



Experimental study of the characteristics of explosions generated by methane mixtures, as a function of the type of atmosphere and environmental conditions

María-Belén Prendes-Gero^a, Martina-Inmaculada Álvarez-Fernández^{b,*},
Lucía Conde-Fernández^b, Juan-Carlos Luengo-García^c, Celestino González-Nicieza^b

^a Department of Construction and Manufacturing Engineering, Polytechnic School of Engineering of Gijón, University of Oviedo, Gijón, Asturias, Spain

^b Department of Mining Exploitation and Prospecting, School of Mining, Energy and Materials Engineering of Oviedo, University of Oviedo, Oviedo, Asturias, Spain

^c Department of Energy, School of Mining, Energy and Materials Engineering of Oviedo, University of Oviedo, Oviedo, Asturias, Spain

ARTICLE INFO

Keywords:

Methane–air mixtures
Explosion characteristics
Experimental study
Pressure characteristics
Environmental conditions

ABSTRACT

The combination of methane – air can cause potentially explosive mixtures, which in contact with an energy source can ignite, resulting not only in the destruction of infrastructure but also in the death of people. This paper studies the ignition of different methane–air mixtures as a function of the type of mixture (methane–air, methane–nitrogen–oxygen), the kind of atmosphere (homogeneous, stratified) and the environmental conditions (initial temperature, pressure, and humidity). For this purpose, the *Rock Dynamics* research group of the University of Oviedo has designed and manufactured an explosive chamber, quasi-spherical in shape, instrumented with dynamic pressure sensors and accelerometers. With the results obtained after a laboratory-scale experimental campaign, pressure-concentration graphs were plotted, obtaining the explosion limits of the different mixtures. Higher oxygen concentrations (O₂) have therefore been found to increase the upper explosive limit of mixtures. However, increasing methane (CH₄) concentrations lead to different behaviours, depending on the type of mixture. The kind of atmosphere does not seem to affect the recorded pressures, as they are similar for homogeneous and stratified atmospheres. Finally, initial pressures above atmospheric lead to higher detonation pressures, while a high initial humidity content decreases the likelihood of explosion.

1. Introduction

Methane–air mixtures are potentially explosive mixtures, which have caused numerous accidents, sometimes involving human casualties. Traditionally, these accidents have been associated with underground coal mining (Kundu et al., 2016). However, these mixtures have also caused devastating accidents in civil underground infrastructures, industrial and even commercial environments (Sezer et al., 2017).

In modern cities, the subsoil is filled with gas, electricity, and water distribution networks, as well as drainage systems. Methane leakage in gas pipelines is a common problem worldwide (Lelieveld et al., 2005) (Alvarez et al., 2012) (Jackson et al., 2014), causing an explosion accident if the concentration of the leaked methane is within the flammability limit and an ignition source exists (Rangel, 2014), (Li et al., 2019).

Many studies analyse the explosiveness of the methane–air mixture

as a function of methane concentration (Gharagheizi, 2008), ventilation conditions (Solberg et al., 1981), obstacles (Johansen and Ciccarelli, 2009) or ignition conditions (Lewis and Elbe, 1987), (Kindracki et al., 2007) (Rocourt et al., 2014). Therefore, it can be said that the explosiveness of the mixture depends on multiple factors (Xu et al., 2020), including environmental conditions.

High (20–200 °C) and ultra-high temperatures (900–1,200 °C) increase the explosion limits by shifting the upper explosive limit and the lower explosive limit to higher and lower values, respectively (Gieras et al., 2006) (Li et al., 2021). The same situation occurs at high pressures (Vanderstraeten et al., 1997) (Goethals et al., 1999) (Huang et al., 2019). However, when both conditions coexist in the same time space, a reduction of the explosion limits occurs (Van den Schoor and Verplaetsen, 2007) (Van den Schoor et al., 2008) (Kondo et al., 2011).

However, humidity also influences the limits of the explosion. In 2016, (Li et al., 2016) conducted an experimental campaign in which

* Corresponding author.

E-mail address: inma@uniovi.es (M.-I. Álvarez-Fernández).

<https://doi.org/10.1016/j.jlp.2022.104878>

Received 12 May 2022; Received in revised form 12 September 2022; Accepted 15 September 2022

Available online 20 September 2022

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explosions were carried out in a chamber with a volume of 0.02 m³ with different humidity contents. They found that an increase in the relative humidity of the mixture slightly influenced the explosion limits: the lower limit increased by 2.2% while the upper limit decreased by 2.1%. This study showed that humidity variation affects the explosive range of methane-air mixtures, although more slightly than the effect produced by changing the ignition energy, the initial pressure or the initial temperature of the mixture.

The lack of knowledge about the influence that different environmental factors (temperature, pressure, humidity content) have on the explosion limits of methane-air mixtures makes it necessary to investigate them to deepen our understanding and, thus, prevent explosions that can later become detonations producing numerous accidents in underground structures (Ajrash et al., 2016) (Pan et al., 2017).

In this paper, the ignition of explosive methane atmospheres has been carried out. The end is to analyse the influence of the type of mixture, the type of atmosphere and the environmental conditions on the explosivity of these mixtures. For this purpose, an experimental campaign is carried out in a quasi-spherical chamber of 0.04 m³, the parameters of analysis being the maximum pressure of each explosion, the rate of pressure rise, and the acceleration of the shock waves.

2. Methodology

As previously said, the laboratory – scale experimental campaign is conducted in a quasi – spherical chamber designed and manufactured by the DinRock Research Group of the University of Oviedo. The chamber (Fig. 1) consists of two 8 mm thick steel caps welded together through a central ring. It has eight threaded sleeves to attach the instrumentation that are located on the sphere, in radial positions at 90° angles to each other. In addition, a 12 mm thick, bulletproof, rounded safety glass with a diameter of 165 mm is installed in the upper cap.

The pressures reached in the explosion are recorded with the help of four EPXH-P3 type pressure sensors. These sensors are attached to the ignition chamber by threading them through the sleeves. Two types of sensors have been used depending on the measurement range (Table 1), although both of them collect 50,000 data per second (Fig. 2).

The accelerations on the ignition chamber due to the explosions are recorded with triaxle accelerometers of the KS813B type. These accelerometers measure accelerations in the three directions of space, with a measurement limit of ±55 g, and they are also located in sleeves of the chamber.

Initially, K-type thermocouples were placed to measure the temperature inside the ignition chamber. However, when analyzing the temperature data in the first tests, it was found that the response of these sensors was very slow with respect to the explosion process. Since the temperatures initially recorded by the temperature sensor coincided with that of the weather station used for the relative humidity measurement, it was decided to use this station to determine the initial temperatures.

In the ignition chamber, a 60 × 60 × 25 mm, 3800 rpm, 2.40 W fan is installed. In this way, when the objective is to test explosive mixtures in homogeneous atmospheres, the fan is turned on for 2 min, after which it is stopped and the ignition process begins. Because of the velocity of the fan is not very high, according to (Willacy, S. 2008), the effect of the turbulence has not been considered. On the other hand, when the objective is to test in heterogeneous atmospheres, the injected gases are left to stratify by themselves according to their molecular weight, during different rest periods (15 min, 30 min, 1 h and 2 h).

At last, recordings of the ignition and explosion are made using a Kodak SR500 high-speed camera, which can record 500 images per second.

Once all the measure elements are mounted in the ignition chamber, the gases are injected inside it by means of a BRONKHORST gas flowmeter, model F-201CV-20K-AGD-22-E with an accuracy equal to ±0,5% RD (reading) plus ±0,1%FS (full scale) to then be mixed with the

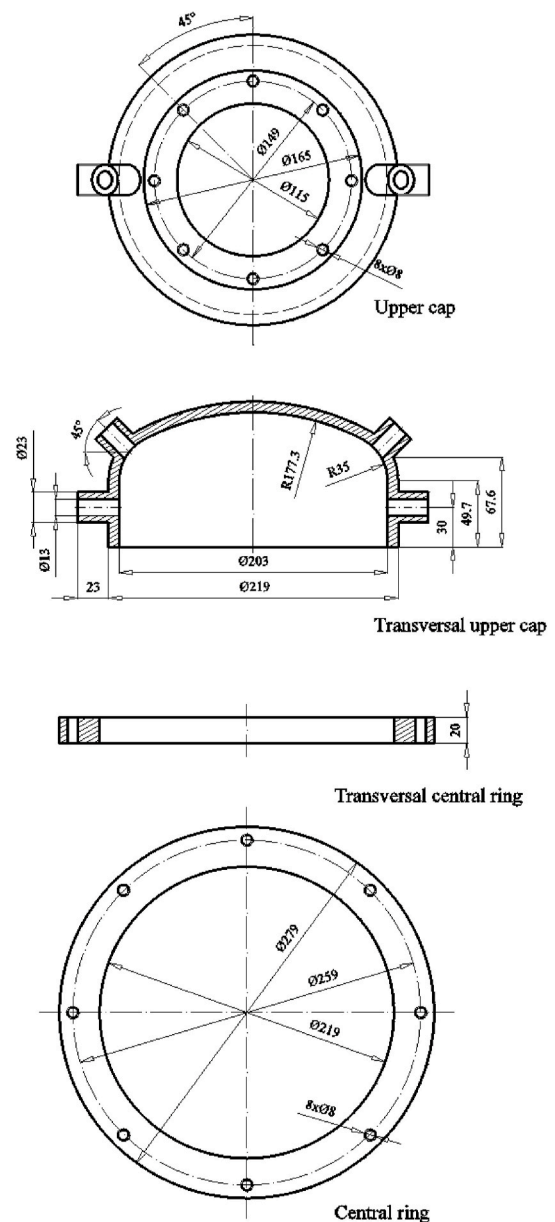


Fig. 1. Views and dimensions (in mm) of the ignition chamber.

Table 1

Technical characteristics of the EPXH-P3 pressure sensors (range 7.0 and 3.5 MPa).

Measurement range	7.00 MPa	3.50 MPa
Maximum burst pressure	14.00 MPa	7.00 MPa
Resonant frequency	200 kHz	150 kHz
Thermal sensitivity shift	±1.5 full scale	±1.5 full scale
Excitation	10 V DC	10 V DC
Impedance in	1200 Ω	1200 Ω
Impedance out	350 Ω	350 Ω
Maximum operating temperature	1650 °C	1650 °C
Zero offset	±10 mV typical	±10 mV typical
Type of pressure measurement	Relative	Relative

fan.

The ignition of the explosive mixtures is performed at a specific point, by increasing the temperature of a steel wire with a length of 120 mm, a diameter of 0.4 mm and a melting temperature of 1535 °C. The increase of the temperature is obtained with electric current with an

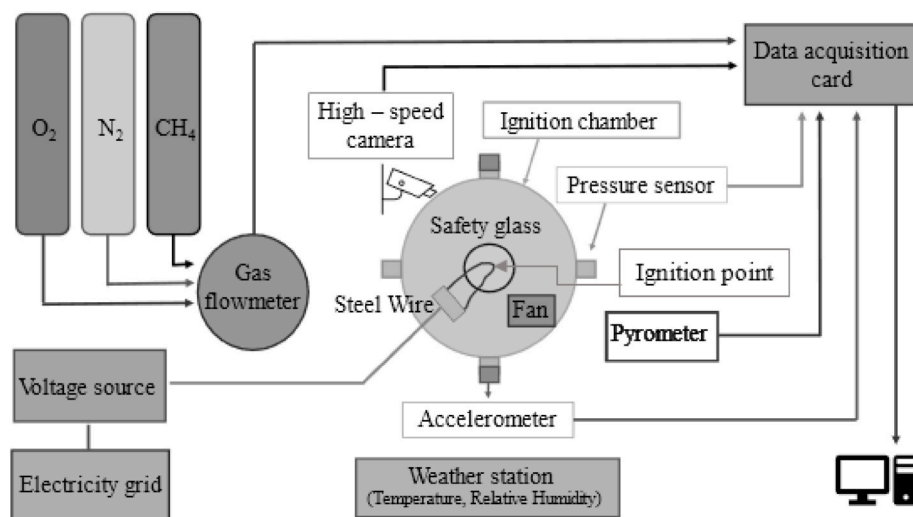


Fig. 2. Schematic diagram of the equipment designed for testing and control of input and output parameters.

adjustable voltage source of 12 V and 8 A (Joule dissipation). The temperature reached, once the electric current is applied, is measured using a Keller pyrometer with a temperature range of 600 to 2,500 °C, being its uncertainty of ± 0.02 °C.

Once the entire equipment is attached, the tests are carried out by varying the explosive mixture, the type of atmosphere, the initial temperature, the initial pressure, and the atmospheric humidity. All of them are carried out with initial pressure equal to the atmospheric pressure, with the exception of the tests that analyse the influence of the initial pressure.

1. Explosive mixture. Two types of explosive mixtures are analysed: methane-air mixtures and methane-nitrogen-oxygen mixtures. In the first case, the methane concentration is varied. In the second case, both methane and oxygen concentrations are varied. The objective is to study so-called depleted atmospheres with oxygen percentages between 17% and 20%, which may exist in certain areas of the mine, normal atmospheres with 21% oxygen and enriched atmospheres with 22% oxygen.
2. Type of atmosphere. Two types of atmosphere are tested inside the ignition chamber, the homogeneous atmosphere and the stratified atmosphere. In the first case, homogenisation is achieved by the use of fans once the gas mixture is introduced into the chamber (Willacy, 2008). The homogenisation process lasts for 2 min, which is the time necessary for all the gases to mix well. In the second case, stratified atmosphere, the fan is switched off after 2 min and the mixture is left to settle so that the gases are stratified. All tests were timed in order to eliminate the variable of time dependent stratification (5 min) with ignitions in periods of 15 min, 30 min, 1 h and 2 h (Willacy et al., 2007), (Kang and Kyritsis, 2005), (Whitehouse et al., 1996). Besides, to check the stratification, verification tests were carried out. In them, the methane concentration was measured with the use of methanometers as a function of height once the fan was switched off. From these verification tests it was observed that for mixtures with 13% of methane and after 2 h, the concentration of methane decreased from values around 12.5% in the vicinity of the injection to values around 5.9% in the most remote areas.
3. Initial temperature. Tests are carried out with methane-air mixtures, with a methane concentration of 9%, for chamber temperatures ranging from 2 °C to 22 °C. These temperatures are achieved by placing the chamber, for 8 h, in the freezer to lower its initial temperature or by using a thermal blanket to raise the initial temperature of the chamber.

4. Initial pressure. In this case, and unlike in the rest of the tests with initial pressure equal to the atmospheric pressure, the tests are conducted at initial pressures above and below atmospheric pressure. For tests above atmospheric pressure, the reference pressure is the pressure generated when the mixture is introduced into the ignition chamber, and the chamber is not opened when the mixture is homogeneous inside. For tests below atmospheric pressure, a vacuum machine is used to lower the pressure to 0.06 MPa inside the ignition chamber.

5. Atmospheric humidity. The relative humidity is measured relative to the air by means of a weather station. It is placed inside the ignition chamber before the test is carried out. The value of the humidity in those cases that the humidity is not varied is around $60\% \pm 0.1\%$. In the tests that analyse the variation of humidity, the interior of the ignition chamber is sprayed with water until the desired humidity is reached, or, on the contrary, the humidity is reduced by drying the chamber. Tests have been carried out for methane-air mixtures with 5, 9 and 10% methane and for methane-nitrogen-oxygen mixtures with 21% O₂.

In total, 180 tests were executed. Of these, 161 (89.4%) were successful, while the remaining 19 (10.6%) were unsuccessful, either because ignition of the mixture did not occur or because ignition did occur but combustion did not progress (Table 2).

Table 2
Summary of tests carried out and explosions achieved.

Tests	Total tests	Explosion (%)	No explosion (%)
Methane-air	12	83.3	16.7
Methane-nitrogen-oxygen (17% O ₂)	13	69.2	30.6
Methane-nitrogen-oxygen (19% O ₂)	13	84.6	15.4
Methane-nitrogen-oxygen (20% O ₂)	15	93.3	6.7
Methane-nitrogen-oxygen (21% O ₂)	18	83.3	16.7
Methane-nitrogen-oxygen (22% O ₂)	19	19	–
Stratified atmosphere	23	91.3	8.7
Influence of initial pressure	12	100	–
Influence of initial temperature	26	100	–
Influence of humidity	29	82.8	17.2
Total	180	89.4	10.6

3. Discussion

The results obtained after the experimental campaign are analysed and discussed below. In all tests, the same ignition energy was used.

3.1. Influence of explosive mixture composition

To analyse the influence of the composition of the explosive mixture, the explosion limits and the maximum pressures reached are evaluated, as well as the evolution of pressure and acceleration over time.

3.1.1. Explosion limits and maximum pressures

More than 113 tests have been carried out, varying the composition of the explosive mixture. Fig. 3 shows the maximum pressures recorded in these tests that are in line with those reported in published studies for with off-stoichiometric methane-air mixtures and with small discrepancies for stoichiometric methane-air mixtures (Cashdollar and Hertzberg, 1985), (Dahoe and de Goey, 2003).

From Fig. 3, the ignition of a methane-air mixture is achieved for methane concentrations in the range between 4.5 and 12.0%. This indicates that the likelihood of ignition decreases significantly for methane concentrations below 4.5% or above 12.0%. With this mixture, the maximum pressure reached is 1.80 MPa for a methane concentration between 8.0 and 9.0%.

For a mixture with 17.0% oxygen, the range of concentrations most likely to generate explosions is between 4.5 and 13.0%. However, the pressure trend suggests that for lower or higher concentrations, the likelihood of ignition is residual. Moreover, with this oxygen concentration, the highest pressure reached is 1.90 MPa, for a methane concentration of 9.0%.

A comparison of the explosion limits of this mixture with the limits obtained for the methane-air mixture shows that there is an increase in the upper explosive limit, despite the lower oxygen concentration in the air. This is justified by the presence of other compounds in the air, mainly water vapour, since the specific heat at constant volume of water vapour is much higher than that of nitrogen (Shen et al., 2016).

When the oxygen concentration is increased to 19.0%, the explosion limits are between 4.5 and 14.5% methane, i.e., the upper explosive limit is increased by 1.5%. Again, the maximum pressures (2.00 MPa) are obtained for a methane concentration of 9.0%. In this case, the average value of the maximum pressure recorded by the four sensors is 1.95 MPa.

20.0% oxygen causes an increase of the explosion limits to between

4.5 and 15.0%. With this mixture, a maximum pressure of 2.10 MPa is recorded for methane concentrations between 9.0 and 10.0%.

By increasing the concentration of oxygen to 21.0%, it has been observed that the trend established for the previous cases is maintained. Thus, the upper explosive limit increases to 17.5% and the maximum pressure recorded was 2.30 MPa for methane concentrations of 10.0%.

For an oxygen concentration of 22.0%, the lower explosive limit increases from 4.5 to 5.0%, while the upper explosive limit hardly differs from the 17.5% obtained with 21.0% oxygen mixtures. In this case, methane concentrations in the 10.0 and 12.0% range give the highest pressures, with values close to 2.40 MPa.

Table 3 lists the maximum explosion limits determined for each composition evaluated, as well as the maximum pressures recorded. The lower explosive limits are practically the same for all mixtures. On the other hand, the upper limits increase as more oxygen is added, thus increasing the explosion limits. On the other hand, methane contents higher than 8.0%, together with an increase in the concentration of oxygen, lead to an increase in the maximum pressures reached.

3.1.2. Pressure and acceleration evolution

The pressure evolution during the course of a test reflects that there is an increase in pressure over time. Initially, the rate of pressure rise is smooth (dP/dt1) since the dominant factor is the temperature that increases due to combustion. At the inflection point of the curve, the

Table 3

Explosivity limits and maximum pressures for methane-air and methane-nitrogen-oxygen mixtures.

Mixture	Explosion limits		Stoichiometric combustion		Maximum pressure P (MPa) ±0.15
	LEL (%)	UEL (%)	%-vol CH ₄	%-vol CH ₄	
Methane-air	4.0	12.5	9.5	8.0	1.86
Methane-nitrogen-oxygen (17% O ₂)	4.5	13.5	7.8	9.0	1.98
Methane-nitrogen-oxygen (19% O ₂)	4.5	14.5	8.7	9.0	1.97
Methane-nitrogen-oxygen (20% O ₂)	4.5	16.0	9.1	9.0	2.25
Methane-nitrogen-oxygen (21% O ₂)	4.5	17.5	9.5	10.0	2.35
Methane-nitrogen-oxygen (22% O ₂)	4.5	18.0	9.9	11.0	2.40

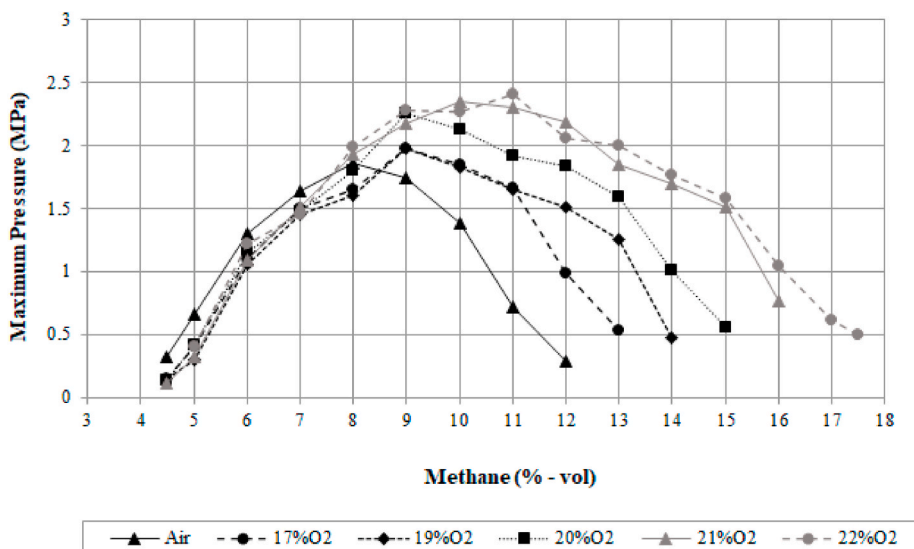


Fig. 3. Pressures generated in the different tested explosive mixtures.

change in slope is greater (dP/dt_2). In this case, not only the temperature increases but also the turbulence phenomena associated with the reflections of the pressure waves appears (Fig. 4) (Willacy, 2008), until the maximum pressure is reached. From this point on, the temperature decreases and, with it, the pressure.

However, in methane-nitrogen-oxygen mixtures with varying oxygen concentrations, it is observed that anomalies or instabilities appear at the change of pressure with time (Fig. 5) for the four pressure sensors (S1, S2, S3, S4) used during the test. This effect is similar to that which occurs in the combustion of gasoline engines, when the fraction furthest away from the ignition source self-ignites. Thus, in this farthest area, before the flame front arrives, a temperature increase occurs because of the compression of the still unburned gases by the pressure wave. The temperature rise over 600 °C, resulting from this compression could be sufficient to generate self-ignition in this area (Robinson and Smith, 1984), (Zhang et al., 2014a).

Table 4 shows the maximum accelerations recorded in the tests for methane-air mixtures and methane-nitrogen-oxygen mixtures. From the table, it can be deduced that, for mixtures with different concentrations of oxygen, the maximum accelerations are above 8.0 m/s², a value much higher than the 2.0 m/s² obtained for a methane-air mixture. Moreover, the maximum accelerations coincide with the change of slope and not with the maximum pressure, which indicates self-ignition without detonation.

Fig. 5 shows the existence of two rates of pressure rise dP/dt_1 and dP/dt_2 . Although most of the published studies work with a global value dP/dt (Cashdollar and Hertzberg, 1985), (Dahoe and de Goey, 2003), it is necessary to analyse the two rates for mixtures with different oxygen percentages and concentrations of methane. The calculus of the two rates of pressure rise has been made according to Zhang et al. (2014b).

The dP/dt_{1max} (Fig. 6) shows the highest values close to 30.00 MPa/s, for methane concentrations of 10.0% and oxygen concentrations of 22.0%. For each mixture, the maximum values of dP/dt_1 correspond to the maximum pressure values increasing the value with the increase of the percentage of oxygen with the exception of the mixture with 19.0% oxygen.

The dP/dt_{2max} study (Fig. 7) shows a similar behaviour to dP/dt_{1max} , including the anomalous behaviour of the mixture with 19.0% oxygen, which has the highest value of dP/dt_{2max} of 55.50 MPa/s (Table 5). From the figure, it is noticed that for methane-air mixtures and stoichiometric compositions good agreement exists between the values obtained with those reported by (Dahoe and de Goey, 2003).

3.2. Influence of the type of atmosphere

Fig. 8 shows the pressures obtained in tests with methane-air mixtures in stratified atmosphere and homogeneous atmosphere, with methane concentrations between 4 and 12.0%. It shows that there are hardly any differences in the pressures recorded in both environmental conditions, in concordance with published works (Tamanini, F., 2000), (Willacy, S.K., 2008).

A similar behaviour is shown by the maximum accelerations recorded in the accelerometers during the tests. Both in homogeneous atmospheres and in stratified atmospheres, 1.5 m/s² are not exceeded, a value obtained for a mixture with 8.0% methane.



Fig. 4. Recording of one explosion with a Kodak SR500 high-speed camera.

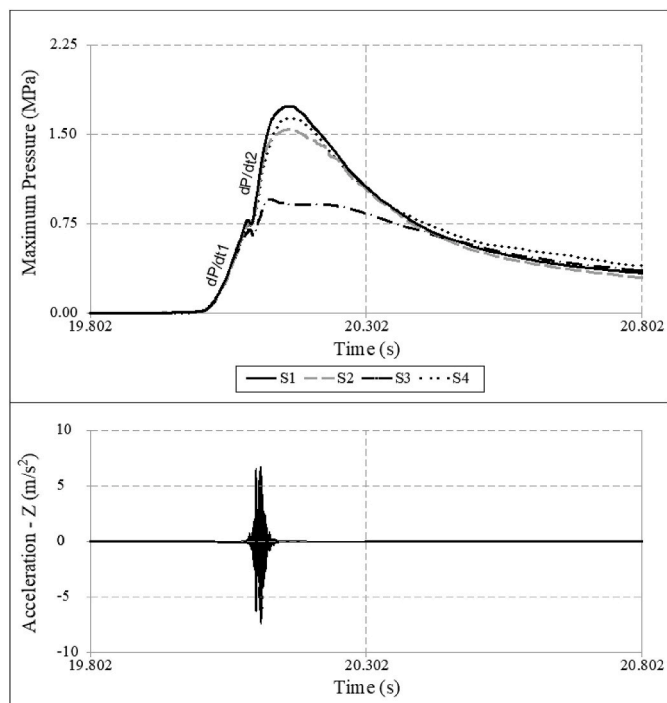


Fig. 5. Pressure evolution and acceleration for a methane-nitrogen-oxygen mixture with 17% oxygen and 9% methane.

Table 4

Maximum accelerations for each of the tested mixtures.

Mixture	% CH ₄	a (m/s ²) ± 3 m/s ²
Methane-air	8	2
Methane-nitrogen-oxygen (17% O ₂)	8	8
Methane-nitrogen-oxygen (19% O ₂)	10	18
Methane-nitrogen-oxygen (20% O ₂)	5	13
Methane-nitrogen-oxygen (21% O ₂)	11	85
Methane-nitrogen-oxygen (22% O ₂)	10	283

As for the rates of pressure rise, it is observed that dP/dt_{1max} has similar values for both types of atmospheres, while dP/dt_{2max} is notably higher in stratified atmospheres (Fig. 9).

The tests conducted for methane-nitrogen-oxygen mixtures, with oxygen concentrations between 20.0 and 22.0%, give the same results as those obtained with methane-air mixtures. No influence is observed on the explosion pressures obtained when working with homogeneous atmospheres or stratified atmospheres.

3.3. Influence of initial temperature

For the analysis of the influence of the initial temperature on the explosion, 26 tests were performed in methane-air atmospheres with different proportions of methane and in three temperature ranges: from 8.0 to 9.0 °C, from 15.0 to 16.0 °C and from 22.0 to 22.5 °C. The results

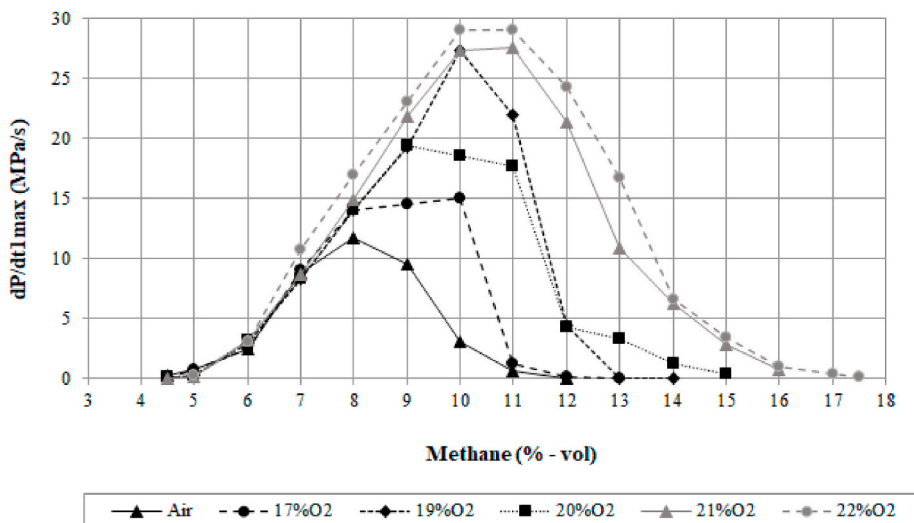


Fig. 6. $dP/dt1_{max}$ evolution for each of the tested explosive mixtures.

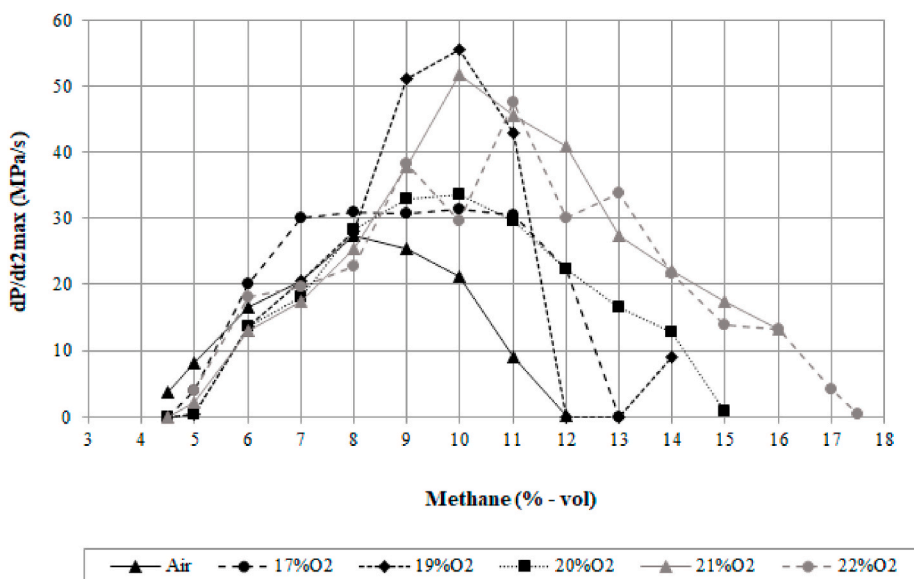


Fig. 7. $dP/dt2_{max}$ evolution for each of the tested explosive mixtures.

Table 5
Rates of pressure rise for each of the tested explosive mixtures.

Mixture	% CH ₄	dP/dt1 (MPa/s) ±0.15 MPa/s	dP/dt2 (MPa/s) ±0.15 MPa/s
Methane–air	8.0	11.74	27.42
Methane–nitrogen–oxygen (17% O ₂)	9.0	14.50	30.80
Methane–nitrogen–oxygen (19% O ₂)	10.0	27.40	55.50
Methane–nitrogen–oxygen (20% O ₂)	9.0	19.39	33.02
Methane–nitrogen–oxygen (21% O ₂)	10.0	27.41	51.70
Methane–nitrogen–oxygen (22% O ₂)	10.0	29.07	47.50

(Fig. 10) show that the initial temperature of the mixture hardly influences the lower explosive limit, around 4.0%, while it slightly lowers the upper explosive limit.

Fig. 10 also shows that in mixtures with a methane concentration

higher than 8.0%, the maximum explosion pressure decreases slightly with increasing temperature. To verify this relationship, a new battery of 6 tests was carried out with an air-methane mixture, keeping the methane concentration at 9.0% and varying the temperatures between 2.0 and 22.0 °C. The results shown in Table 6 reflect a decrease in pressure as the initial temperature increases, although of small magnitude. This behaviour may be the effect of the decrease in density when the temperature increases. Although, the initial temperature of the mixture is not considered to be decisive for the effects of the explosion, at least in the range analysed, in concordance with (Gieras et al., 2006).

3.4. Influence of initial pressure

Both inside a mine and inside a tunnel, the pressure may vary, mainly due to ventilation and the external atmospheric pressure itself. Therefore, the influence that the variation of the initial pressure, in relative terms with respect to the ambient pressure, of the mixture has on the explosion parameters is analysed. Thus, tests are carried out with initial pressures above and below atmospheric pressure, with methane-air mixtures and methane-nitrogen-air mixtures, with oxygen

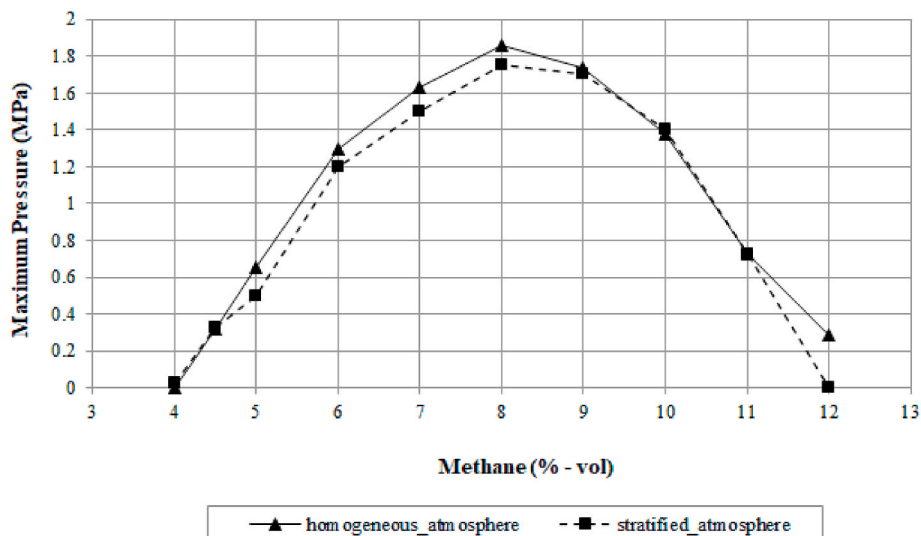


Fig. 8. Maximum explosion pressures of methane–air mixtures, with and without stratification.

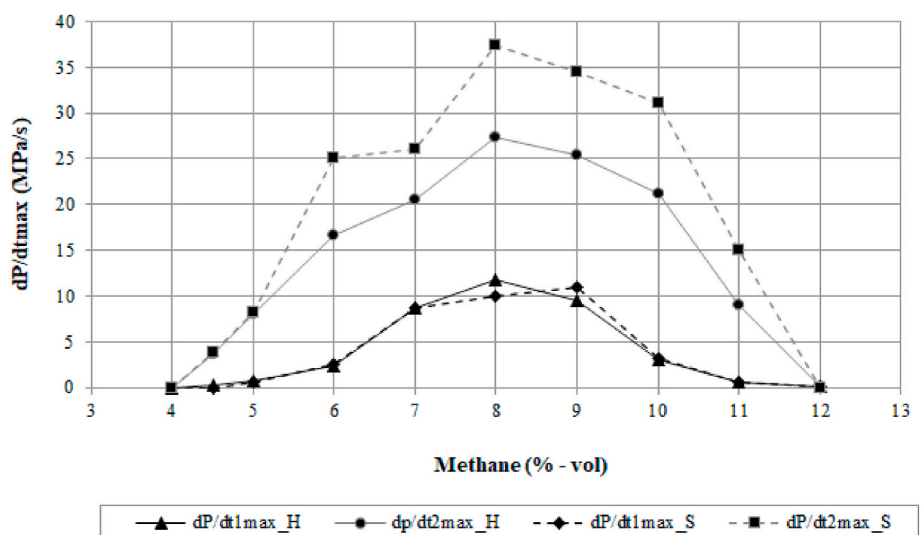


Fig. 9. Rates of pressure rise with and without stratification of mixtures.

concentrations of 20, 21 and 22%. In all cases, the methane percentages coincide with those that caused the maximum explosion pressures in the previously described tests.

Fig. 11 shows the results of the tests. It is observed that the maximum explosion pressure in the explosion chamber increases as the initial pressure of the mixture rises. Thus, for every 0.01 MPa increase in initial pressure, the maximum explosion pressure rises by about 0.20 MPa.

This is due to the effect of the initial pressure on the density of the mixture:

- With initial pressures lower than atmospheric pressure, the density of the mixture is lower. As the initial pressure increases, the density decreases and therefore a greater amount of mixture is introduced into the ignition chamber, which allows higher maximum pressures to be reached.
- With initial pressures greater than atmospheric pressure, the same behavior is observed, although in this case the increase in pressure is smoothed out.

Therefore, it can be established that the initial pressure of the mixture has influence over the rate of pressure rise that will be bigger for

initial pressures lower than the atmospheric one.

3.5. Influence of air humidity

Another parameter that, a priori, seems to be important in characterizing an explosion is humidity. In order to assess its influence, tests have been carried out with methane-air mixtures, with different degrees of humidity and methane concentrations.

Fig. 12 shows graphically the maximum pressure values achieved for mixtures with varying methane concentrations at diverse humidity conditions. It should be noted that only the results of those tests where explosions have occurred have been plotted. From the figure, it can be seen that, as the percentage of methane increases, the percentage of humidity at which the mixture is no longer explosive decreases. It is 95% for 10% methane, 88% for 11% methane or 58% for 12% methane. This is due to the high specific heat of water (1.39 kJ/kgK), which “absorbs” much of the available heat of combustion in heating up. On the other hand, a small decrease of the maximum explosion pressure is observed with increasing humidity.

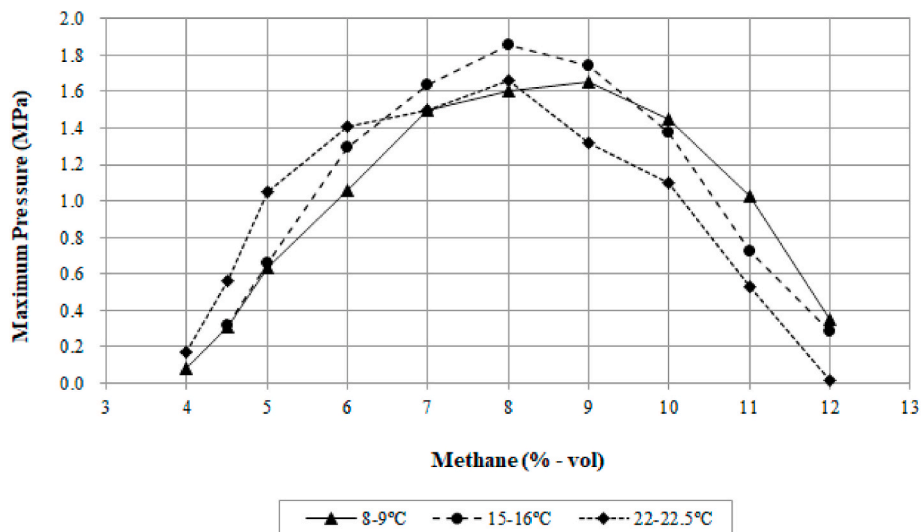


Fig. 10. Maximum explosion pressures for different initial temperatures of the methane-air mixture.

Table 6

Maximum explosion pressures versus initial temperature in methane-air mixture with 9% of methane concentration.

Temperature (°C)/±0.1 °C	2.0	8.3	9.2	14.5	15.2	18.1	18.9	21.8	22.1
Pressure (MPa)/±0.15 MPa	1.75	1.65	1.80	1.65	1.68	1.52	1.52	1.49	1.50

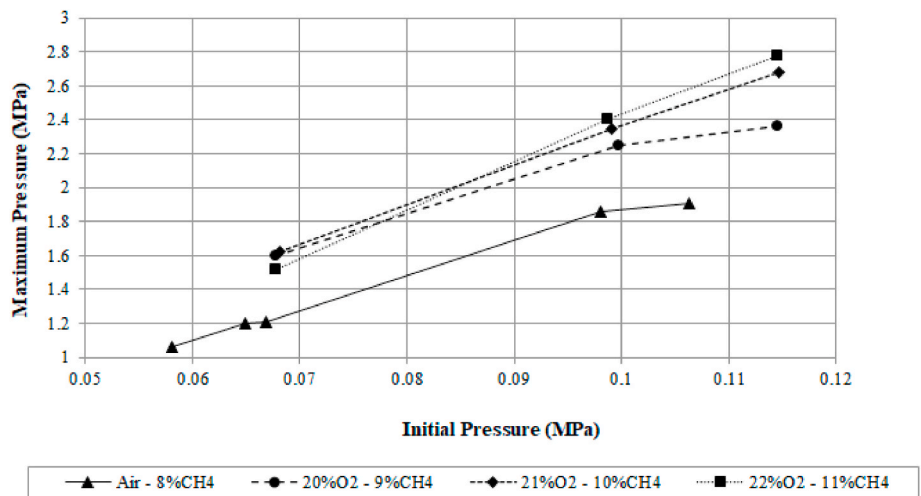


Fig. 11. Maximum explosion pressures, varying the initial pressure.

4. Conclusions

It is deduced from the study conducted that:

- The pressure-concentration graphs make it possible to obtain the explosion limits, understanding these as the extremes of the explosion limits, outside of which the likelihood of ignition is marginal.
- The lower explosive limits for methane-air mixtures are similar to those for methane-nitrogen-oxygen mixtures, including oxygen-depleted mixtures, and are around 4%.
- The upper explosive limits increase with increasing oxygen content, from 12% for a methane-air mixture, to 17.5% for a methane-nitrogen-oxygen mixture with 22% oxygen.
- For a methane-air mixture, maximum explosion pressures are obtained near the stoichiometric mixture, i.e., around 8% methane. Above this value, the maximum pressures measured in tests with this

type of mixture are lower than the pressures obtained in tests with methane-nitrogen-oxygen mixtures, including oxygen-depleted mixtures. This difference is due to the fact that, in methane-air mixtures, gases other than nitrogen and oxygen are present.

- For methane-air mixtures, with concentrations of methane above 10%, the presence of other gases, mainly water vapour, causes an oxygen deficit and hinders the reaction, by thermal and chemical effect. For low methane concentrations, the presence of other gases does not seem to be relevant, as there is an excess of oxygen.
- The influence of humidity is significant on the explosion limits. Thus, as the concentration of methane increases, the mixture is no longer explosive at lower humidity values. In addition, as the humidity increases, the maximum explosion pressure decreases slightly.
- For methane-nitrogen-oxygen mixtures and methane contents above 8%, an increase in the oxygen concentration leads to an increment in the maximum explosion pressure.

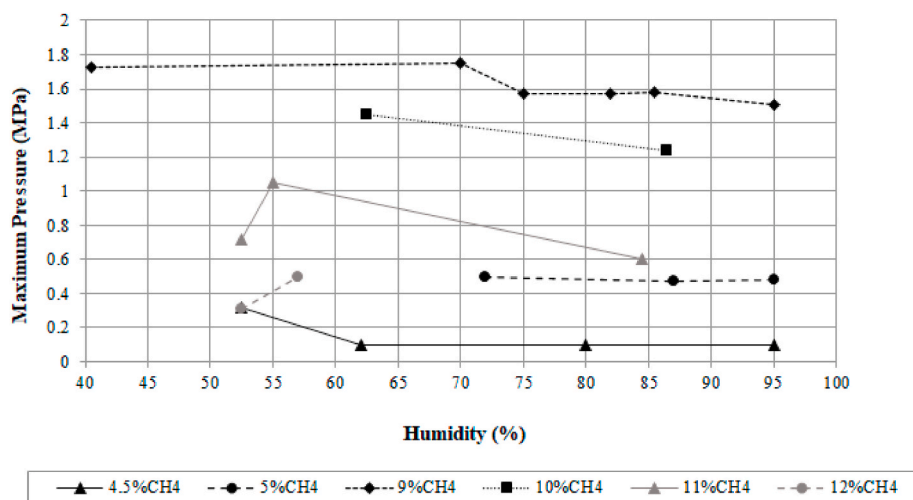


Fig. 12. Maximum explosion pressures at different humidity values.

- No significant differences in the pressures recorded in tests with stratified and homogeneous atmospheres are detected. However, it is observed that the second section of the pressure-time curve, is higher in the stratified mixture.
- The explosion pressure increases as the initial pressure of the explosive mixture rises, so that for every 0.01 MPa increase in atmospheric pressure, the maximum explosion pressure rises in the order of 0.2 MPa.
- The initial temperature of the mixture does not influence the lower explosive limit, while it slightly lowers the upper explosive limit. On the other hand, with methane concentrations above 7%, an increase in the initial temperature causes a small decrease in the maximum explosion pressure.

Author statement

Juan-Carlos Luengo-García: Conceptualization, Methodology, Supervision. Martina-Inmaculada Álvarez-Fernández: Conceptualization, Methodology, Writing—review and editing, Supervision. Celestino González-Nicieza: Methodology, Formal analysis, Lab tests. María-Belén Prendes-Gero: Formal analysis, Lab tests, Writing – original draft preparation, Writing—review and editing. Lucía Conde Fernández: Formal analysis, Lab tests, Writing – original draft preparation, Writing—review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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