fire

Article

Parameters Affecting the Explosion Characteristics of Hybrid Mixtures Arising from the Use of Alternative Energy Sources

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Abstract: Explosions of hybrid mixtures are an interesting theoretical and experimental problem in explosion sciences, because they combine the physicochemical properties of flammable gases and dusts. A hybrid mixture is composed of at least two substances in two or more states. The influence of the common presence of flammable gas on the explosiveness parameters of the combustible dust itself is proven. In this study, we present the effect of higher initiation temperatures, different initial sources of initiation with different energies, and the effect of the volume of explosion chambers on the explosions of hybrid mixtures arising from the use of alternative energy sources. The experiments were carried out in 20 L and 1.00 m^3 explosion chambers (according to EN 14034-1+A1:2011–EN 14034-4+A1:2011). The accredited method of the Energy Research Centre, VSB-TU Ostrava, for tests was used. The goal is to approximate the behaviour of these systems under different initiation conditions so that it is possible to avoid excessively conservative or overly optimistic results, which then affect the determination of explosion parameters for practical use. It was found that the volume of the explosion chambers in combination with the used initiation source has a fundamental influence on the course of the explosion characteristics.

Keywords: hybrid mixture; explosion characteristics; humidity; initial temperature; initial pressure; initiation source

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1. Introduction

Research in the area of explosion processes is highly desirable in terms of protecting employees from the effects of explosions in the context of occupational health and safety, but also in relation to the prevention and minimisation of potential damage related to the effects of explosions on technology. The processes involved in explosions of single gas mixtures and dust dispersions are relatively well known and understood. This is not the case for mixtures of these, i.e., a mixture of a combustible gas (vapor), combustible dust and an oxidising agent (e.g., air), nor are these mixtures much addressed in terms of the legislation of the European Union. Initial research focused on measuring the explosion parameters of only single pure substances in gaseous, liquid, and solid states. Internationally, there has been a significant increase in research activities in the field of explosion prevention, particularly in the context of major industrial accidents [1]. A number of experimental and theoretical studies have also been carried out on the nature of solid dispersion and pressure wave transmission in explosions [1–3].

The determination of the parameters of explosion is usually based on the concept of ideal (homogeneous) agitation of the combustible dust. Theoretically, it is then possible to derive the normalized rate of explosion pressure rise from the Cubic law [4]. However, a high degree of uncertainty is introduced into this procedure, in particular by the manner and degree of agitation of the combustible dust in the test explosion chamber, the homogeneity of the explosion atmosphere inside the explosion chamber and the mode of initiation. Determination of homogeneity is also a fundamental step required to quantify the maximum explosion pressure in studies where pressure measurement systems are typically calibrated to model dust dispersions of nicotinic acid (niacin), lycopodium and Pittsburgh coal.

Current research in the field of explosion parameters is focused on partial fragments of this area, and the complexity of the view of the problem is suppressed. Research results summarized, for example, in [5], present that two types of explosion chambers, accepted by the professional community as standard, namely 20 L and 1 m^3, are currently used for research. The type and size of the initiating source is also monitored. In addition to the standard dusts, a wide spectrum of explosion characteristics of industrially produced dusts is available [5–9]. In addition to the explosion parameters of dust dispersions, the explosion parameters of gases and vapours of flammable liquids are also studied. The results show that it is possible to study the explosion characteristics of various molecular systems in the range from standard initial conditions of atmospheric pressure and temperature to extreme (250 °C, 30 bar) initial conditions [10,11]. These analytical instruments cover a relatively high range of volumes from 0.005 to 1.00 m^3. The representative substances investigated were hydrogen, methane, ethane, ethylene, propane, propene, n-butane and carbon monoxide. Emphasis was placed on the concentration ranges of the substances studied. These conditions and representative substances were chosen with a view to the direct applicability of the results in specific industrial applications. Among the results of these studies, it is particularly interesting to compare the significant differences between the values obtained in the 20 L and 1.00 m^3 volumes and to point out the absence of data for 1.00 m^3.

Research on the explosion parameters of pure substances was later joined by the research of hybrid mixtures. The term "hybrid mixture" is used for an explosive assembly consisting of at least two substances in two or more states of matter. For interest, the German researcher Engler was the first to mention the possible different behaviour of explosions of substances of the same state and hybrid mixtures already in 1885 (he studied soot and charcoal dust in combination with methane or coal gas) [12]. The formation of an explosive hybrid mixture can occur by mixing quantities below the lower explosion limit (LEL) in the case of a pure gas and the minimum explosive concentration (MEC) in the case of a pure combustible dust. When discussing hybrid mixtures, emphasis is often placed on mixing combustible gas at concentrations below the lower explosive limit of the gas itself into an already explosive concentration of dust. Real experiments are performed according to European (EN) standards. The effect of the common presence of combustible gas on the explosive parameters of combustible dust itself is well established. These effects include higher values of maximum explosion pressure and maximum rate of explosion pressure rise and lower values of minimum explosive concentration (MEC) and minimal initiation energy (MIE) [13].

The danger of explosions of flammable liquid vapours, gases mixed with oxidising agents and combustible dusts is associated with a number of technological installations in various industrial sectors, especially in the energy, petrochemical, pharmaceutical and food industries, where explosions, or the number of flammable materials and suitable conditions, are often considered as one of the possible emergency scenarios [14]. The effect of the presence of flammable gas or flammable liquid vapour on the explosion parameters of a combustible dust (particle diameter: 70 to 500 μm) is described in the literature [15–17]. The presence of flammable gas increases the already existing explosion hazard. Perhaps the most well-known hybrid mixture is methane with coal dust [8]. This system is often encountered in deep coal mining. There are also several examples of the formation of hybrid mixtures in other industries, such as the hybrid mixture of natural gas and dust dispersion in the combustion of fossil fuels in thermal power plants [18] and the various hybrid mixtures of hydrocarbons and resins found in the production of plastic dusts [19]. Another example of an industry with unintentional hybrid explosions is the pharmaceutical and drug manufacturing industry, which often involves the transfer of combustible dusts into a container containing a flammable solvent [20].

One of the factors that affect the measurement of explosion parameters of hybrid mixtures is the volume of the explosion chamber and the type and energy of the initiating source. In article [21], values of explosion parameters are determined for hybrid mixtures of coal dust, lycopodium and niacin with methane and hydrogen in chambers of 1.00 m^3 and 20 L volume. The results show a significant increase in the normalized maximum rate of explosion pressure rise in the 20 L chamber compared to the 1.00 m^3 chamber, due to the higher turbulence level in the smaller chamber. It has also been shown that permanent spark can be used for easily ignitable dusts and, in some cases, can produce even higher pressure rise rates than chemical igniters.

There is no internationally recognised standard for determining the technical safety characteristics of hybrid mixtures. In the development of a new standard, first results from parametric studies in a joint research project in Germany have led to a state-of-the-art procedure that can be adopted by laboratories already testing dust explosions in a 20 L explosion chamber [22]. In a round robin test of hybrid mixtures, with methane as the gas component and specific corn starch as the dust sample, the practicality of the procedure, the scatter of results and the variance between test facilities in different laboratories were investigated. The outcome of these measurements is intended to help unify the requirements for testing hybrid mixtures. The results measured at the Energy Research Centre of the VSB—Technical University of Ostrava were also used in the development of the new standard.

Today, there is a noticeable shift away from fossil fuels and a search for various alternative energy sources. However, alternative energy sources bring new technologies and materials, where in some cases, a hybrid mixture can be created. This also brings new challenges in terms of explosion protection. An example of an alternative energy source can be the biomass (or biochar) gasification technology located at the Energy Research Centre of the VSB—Technical University of Ostrava, in which a hybrid mixture of synthetic gas and carbon-based dust dispersion (ash, soot, etc.) can be formed, where the syngas as an alternative energy source is the output of the whole technology. In the technology, the two substances come into contact in a so-called hot filter where the temperature is above 400 °C. This can create an explosive hybrid mixture. This technology is not unique; similar gasification technologies are found at other academic or industrial worksites around the world. In the context of increasing concern for environmental protection, the number of similar gasification technologies can be expected to increase. This will also increase the risks arising from the use of these technologies, including the risks of fires and explosions (and not only from potential hybrid mixtures resulting from these technologies). Although the original hybrid mixtures have been investigated, the new mixtures to be used as alternative energy sources raise a number of issues, particularly in terms of their safety.

The aim of this paper is to compare the explosion characteristics of selected hybrid mixtures, focusing mainly on alternative energy sources, under different initialization conditions. The substances selected were hydrogen, methane, syngas from gasification technology, corn starch, dust from gasification technology and their hybrid mixtures. In the explosion chambers, mainly, the maximum explosion pressure (p_{max}) and the maximum rate of explosion pressure rise $(dp/dt)_{max}$ and the cubic constant K, respectively, were investigated.

2. Materials and Methods

This section will describe the experimental equipment used, the test substances, the initiating sources and the operating procedures that were used in the measurement of the explosion parameters. The following are the definitions of the explosion parameters that are important for this article.

Maximum explosion pressure p_{max} (bar)—Maximum overpressure arising in a closed vessel during an explosion of an explosive atmosphere, determined under the given test conditions and standard atmospheric conditions (the maximum value of the explosion pressure measured in tests covering dust concentrations in the explosive range).

Maximum rate of explosion pressure rise $(dp/dt)_{max}$ ($bar \cdot s^{-1}$)—Maximum value of explosion pressure rise per unit of time during the explosion of all explosive atmospheres in the range of explosiveness of a flammable substance in a closed vessel under specified test conditions and standard atmospheric conditions.

Cubic constant K ($bar \cdot m \cdot s^{-1}$)—The volume-dependent parameter of a given dust/gas/hybrid mixture, which is calculated using the cubic law equation:

$$\text{Cubic law: } K = (dp/dt)_{max} \times V^{1/3}, \tag{1}$$

where

V—the volume of the explosion vessel.

The values for dusts weres determined according to the standard EN 14034-1+A1:2011, EN 14034-2+A1:2011 and the values for gases were determined according to EN 15967:2022. The values for hybrid mixtures weredetermined by combining the two previous standards with slight modifications.

Figure 1 shows an example of primary pressure records for H_2.

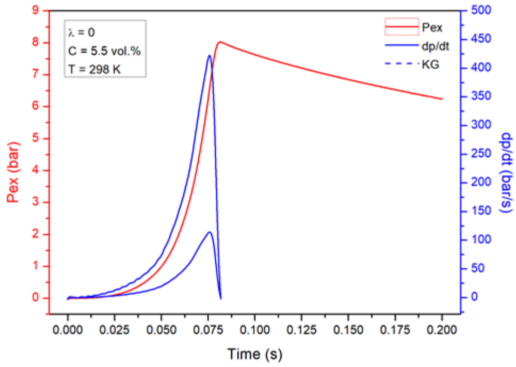

Figure 1. Example of primary pressure records for H_2.

2.1. Experimental Equipment Used

The experimental equipment used for the measurements consisted of a combination of explosion techniques and techniques enabling the characterisation of the properties of mixtures of materials and the monitoring of gaseous substances, with which the flammable ensemble and the composition of the explosible atmosphere were characterised. Both instruments for determining flammability (LEL, UEL) and instruments for determining flash points and ignition temperatures of flammable gases and vapours of flammable liquids were used as tools for investigating combustion processes. This experimental equipment belongs among the standard ones at the level of the Czech Republic and the European Union. For the measurement of explosion parameters, explosion chambers specified in EN 14034-1+A1:2011 [23] and EN 14034-2+A1:2011 [24] were used with a volume of 20 L and 1.00 m^3. These chambers represent a sufficiently effective tool for investigating the explosion parameters of hybrid mixtures with dispersed dust with particle diameter of 1 to 500 µm. The explosion chamber with a volume of 1.00 m^3 is one of the superior ones at the level of the Czech Republic and the European Union (Note: "Superior" in this case means that there is no such device in the world in which it is possible to prepare hybrid mixtures of gases dust or vapours and heated them up to 250 °C before ignition).

2.1.1. Explosion Chamber CA 1M3

The first experimental technique for the study of explosions is a specific variant of the 1.00 m^3 explosion chamber manufactured by OZM Research s.r.o., Bliznovice 32, 538 62 Hrochuv Tynec, Czech Republic It is a spherical vessel with an inner diameter of 1240 mm.

The material and components used are suitable for use in experiments at atmospheric initial pressure and initial temperature (up to 200 °C). The maximum operating pressure is 3 MPa, and the chamber is subjected to a 4 MPa hydraulic test. The inner surface of the chamber is coated with a protective layer of nickel (99.9% purity) with a minimum thickness of 0.5 mm. The chamber is equipped with an electrically heated jacket. For this reason, the shell is covered with 80 mm thick thermal insulation and a cover. The system allows the measurement of the explosion parameters of three states of matter, i.e., dust dispersion, gaseous mixture and vapour mixture of flammable liquids in air or oxygen atmosphere and hybrid mixtures [25]. An illustrative picture of the explosion chamber is shown in Figure 2.

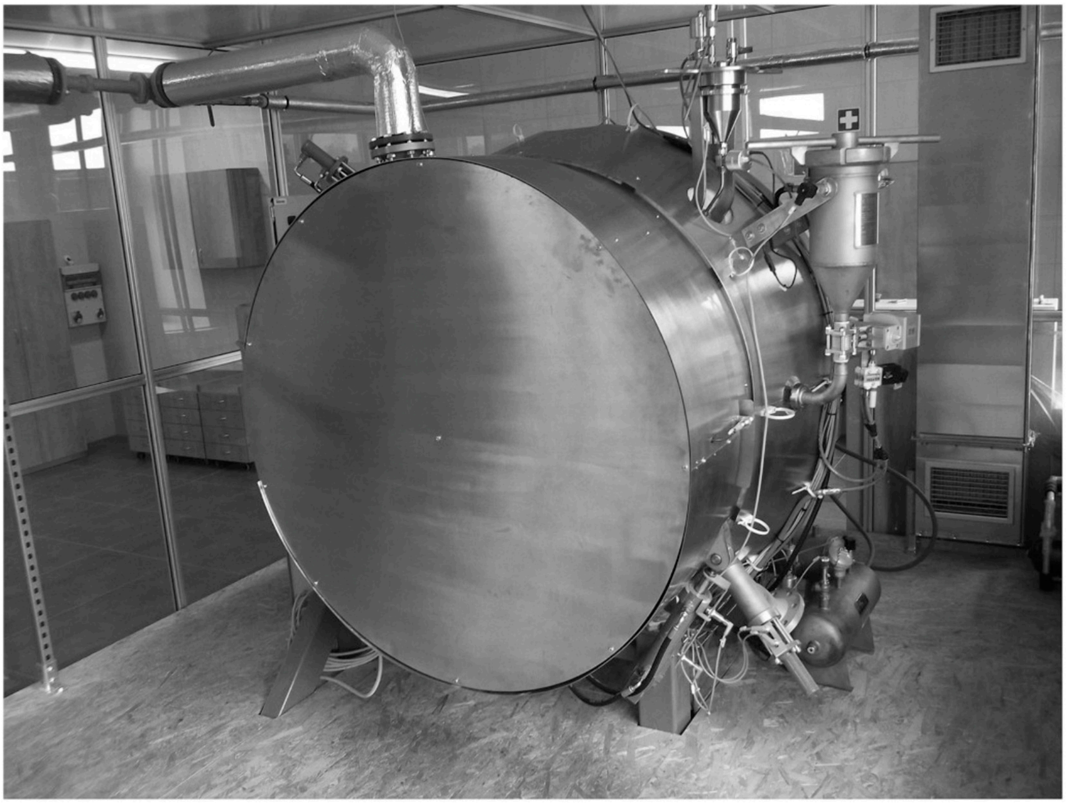

Figure 2. Illustrative picture of the explosion chamber CA 1M3 [21].

2.1.2. Explosion Chamber CA 20 L

The second experimental technique for studying explosions is a specific variant of the 20 L explosion chamber manufactured by OZM Research s.r.o., Bliznovice 32, 538 62 Hrochuv Tynec, Czech Republic. The body of the explosion chamber consists of a spherical double-walled stainless-steel vessel, with an inner diameter of 0.362 m and a volume of 20 L. The vessel is also equipped with a glass opening, allowing easy observation of the events inside the chamber. The materials and components of the chamber are suitable for use in experimental equipment at atmospheric pressure and initial temperature up to 160 °C and a maximum chamber operating pressure of 3 MPa [26]. An illustrative picture of the chamber is shown in Figure 3.

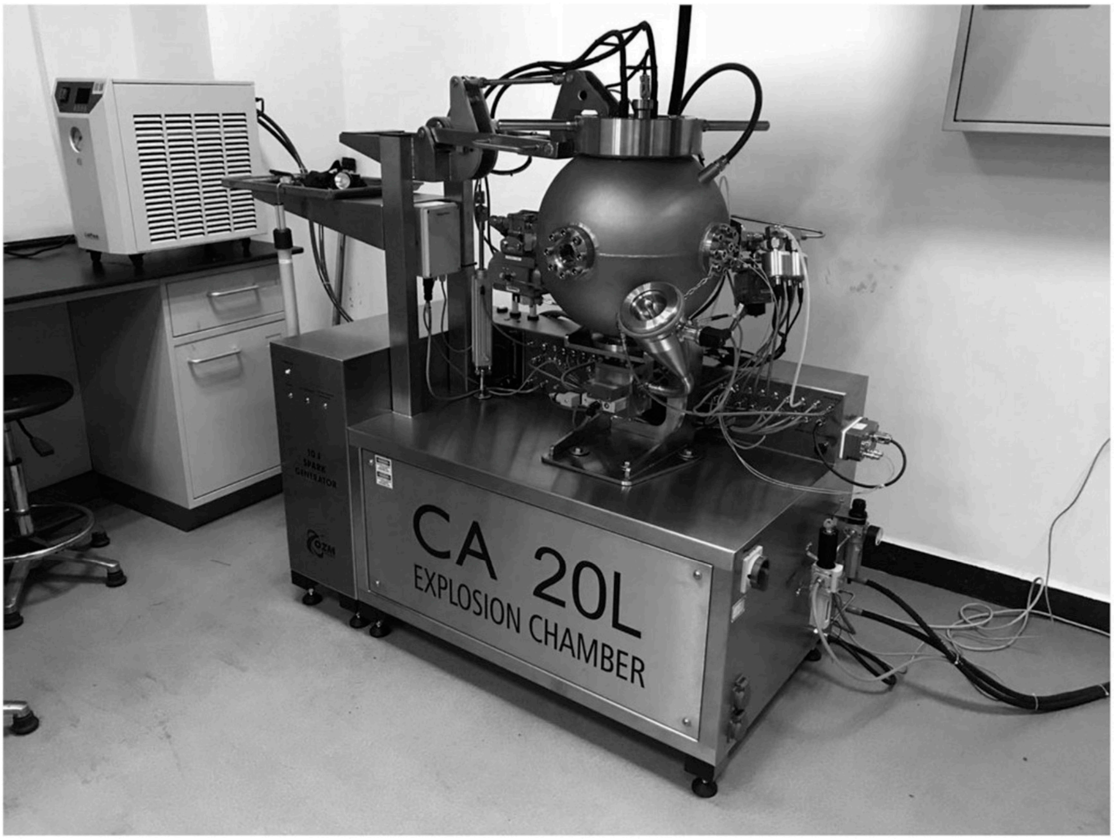

Figure 3. Illustrative picture of the explosion chamber CA 20 L [21].

A pair of piezoelectric pressure sensors by Kistler, type 701A (natural frequency 70 kHz), measured the explosion pressure in both chambers. The pressure range for the sensors was set to 2.5 MPa. The acquisition of the measured data was carried out using a data card (Tedia type UDAQ-3644) with a sampling rate of up to 800,000 samples/s/channel with a possible number of 4 channels.

The dust inserted from the reservoir was pressurized to 20 bar for a chamber with a volume of 1.00 m^3. Atmospheric pressure was then measured in the explosion chamber. An injection nozzle with retroreflection according to the EN 14034-1+A1:2011 standard was used in the measurements.

The explosion chamber with a volume of 20 L was partially evacuated to 0.4 bar before dust injection, so that after dust injection, the pressure in the chamber was equal to 1 bar. The stirring pressure was then 20 bar. An injection nozzle with retroreflection according to the EN 14034-1+A1:2011 standard was used in the measurements.

In the case of a hybrid mixture, the air volume in both chambers was determined according to the partial pressure method.

Indicate ignition delay in gas/dust/hybrid experiments and for both volumes were as follows:

Chemical Igniters

The delay between the start of dust swirling and the activation of the initiation source in a 1.00 m^3 explosion chamber (initiation delay) was (0.6 ± 0.01) s. The initiation time delay in a 20 L explosion chamber was 60 ms.

Induction Spark

The time of discharges (spark generation) was set to (0.2 ± 0.02) s. If the time of discharges of 0.2 s did not lead to the ignition of the test mixture, the test was repeated with the duration of the discharges extended up to (0.5 ± 0.02) s.

2.2. Substances Investigated

Substances related to alternative energy sources were selected as representative. Specifically, substances occurring in gasification technology were selected. The product of the technology is syngas. Biomass (in this case, specifically biochar) is used for gasification. Syngas, which was the measured substance, is the final product of gasification. The basis of this technology is a gasification generator with a fixed bed. Fuel (biomass, biochar) is automatically fed to the lower part of this reactor from the fuel tank by two screw conveyors based on the measured temperature inside the reactor. The reactor operates at temperatures up to 950 °C, while syngas is produced at a temperature of approximately 750 °C. The produced gas from the reactor is transported to a filter (high-temperature solid pollutant separator—so-called hot filter), where dust particles are removed by the dry method with filter candles made of ceramic fibres. It is in this filter that there is a hybrid mixture, i.e., not yet purified syngas mixed with flammable solid dust particles.

Other gaseous substances selected as representatives were hydrogen and methane, which are also currently produced and used as alternative energy sources.

2.2.1. Substances in One State

Gases

- syngas (gas of composition: 8% CO_2, 10% H_2, 29% CO, 4% CH_4, 48% N_2, 1% O_2),
- hydrogen,
- methane.

Solids

- solids in the form of dust from the gasification technology (where biomass or biochar is the input to the gasification process, and soot and ash are the output “waste” gasification substance,
- corn starch.

All substances were investigated in the presence of air as a dispersion medium. The exact composition of the hybrid mixtures was determined in the laboratory. The corn starch sample and solids in the form of dust from the gasification technology was analysed for particle size distribution using a 1090 CILAS particle size analyser. The results are shown in Figures 4 and 5.

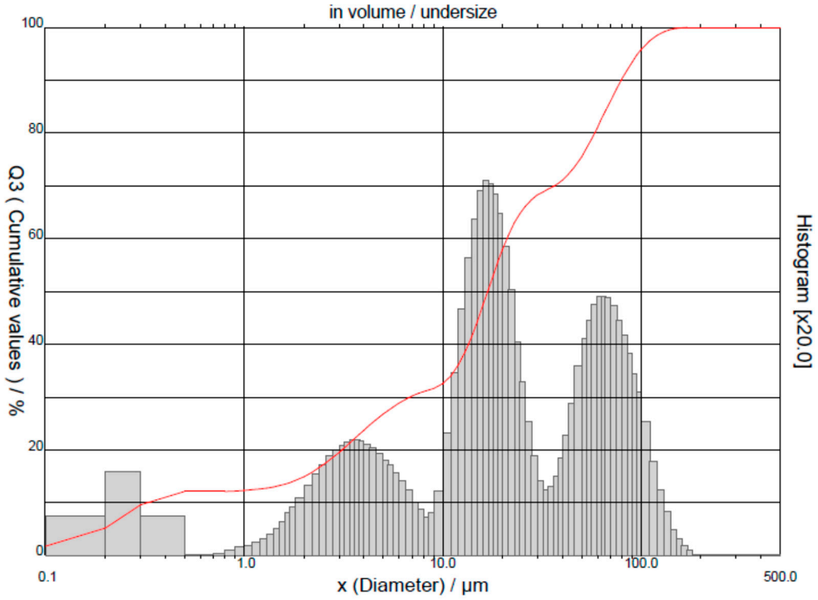

Figure 4. Particle size distribution of corn starch (Note: The part on the left side of figure are diameters of particles distributions cumulative values in logarithmic scale.) [27].

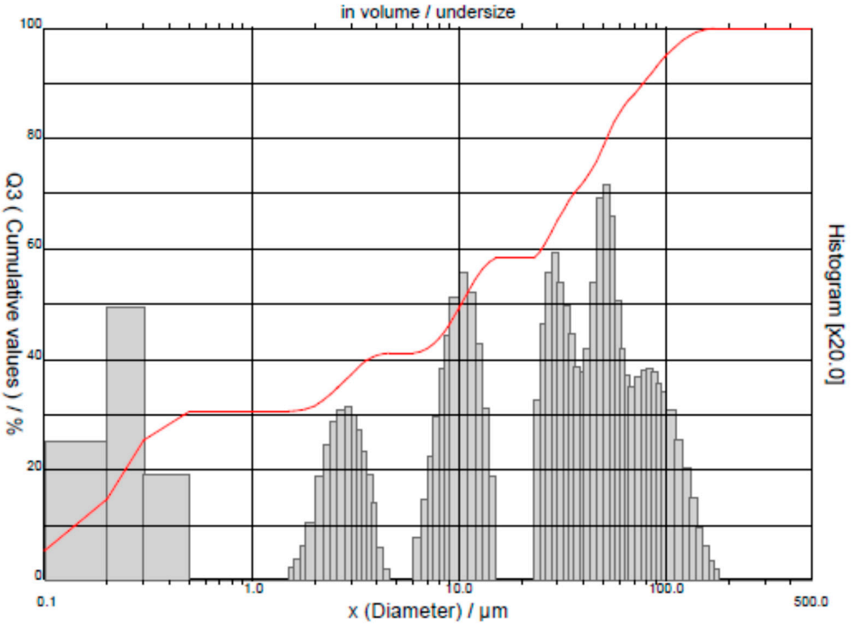

Figure 5. Particle size distribution of solids in the form of dust from the gasification technology (Note: The part on the left side of figure are diameters of particles distributions cumulative values in logarithmic scale.) [28].

2.2.2. Hybrid Mixtures

An overview of the hybrid mixtures investigated and compared is given in Table 1.

Table 1. Hybrid mixtures investigated.

Hybrid Mixture	Volume Percentage of Gas	Chamber Volume	Initiation	Temperature	Explosion Parameters
Dust from gasification technology and synthesis gas	Concentration of synthesis gas corresponded to the maximum of its explosion pressure—20 vol.%	20 L	1 piece of chemical igniter 5 kJ	Standard	p_{max} $(dp/dt)_{max}$
Methane and corn starch	3 vol.%	1.00 m^3 20 L	Spark energy 50 J, 1 piece of chemical igniter 5 kJ	Standard	p_{max} $(dp/dt)_{max}$
Hydrogen and corn starch	3 vol.% 9 vol.%	1.00 m^3 20 L	1 piece of chemical igniter 5 kJ 1 piece of chemical igniter 2 kJ	20 °C 50 °C 100 °C	p_{max} $(dp/dt)_{max}$

2.3. *Workflows*

In particular, EN, ISO and ASTM normative standards were used. Mainly used were the following:

- ASTM E1226:2019 [29],
- EN 14034-1+A1:2011 [23],
- EN 14034-2+A1:2011 [24],
- EN 15967:2022 [30],

adapted to the measurement of hybrid mixtures. Some facts from the now obsolete ISO 6184-3:1985 [31] were also used. For the measurement of explosion parameters for the problem of this paper, the methodology [32] published at the German BAM Institute was partly used, where a series of comparative tests of explosions of a hybrid mixture of cornstarch and methane in explosion chambers with a volume of 20 L were carried out.

To measure the explosion parameters of hybrid mixtures in the explosion chamber with a volume of 1.00 m^3, the author of the paper compiled a methodology in [28]. This methodology characterizes the procedure for measuring the explosion parameters p_{max} and $(dp/dt)_{max}$ of hybrid mixtures of flammable gas and combustible dust in an explosion chamber with a volume of 1.00 m^3.

This methodology was created during the course of individual measurements and was followed for the measurement of explosion parameters. Two substances are measured in two different states, so it is not possible to proceed exactly according to EN 15967:2022 [30], EN 14034-1+A1:2011 [23] or EN 14034-2+A1:2011 [24]. However, the initial steps of the measurement procedure are identical to the standards mentioned above. The main difference is in the injection of substances into the explosion chamber. The procedure is as follows: first, flammable gas is injected into the explosion chamber using the method of partial pressures; then, the atmosphere inside is homogenized. Explosive dust is then injected into the chamber, and the entire mixture is initiated. The final steps are further similar to the standards mentioned above.

The specific conditions and purpose of the methods described in EN 14034-1+A1:2011, EN 14034-2+A1:2011 and EN 15967:2022 (according to which the explosion parameters were measured) do not allow the results to be evaluated by classical statistical methods. These methods are not applicable here because the conditions for the distribution of random deviations are not met, and systematic deviations—caused by the influence of measurement conditions—cannot be separated from random deviations. In accordance with test standards, the measurement error is set at ±10% of each measured value.

Note: In the case of measuring hybrid mixtures, the following standards were mainly observed: EN 14034-1+A1:2011, EN 14034-2+A1:2011 and EN 15967:2022, where the calibration of instrumentation, conversions and permitted measurement deviations, etc. are specified in their individual parts.

3. Results

For individual pure substances and hybrid mixtures, the results and their comparison are presented in this chapter. In Figure 6, an explosion of the hybrid mixture taken through the optical access in the explosion chamber is shown for illustration.

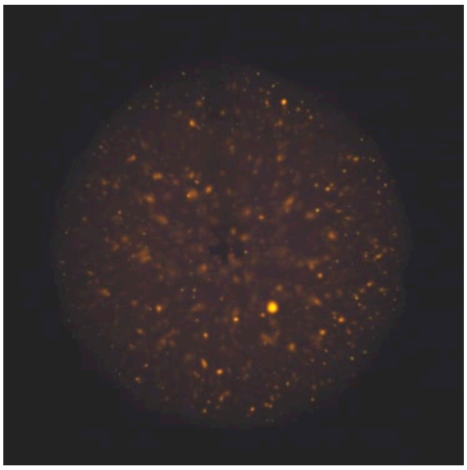

Figure 6. Photo of explosion of the hybrid mixture.

3.1. Syngas, Gasification Dust and Their Hybrid Mixture

In Figures 7 and 8, there is a comparison of the explosion parameters of syngas and dust from the gasification technology and a hybrid mixture of both. The measurements were carried out in a 20 L explosion chamber. The source of initiation in the case of the gas was an electric spark with an energy of 50 J (in accordance with EN 15967:2022 [30]); in the case of the dust, it was two chemical igniters of 5 kJ (10 kJ in total). For the hybrid mixture, one chemical igniter with an initiation energy of 5 kJ was used. The syngas concentration in the hybrid mixture was 20% by volume. Table 2 shows the measured explosion parameters.

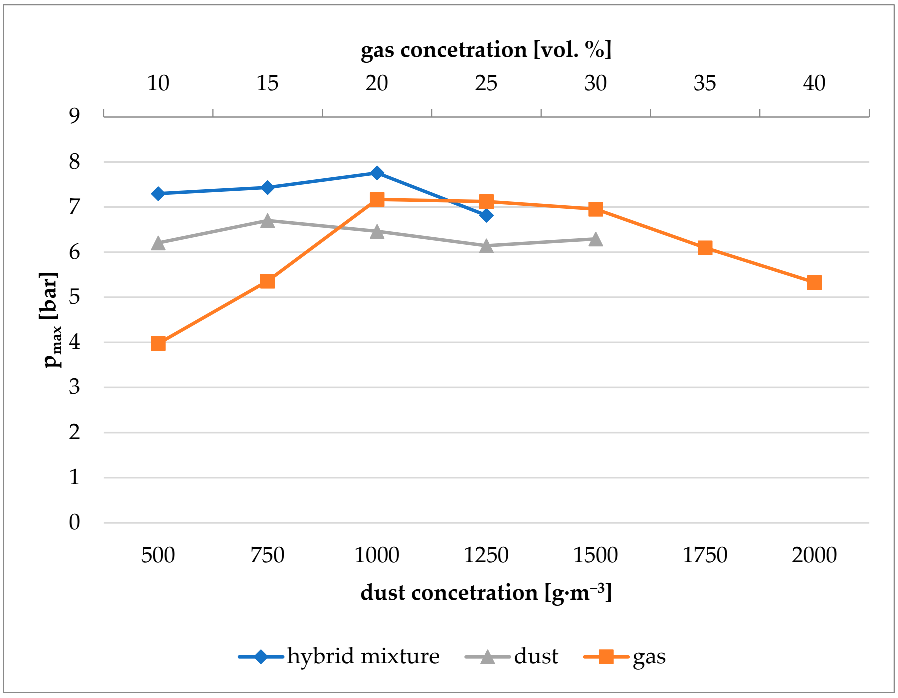

Figure 7. Comparison of maximum explosion pressure of syngas, gasification dust and their hybrid mixture.

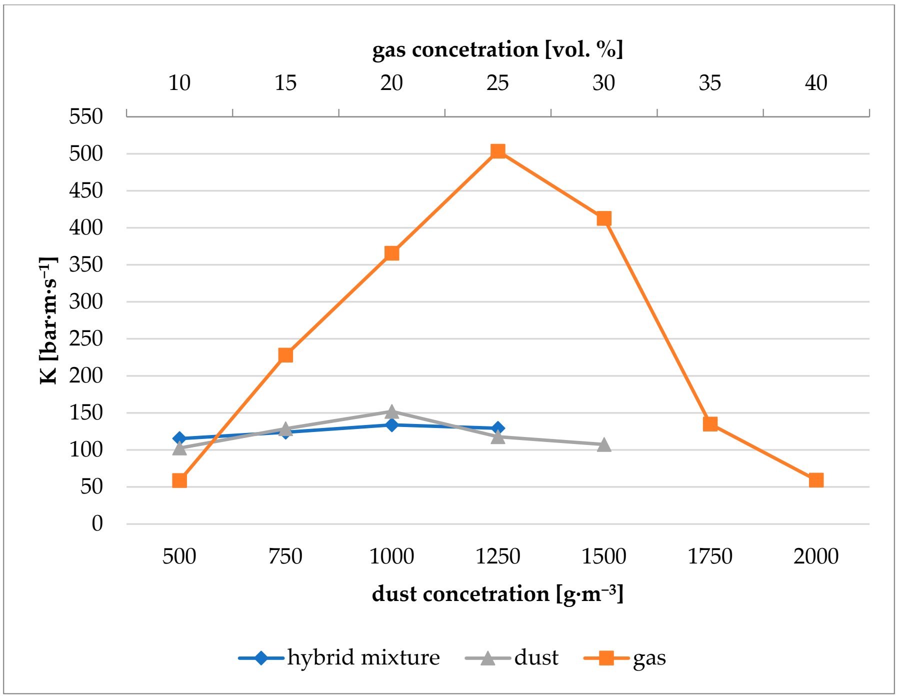

Figure 8. Comparison of the cubic constant of syngas, gasification dust and their hybrid mixture.

Table 2. Explosion parameters of a hybrid mixture of syngas and dust from gasification technology.

Concentration ($g{\cdot}m^{-3}$)	p_{max} (bar)	$(dp/dt)_{max}$ ($bar{\cdot}s^{-1}$)	K ($bar{\cdot}m{\cdot}s^{-1}$)
500	7.30	425.00	115.36
750	7.44	456.00	123.78
1000	7.76	493.00	133.82
1250	6.82	476.00	129.20

3.2. Hydrogen, Corn Starch and Their Hybrid Mixture

In Figures 9 and 10, a comparison of the explosion parameters of pure hydrogen and cornstarch, and a hybrid mixture of both, is made. Measurements were carried out in 20 L and 1.00 m^3 explosion chambers. The source of initiation in the case of the gas was an electric spark with an energy of 50 J (in accordance with EN 15967:2022 [30]); in the case of the dust, it was a chemical igniter of 5 kJ. For the hybrid mixture, it was one chemical igniter with an initiation energy of 5 kJ and also an electric spark with an energy of 50 J. The concentration of hydrogen in the hybrid mixture was 3% by volume. For comparison, Figure 9 shows the maximum explosion pressure values for pure hydrogen from work [33] and standard EN 15967:2022.

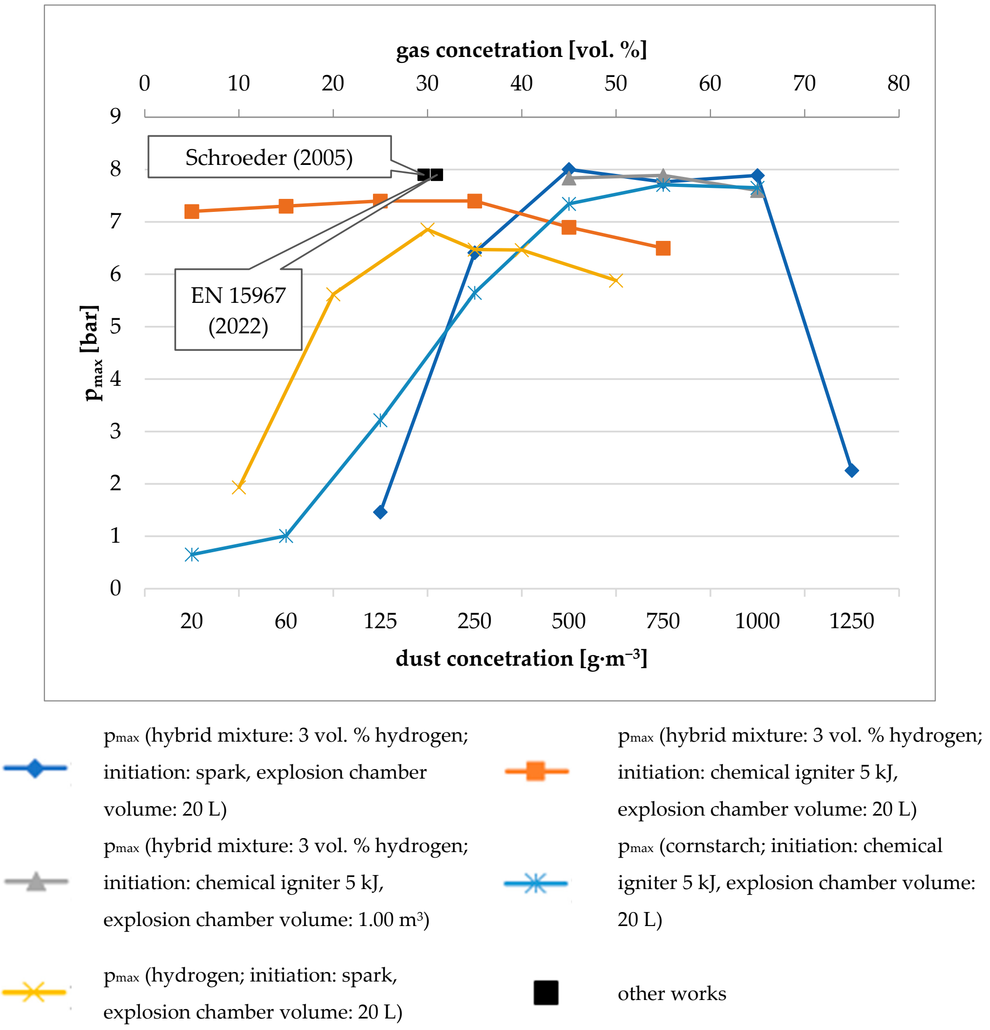

Figure 9. Comparison of the maximum explosion pressure of hydrogen, cornstarch and their hybrid mixture [30,33].

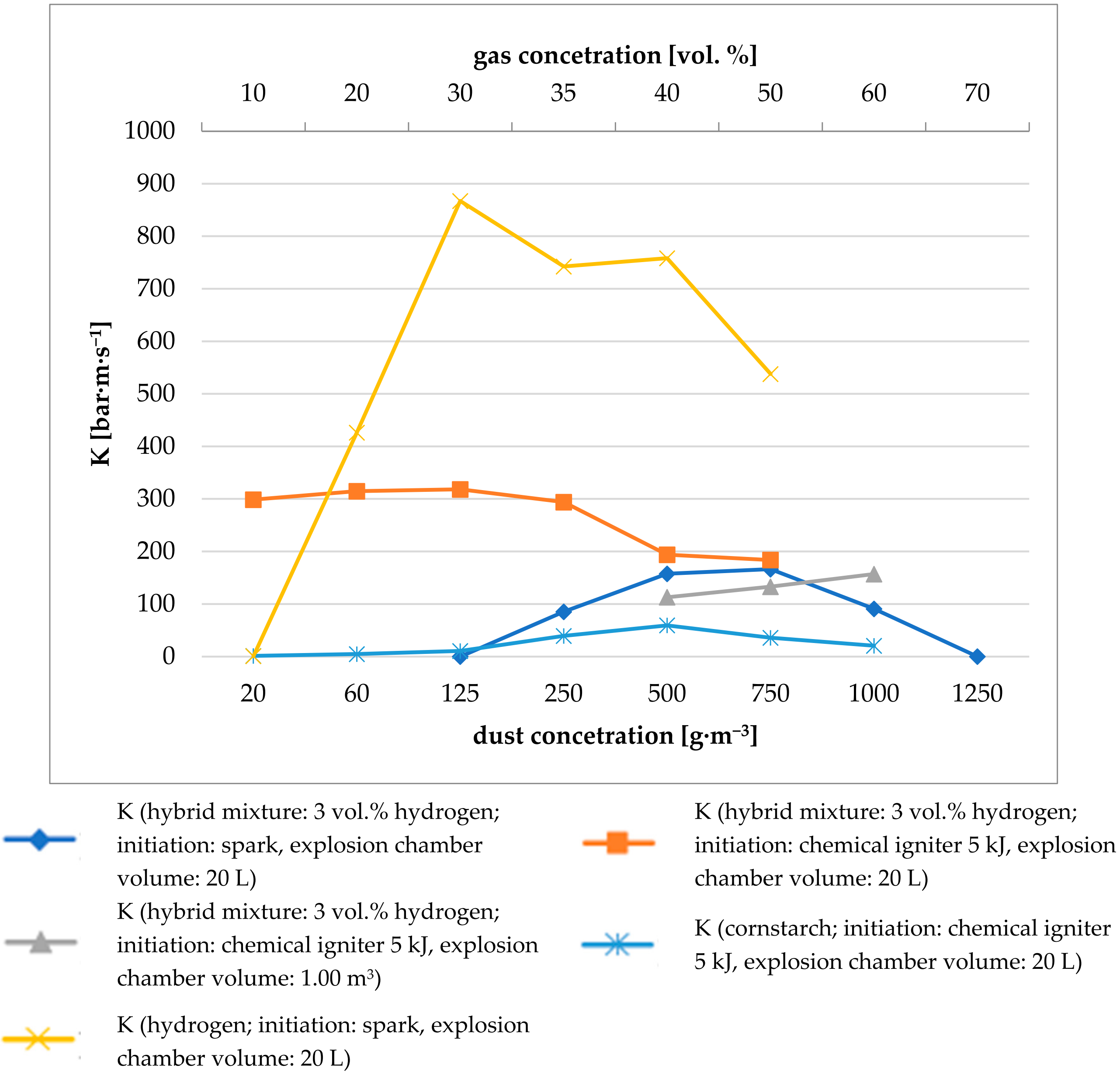

Figure 10. Comparison of the cubic constant of hydrogen, corn starch and their hybrid mixture.

3.3. Methane, Corn Starch and Their Hybrid Mixture

3.3.1. Measurements under Standard Conditions

In Figures 11 and 12, there is a comparison of the explosion parameters of methane, starch and their hybrid mixture under standard laboratory conditions. The measurements were carried out in 20 L and 1.00 m^3 explosion chambers. The source of initiation was one chemical igniter with an initiation energy of 2 kJ or 5 kJ. The concentration of methane in the hybrid mixture was 3 vol.% or 9 vol.%. For comparison, Figure 11 shows the maximum explosion pressure values for pure methane from work [10].

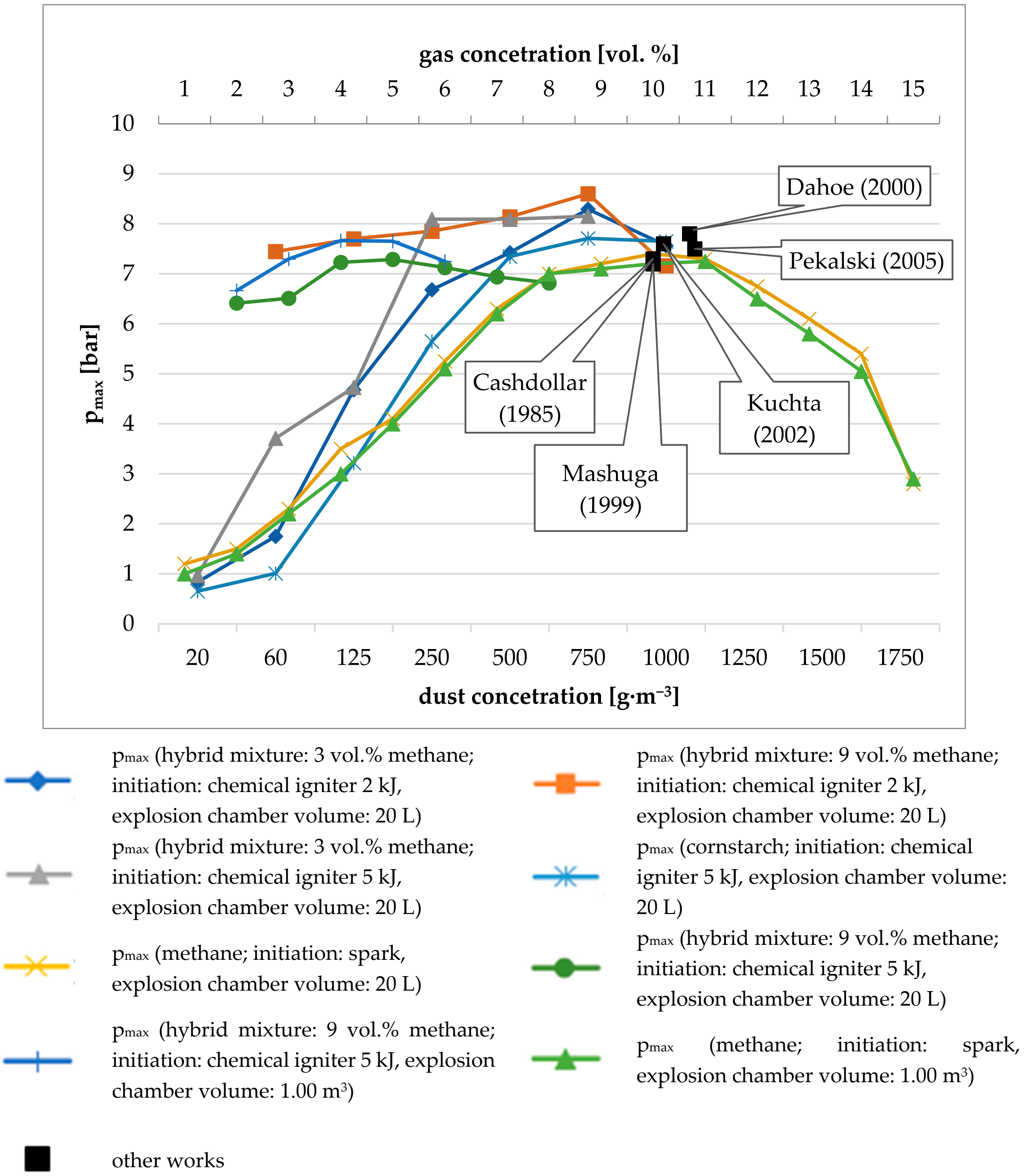

Figure 11. Comparison of the maximum explosion pressure of methane, cornstarch and their hybrid mixture [10].

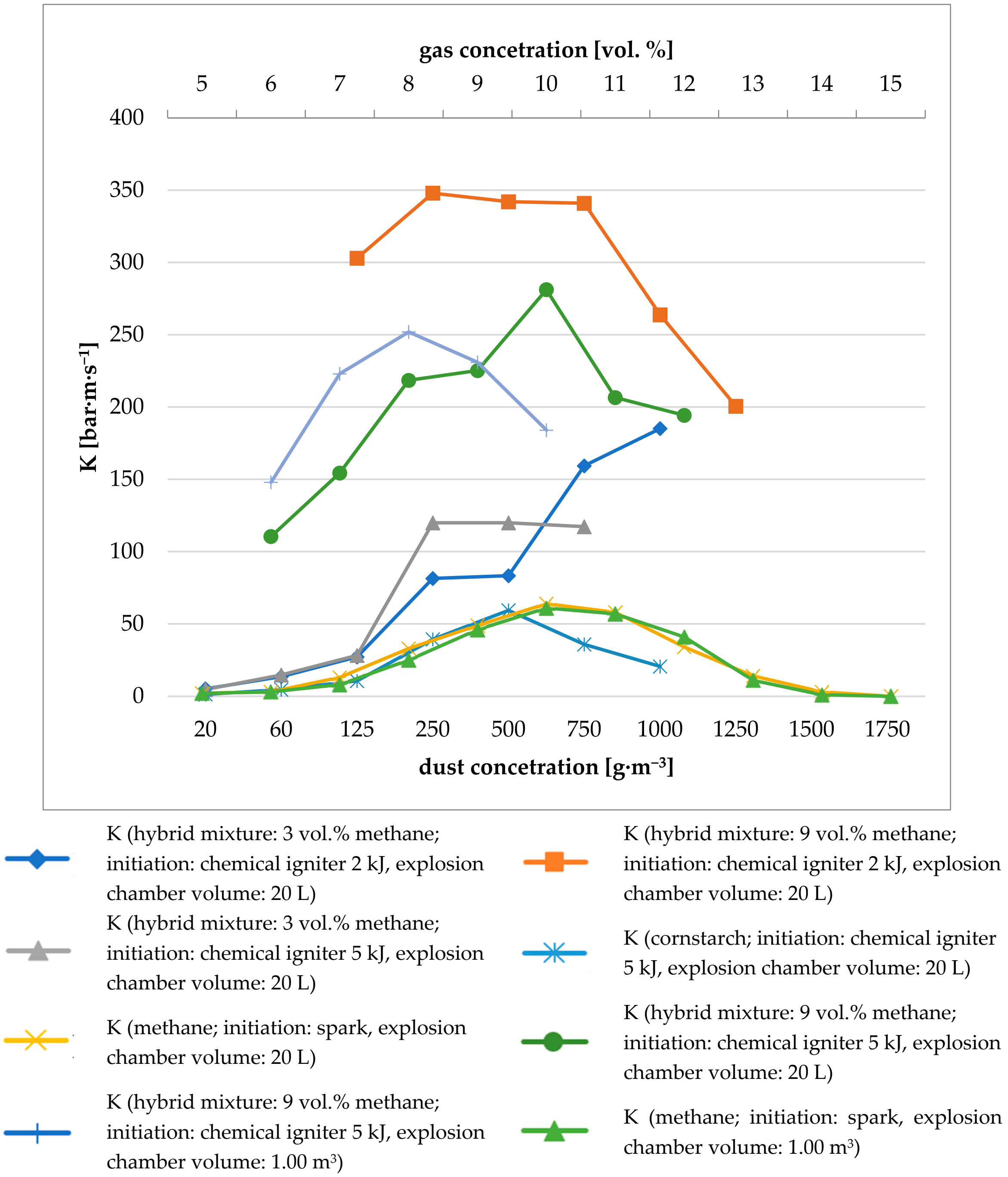

Figure 12. Comparison of the cubic constant of methane, corn starch and their hybrid mixture.

3.3.2. Measurements at Different Initial Temperatures

In the following section, the explosion characteristics of a hybrid mixture of methane and corn starch under non-standard conditions are presented. Comparison of the explosion characteristics of the hybrid mixtures was performed for different initial temperatures (20 °C, 50 °C, 100 °C), at methane concentration of 9 vol.% for different explosion chamber volumes (20 L, 1.00 m^3) and different initiation energies (chemical igniters 2 kJ and 5 kJ). The results are shown in Figures 13 and 14.

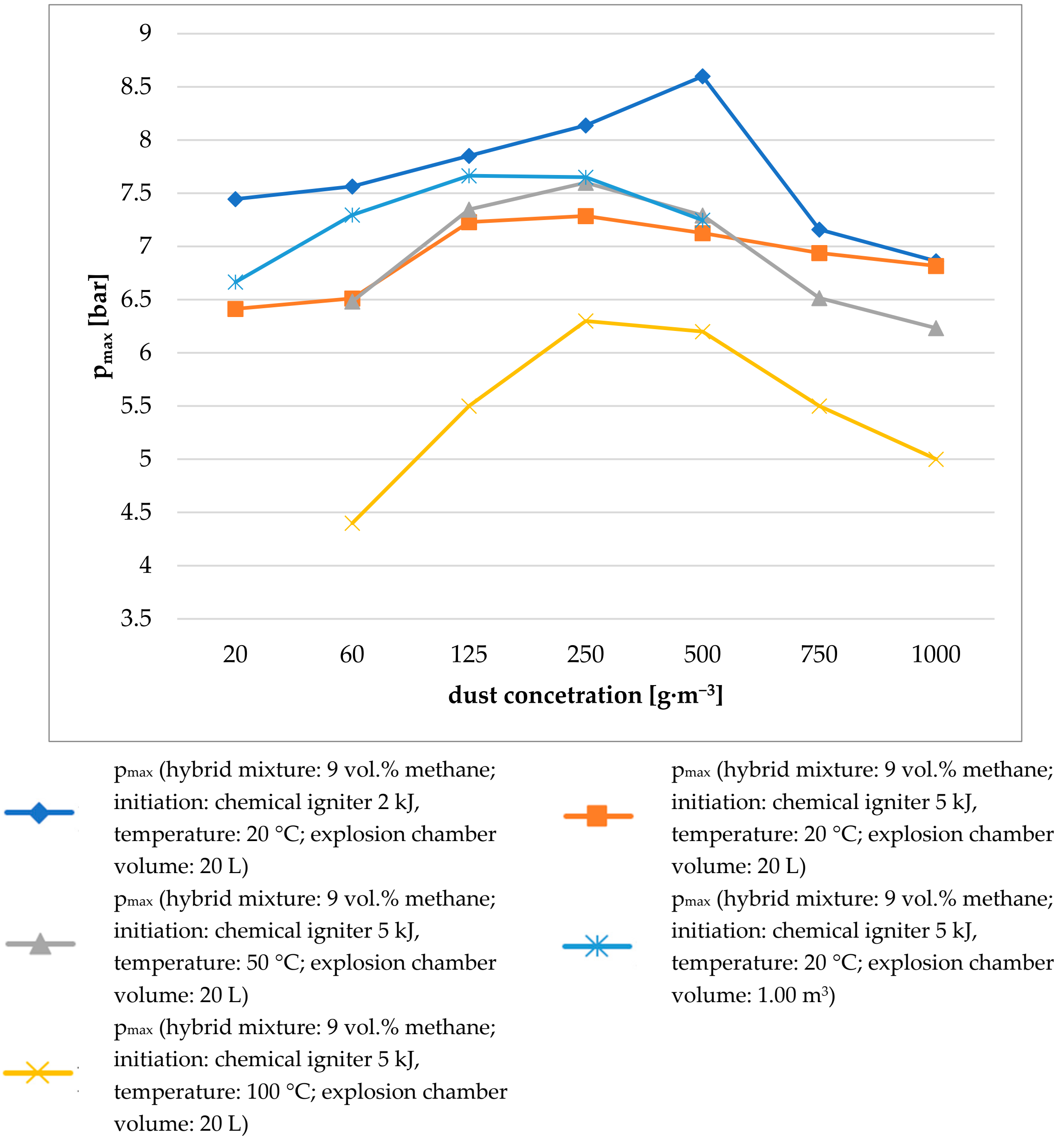

Figure 13. Comparison of the maximum explosion pressure of a hybrid mixture of methane and corn starch.

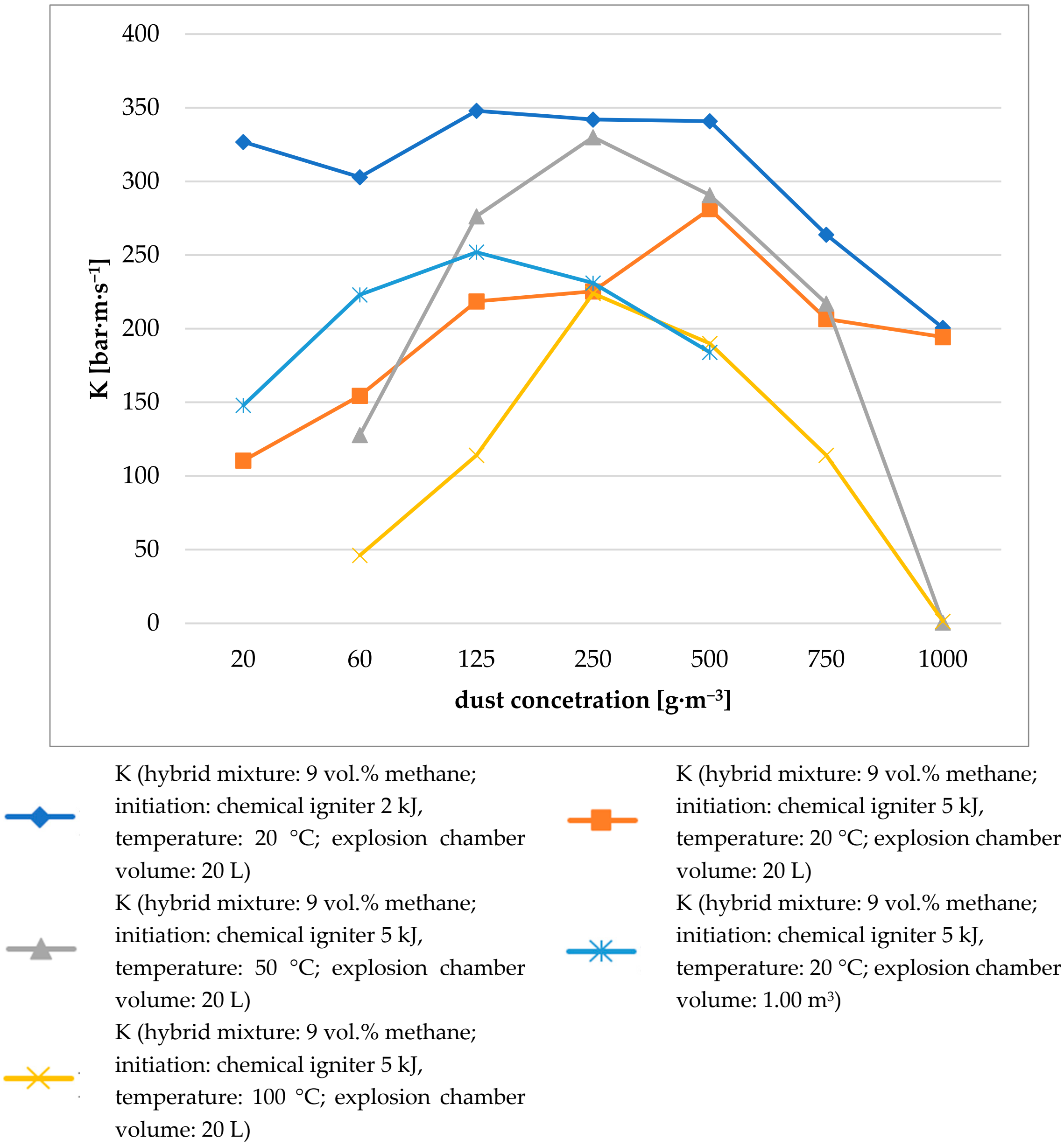

Figure 14. Comparison of the methane cubic constant of a hybrid mixture of methane and corn starch.

4. Discussion

From the comparison of explosion testing results in the case of syngas and dust from gasification technology (Figures 7 and 8), it was found that, in the case of this experiment, the p_{max} values are lower for substances in one state than for the hybrid mixture. The explosion pressure is also higher at all combustible dust concentrations tested in the hybrid mixture. This is different for the cubic constant. Its values are comparable for both the dust and the hybrid mixture, but for the gas, the cubic constant is many times higher than these values. This outcome is, to some extent, to be expected. It is important to mention that the dust (which is actually a “waste” product of the gasification technology) still contains a large amount of energy that can be released during the explosion; therefore, the explosion parameters of the hybrid mixture were mainly influenced by this factor. This can be seen especially in Figure 7, where the maximum explosion pressure of the dust approaches the maximum explosion pressure of the hybrid mixture at higher concentrations.

Comparing the results of the explosion tests of pure substances and the hybrid mixture of hydrogen and cornstarch (Figures 9 and 10), it was found that the initiating source had the greatest influence on the explosion characteristics, with the p_{max} value being highest when an electric spark was used. The p_{max} value was lower for the pure substances than for the hybrid mixture. The value of explosion pressure was higher when a chemical igniter of 5 kJ was used, even at lower concentrations of cornstarch. The highest value of cubic constant K was recorded for pure hydrogen. The highest value of the cubic constant for the hybrid mixture was recorded when using a chemical igniter of 5 kJ.

Comparing the results of the explosion testing of the pure substances and the hybrid mixture of methane and corn starch (Figures 11 and 12), it was found that the initiating source had the greatest influence on the explosion characteristics, with the p_{max} value being highest when 2 kJ of chemical igniter was used for the hybrid mixture with 9 vol.%. The p_{max} value was lower for pure substances than for hybrid mixtures. For a methane concentration of 3 vol.%, the p_{max} value was mostly slightly higher than the p_{max} of the pure substances. The effect of the explosion chamber volume on the p_{max} value was demonstrated for hybrid mixtures when using a chemical igniter of 5 kJ, where at a methane concentration of 9 vol.%, this value was higher in a 1.00 m^3 explosion chamber. The p_{max} value of methane was almost unaffected by the volume of the explosion chamber. At a methane concentration of 9 vol.%, the explosion pressure was higher even at lower concentrations of cornstarch. The highest value of the cubic constant K was recorded when 2 kJ of chemical igniter was used for the hybrid mixture with 9 vol.%. The K value was lower for the pure compounds than for the hybrid mixtures. For a methane concentration of 3 vol.%, the K value at higher cornstarch concentrations was significantly higher than the K of the pure substances. The effect of the explosion chamber volume on the K value was demonstrated for the hybrid mixtures using a chemical igniter of 5 kJ, where at a methane concentration of 9 vol.%, this value was higher at lower cornstarch concentrations in a 1.00 m^3 explosion chamber. In contrast, at higher cornstarch concentrations, the K value was higher in the 20 L explosion chamber. The volume of the explosion chamber had an effect on the K value of methane. It was up to four times lower in the 1.00 m^3 volume than in the 20 L volume. At a methane concentration of 9 vol.%, the value of the cubic constant was many times greater even at lower cornstarch concentrations.

Comparing the results of explosion testing of the hybrid mixture of methane and corn starch for different initial temperatures (20 °C, 50 °C and 100 °C, see Figures 13 and 14), it was found that the p_{max} of methane decreases with increasing temperature. The same finding applies to the value of the cubic constant K. The p_{max} values measured in 20 L explosion chamber and 1.00 m^3 at 20 °C are not very different from each other. K values determined at 20 °C in an explosion chamber with a volume of 1.00 m^3 are mostly lower than those measured in an explosion chamber with a volume of 20 L. The same applies to the value of the cubic constant K. In the case of the hybrid mixture, it was found that the initiation energy has a great influence on the explosion parameters of the hybrid mixture. Surprisingly, higher values of explosion parameters were measured with chemical igniters of 2 kJ. This may be due to less "overexcitation" or turbulence of the hybrid mixture before initiation when using a 2 kJ igniter, than in the case of using a 5 kJ igniter. The mixture is not subject to such turbulence caused by the igniter explosion, and the explosion is then more laminar. The K values of the hybrid mixture decreased with increasing temperature, with values for an explosion chamber volume of 1.00 m^3 being significantly lower than those for an explosion chamber volume of 20 L. Experiments conducted at an initial temperature of 100 °C further revealed the effect of initial temperature on the explosion characteristics of the hybrid mixture. The p_{max} values were lower by more than 17%, and the K values were lower by more than 44% at an initial temperature of 100 °C compared to the values of the explosion parameters at 50 °C.

From the overall context of the paper, it is clear that the volume of the explosion chamber has an effect on the measured explosion parameters of hybrid mixtures. The 1.00 m^3 explosion chamber is more suitable for testing the explosions of hybrid mixtures because of the lower influence of turbulence (the difference between the initiation delay time for gases was 2 min and for combustible dusts was 60 ms). Since the standard for dusts was followed, the hybrid mixture explosion was therefore more enhanced by turbulence in the 20 L chamber than in the 1.00 m^3 chamber, which increased the explosion parameters in the 20 L chamber. Levels of turbulences were given and fixed by the experimental equipment and method used. If following the standard, the repeated values for gases, dusts and vapours are similar and mostly influenced by the initial pressure in explosion chambers of dust or vapour. In the case of gases, it is mostly given by the period after stopping the homogenization, which is also given by the standard method. Different explosion parameters were measured for hybrid mixtures of the same composition using different initiation sources of different energies. Similar findings were reported in ASTM standards E1226:2019 [29] and E1515:2022 [34], where the energy of chemical igniter is discussed, which will be presented in the paragraphs below.

Inconsistencies between tests in 20 L and 1.00 m^3 explosion chambers were observed for dust with low K values. A strong igniter can "reawaken" a 20 L explosion chamber as discussed in references [5,35–37]. On the contrary, more recent tests have shown that some metal dusts may be prone to "underrun" in a 20 L explosion chamber, showing significantly lower K values than in a 1.00 m^3 chamber [38]. Reference [39] provides supporting calculations showing that a test vessel of at least 1.00 m^3 is necessary to obtain a K value for a dust explosion with an abnormally high flame temperature. Therefore, in the two scenarios of "over-excitation" and "underrun" described above, it is recommended that tests be carried out in 1.00 m^3 or larger calibrated explosion chambers to accurately measure the explosive parameters of the combustible dust.

Reference [5] concluded that dust with K values lower than 45 $bar \cdot m \cdot s^{-1}$ when measured in a 20 L chamber with a 10 kJ chemical igniter may not be explosive when tested in a 1.00 m^3 chamber with a 10 kJ chemical igniter. Reference [5] and unpublished testing also showed that in some cases, K values measured in a 20 L chamber can be lower than values measured in a 1.00 m^3 chamber. References [35,37] found that for some dusts, it is necessary to use a lower initiation energy in the 20 L chamber to match the MEC test data in the 1.00 m^3 chamber. If a dust has measurable (non-zero) p_{max} and K values with a 5 or 10 kJ igniter when tested in a 20 L chamber but no measurable p_{max} and K values when tested with less than 2.5 kJ igniter, it may be useful to test the material in a larger chamber such as a 1.00 m^3 chamber using a chemical igniter of at least 10 kJ to further characterize the explosiveness of the material in dust dispersion form.

In certain industrial conditions where extreme levels of turbulence may be encountered, such as the rapid introduction of expanding combustion gases in a connected pipe or operations where hybrid mixtures (combustible dusts and flammable gases or vapours) are present, the use of explosion parameters based on this test methods may not be sufficient for dimensioning devices used for explosion relief [29].

If too weak an initiation source is used, the measured MEC value would be higher than the "true" value. The value measured in this way is the flammability limit rather than the explosive limit, and the test can be described as "subordinate" to it. Ideally, the initiation energy is increased until the measured MEC value is independent of the initiation energy. However, at some point, the initiation energy may be too strong for the size of the test chamber, and the system becomes so-called "overexcited". When the igniter flame becomes too large relative to the volume of the chamber, the test may appear to result in an explosion, when in fact, it is just dust burning in the igniter flame with no real propagation beyond the initiation source.

The recommended initiation source for measuring the MEC values of dusts in 20 L chambers is a chemical igniter with an energy of 2.5 or 5 kJ. Measurement of MEC values at both initiation energies will provide information on possible "overexcitation" of the system. To evaluate the effect of "overexcitation" in a chamber with a volume of 20 L, comparative tests can also be performed in a larger chamber, e.g., with a volume of 1.00 m^3 [34].

The publication [21] also mentions, among other things, that permanent spark initiation appears to be suitable for easily ignitable dusts, where higher explosion parameters have been measured for these dusts. Permanent spark as an initiation source generates lower explosion parameters for less flammable dusts, and therefore, chemical igniters are considered necessary for these dusts.

Given the shift away from fossil fuels as energy sources and towards alternative energy sources, we can expect an increase in gasification technologies such as the one mentioned at the beginning of this article, where the substances involved have been the subject of research. This means that the risk of explosions in these technologies is also increasing. As there is no standardised procedure for measuring the explosion parameters of hybrid mixtures, this research was undertaken to lay the foundations for the development of a standardised procedure for measuring this specific explosive set.

Gasification takes place at higher temperatures, while the measurement of explosion parameters is usually carried out at standard conditions (temperature 20 °C or 25 °C), which is why the research was also oriented towards the measurement of explosion parameters at higher temperatures, where the influence on the measured values of explosion parameters was to be demonstrated. In addition, the influence of the volume of the explosion chamber used (20 L or 1.00 m^3) was demonstrated, and the type and energy of the initiating source used all had a significant influence on the measured values of the explosion parameters of the hybrid mixtures. Furthermore, the explosion parameters are used in practice mainly for the sizing of explosion pressure or shock resistant devices or explosion relief devices. As can be seen, these elements make measures for explosion prevention and thus for the protection of health and life of persons, property and, also, the environment. The correct oversizing of the equipment according to the measured explosion parameters therefore has a major impact on the safety of the equipment in question for the surroundings in the event of an emergency, which is especially the case in the event of an explosion.

5. Conclusions

This article dealt with the issue of determining the explosion parameters of hybrid mixtures of selected alternative energy sources. This paper started with a critical analysis of the current state-of-the-art in the field of explosion characteristics of pure substances and hybrid mixtures and their interpretation depending on the defined conditions of their determination. The explosion parameters of hydrogen, methane, syngas from gasification technology, corn starch and dust from gasification technology and their hybrid mixtures were measured. Measurements of the explosion parameters of the hybrid mixtures were carried out in explosion chambers with volumes of 20 L and 1.00 m^3. The maximum explosion pressure (p_{max}) and the maximum rate of explosion pressure rise $(dp/dt)_{max}$ were measured, and the cubic constant (K) was calculated. The measured (calculated) values of the explosion parameters of the hybrid mixtures were compared with the explosion parameters for pure substances.

From the presented experimental results, it is clear that the type and size of the initiating source in combination with the volume of the explosion chamber used had a major influence on the explosion parameters of the hybrid mixtures. The maximum explosion parameters also do not provide data on the value of the maximum burning velocities of the hybrid mixture, among others. The turbulence inside the explosion chamber caused by dust agitation just before the initiation of the mixture also had a significant effect on the measurement of the explosion parameters. It has been shown that the effect of turbulence is more pronounced in the 20 L chamber. Among other things, the initial temperature also had a significant effect on the determination of the explosion parameters, where the values of the explosion parameters decreased with its increase. From the investigations carried out, it is concluded that the 1.00 m^3 explosion chamber is more suitable for testing the explosions of hybrid mixtures. The focus of the research was mainly on alternative energy sources, specifically on gasification technology, where this particular hybrid mixture was measured for the first time. Thus, it was shown that the effect of the joint presence of combustible gas and combustible dust (i.e., hybrid mixture) has an influence on the measured values of the explosion parameter p_{max} in particular. To measure the explosion parameters of hybrid mixtures in a 1.00 m^3 explosion chamber, a proprietary methodology was developed by the author of this paper.

A suggestion for future research on hybrid mixtures may be to carry out measurements of the explosion parameters of hybrid mixtures at initial temperatures of 0 °C and below or at initial temperatures of 100 °C and above and then, to monitor further trends in the evolution of the explosion parameter values of hybrid mixtures.

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