the inherent uncertainties associated with the experimental approach.

Further work can elaborate on the mitigating effect of different types of solid inert diluents on fuel-air explosions in confined and/or congested geometries, as well as the effect of the particle size of the solid suppressant (Hoorelbeke & van Wingerden, 2009; Roosendans & Hoorelbeke, 2019).

It is also relevant to explore the possibility of mitigating the consequences of explosions involving highly reactive fuels, such as hydrogen. This is particularly relevant for hydrogen systems located in relatively weak enclosures, such as containers, buildings or fuel cell rooms in trains, ships and planes. Deflagration venting is not very effective for highly reactive hydrogen-air mixtures, but a combination of partial suppression and venting may reduce the risk to an acceptable level.

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