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The ignition phenomenon of gases—part I: the experimental analysis—a review

Wojciech Uchman[a,*], Sebastian Werle[b]

[a] *Institute of Power Engineering and Turbomachinery, Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland*
[b] *Institute of Thermal Technology, Silesian University of Technology, Konarskiego 22, 44-100 Gliwice, Poland*

Abstract

Ignition has a significant impact on the efficiency of the combustion process. Spark ignition is the most commonly used method and is characterized by two important parameters: minimum ignition energy and quenching distance. This paper presents a review of various ways ahead in experimental investigation in the area. We focus on the conditions influencing the experiments and estimation of the minimum ignition energy. The main issues in previous experimental studies are: construction of the ignition apparatus, spark energy estimation and the statistical nature of the phenomenon. A summary of the research conditions data is presented.

Keywords: ignition; minimum ignition energy; spark ignition

1. Introduction

The use of gaseous fuels has developed dynamically in many areas of the economy, creating a greater need for wide-ranging basic research into the behavior of flammable mixtures in varied conditions. These studies have contributed significantly to our knowledge of fuels. Most issues concern, directly or indirectly, safety aspects of gas storage and the efficiency and stability of combustion processes. Moreover, the noticeable increase in interest in lean gases requires recognition of basic parameters that characterize the combustion process, including perhaps most importantly ignition.

Ignition of a combustible mixture, given homogeneity and composition within the limits of flammability, may be achieved by: heating the mixture to a temperature higher than or equal to the auto-ignition temperature, contact with flame, electric spark, hot surface, shock wave or chemical reactions [1]. The most important role is played by spark ignition, as it is the most commonly used type of forced ignition.

The aims of the study are: to review previous experimental investigations into minimum ignition energy (MIE), to present the most significant parameters influencing the ignition phenomenon and to look at possible future directions in experimental research.

2. Spark ignition

The basic parameters characterizing spark ignition are: MIE, quenching distance (QD) and the electrical discharge parameters. These are the main factors when assessing hazards posed by possible electrostatic discharges [1–3].

Ignition systems fall into two main groups: capacitive, with the energy stored in the capacitance, and inductive, with the energy stored in the inductance. While every ignition system has both capacitance and inductance—meaning the categorization is quite loose [1]—the nature of the electric spark (capacitive or inductive) has a significant influence on the ignition phenomenon, in particular as regards the power and energy in particular phases of the electrical discharge. Fig. 1 presents the voltage and current as a function of time of a spark.

There are three main phases of electrical discharge: breakdown phase (II), arc phase (IV) and glow phase (VI). The collateral phases are: pre-discharge phase (I) and transition phases (III and V).

The breakdown phase lasts about 10^{-9} s. During this phase, the voltage is high, about 10 kV, and the current quickly increases to 200 A. A plasma column forms that reaches temperatures of up to 60,000 K and pressure of 20 MPa, resulting in a shock wave with a diameter of 1 .. 2 mm. The lowest energy losses occur in the breakdown phase, approximately 6%, and the bulk of the energy transfers to plasma. An electric arc appears during the arc phase. Much of the arc energy transfers to the electrodes. The temperature falls to about 6,000 K, the current decreases and the voltage is generally constant at about 50 V. The en-

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[*] Corresponding author
Email address: `wojciech.uchman@polsl.pl` (Wojciech Uchman)

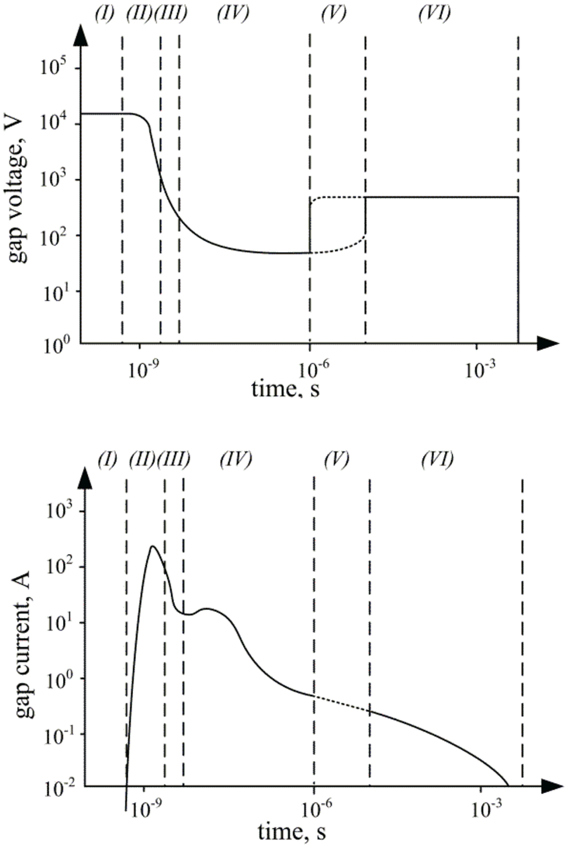

Figure 1: Schematic diagram of voltage and current as functions of discharge time of a spark [4]

ergy losses in the arc phase reach 50%. During the glow phase the voltage is constant at about 500 V, current decreases below 200 mA and the temperature is about 3,000 K. The largest energy losses occur in this phase, approximately 70% [1, 4–6]. The authors of [5] note that the times of particular phases and the amount of transported energy may vary depending on the construction of the spark ignition system circuit.

There is an unclear relationship between the spark phase and ignition. In the analysis set out in [1], the researchers do not agree whether it is the breakdown phase or the glow phase that determines ignition. In the case of lean mixtures (φ<1) the breakdown phase is more important. The type of ignition system determines the dominant phase of discharge, because during the breakdown and arc phases the energy stored in capacitance is discharged and during the glow phase the energy is stored in inductance [1, 6].

The energy stored in the ignition system consists of the discharge energy and the dissipated energy. And the discharge energy is not entirely transferred to the gas. Energy losses, as mentioned earlier, consist of the heat transported to the electrodes during particular phases of discharge. The rest of the energy, if it is able to cause ignition, is called the ignition energy of the flammable mixture [1]. The definition of MIE varies between individual works. Some works describe spark ignition energy as the minimum spark energy that causes ignition under certain conditions [3, 7, 8].

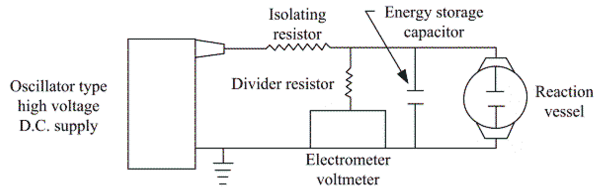

Figure 2: Diagram of the electrical spark generation circuit of ASTM E582 [18]

Ignition is probabilistic in nature and there is no hard and fast point in terms of ignition energy below which there is no ignition at given conditions and above which the mixture will always ignite. In [2] the definition of MIE was proposed which takes into account the statistical nature of the phenomenon and determines the lowest energy at which the mixture is ignited, below which ignition is highly unlikely though not physically impossible. There has been much research on measuring the MIE in different conditions for various fuels. A selection of the experiment conditions collected by the authors is presented in Tables 1 .. 6 (Appendix).

The experimental conditions, such as concentration, pressure and temperature, are shown for each investigated mixture. The ignition apparatus is briefly described—plain or flanged electrodes—and voltage, spark distance gap and capacitance range are shown. The differences in spark energy estimation and ignition criteria can be seen. Researchers carry out the studies of MIE with varied probabilistic criteria of ignition. In the literature analyses have been carried out with 5% [6, 8], 20% [9], 50% [10–14] and 80% [7] probability criteria; however, some authors do not mention the precise probability value [2, 15–17]. The work [15] is widely commented on in publications and some researchers estimated that those investigations were carried out with a 1% probability criterion [6, 7]. The analysis of [14] does not confirm those estimations.

The authors of [12] point out the difference between absolute minimum ignition energy (MIE$_{abs}$) with the spark distance gap equal to the quenching distance and minimum ignition energy for given conditions (varied electrode spacing and probability criteria). During their experiments, they use the MIE definition.

3. Spark energy estimation

The ASTM E582 standard represents an attempt to standardize the methodology for determining MIE [18] and is based on investigations carried out in the 1960s [19, 20]. The E582 method determines the MIE in a constant volume reactor, with varied electrode spacing and the visual criterion of ignition. Essential for the procedure is to apply an ignition system based on the circuit presented in Fig. 2. Minimizing the inductance and stray capacitance is vital for this method.

The power supply of the ignition system should be able to vary the voltage in the range 1-30 kV, the capacitance 8-12 pF and the resistance $10^{12}\Omega$. If the capacitance of the voltmeter is higher than the capacitance of the capacitor, the voltmeter should be applied with the voltage divider with resistance of at least $10^{14}\Omega$.

In ASTM E582 [18], the MIE can be calculated using the following formula:

$$E = \frac{1}{2}CU^2 \tag{1}$$

where: E—spark energy, J; C—sum of the capacitor and stray capacitance, F; U—breakdown voltage, V.

Most researchers use this method for calculating MIE (as energy stored in capacitor) [2, 6, 8, 10, 11, 15–17, 21, 22], but in some works the authors estimate MIE as the difference between the energy stored in the capacitor and residual energy [13, 14, 23]. For the complete methodology, please see [14]. The spark energy in this case can be estimated using the equation:

$$E_{spark} \approx E_{stored} - E_{residual} \tag{2}$$

where E_{stored} equals E according to ASTM E582, and the residual energy:

$$E_{residual} = \frac{1}{2}\frac{Q^2_{residual}}{C} \tag{3}$$

$$Q_{residual} = Q_{stored} - Q_{spark} = CU - \int i(t)\,dt \tag{4}$$

where: $Q_{residual}$—residual charge, C; Q_{stored}—charge stored in capacitor, C; Q_{spark}—charge transferred to the spark calculated as integral of the waveform current from transformer, C.

Direct measurement of the electrical discharge energy is complex and is presented in [9]. The work [24] presents the calculations of measurement uncertainty taking into account stray capacitance. The measurements of spark energy using various triggering methods presented in [25] also involve spark power as a parameter characterizing the ignition.

In the works [13, 14, 23, 26] the use of spark energy density—the ratio of spark energy to the spark distance gap—as a parameter describing the ignition phenomenon was proposed. The experiments were conducted to demonstrate that minimum electrical discharge energy is not the appropriate factor to characterize the ability to ignite the mixture, especially with varied-length sparks, and it cannot be used to compare incendivity with fixed-length sparks. The spark energy density is lower for long sparks due to the limited effects of the electrodes quenching of flame kernel and heterogeneity of the spark channel. Increasing the length of the sparks results in bulges in the plasma channel due to plasma instability. It is postulated that the bulges are characterized by higher energy density and lead to the occurrence of local ignition kernels. As expected, longer sparks required higher energy to ignite the mixture, but the energy density was lower than the energy density for fixed-length sparks at MIE. According to the authors, spark energy density is also a more comparable factor for different studies.

4. Ignition occurrence criteria

Ignition occurrence criteria are a significant aspect of the ignition phenomenon and flammability limits studies. For determination of flammability limits the visual criterion is used in the American (ASTM E681) [27] and European (EN 1839T) [28] standards. The pressure rise criterion is also used in the American (ASTM E918) [29] and European (EN 1839B) [28] standards.

Although the E918 standard refers to the mixtures at elevated temperature or pressure, the researchers successfully applied the constant volume bomb (CVB) method with spark ignition for mixtures at atmospheric pressure [7, 30–32].

The authors [33] carried out an analysis which shows that the results obtained from the CVB method of determining flammability limits match the results obtained during industrial scale investigations. This demonstrates why this method is frequently used in laboratory practice. The pressure rise criterion differs between American and European standards. The ASTM includes the rule of a 7% rise while the EN pressure rise is 5%. However, some studies [31, 34] show that both values may be too high.

According to ASTM E582 ignition occurrence is observed by the visual criterion. Whereas most researchers use schlieren visualization and high speed cameras [2, 6, 8, 10–14, 23, 35], some additionally measure the pressure and temperature peak [9, 13, 14, 35].

5. Parameters influencing the minimum ignition energy

The electrodes—spark distance gap has a strong influence on the spark ignition energy due to heat transfer from the flame kernel to the electrodes. This can be seen when comparing flanged and plain electrodes—Fig. 3 presents MIE as a function of the distance gap for both types of electrodes. The small range within the MIE is constant at atmospheric pressure, for lower pressures this relationship does not exist [3].

The use of the flanged electrodes strongly increases the effects of flame-quenching at the walls and can be used to determine the quenching distance in experiments [1, 3]. In practice, the spacing of electrodes is often greater than the quenching distance, so the spark energy density as described in [13, 14, 23, 26] may become a relevant factor characterizing ignition. The QD changes with the flammable mixture composition [3]. According to [1, 3] whereas the material of the electrodes does not have a significant influence on the MIE value for short-duration sparks, during the discharge and absorbing of heat by the electrodes, their surface boils. The conclusions of analyses of the electrodes surface scans are presented in [7]. Surface erosion of the anode was noted. Degradation of the electrodes after the discharge results in a slight increase in breakdown voltage for subsequent discharges [7]. In the case of long-duration discharges, the electrodes material may have an indirect influence on the duration of the particular spark phases [3].

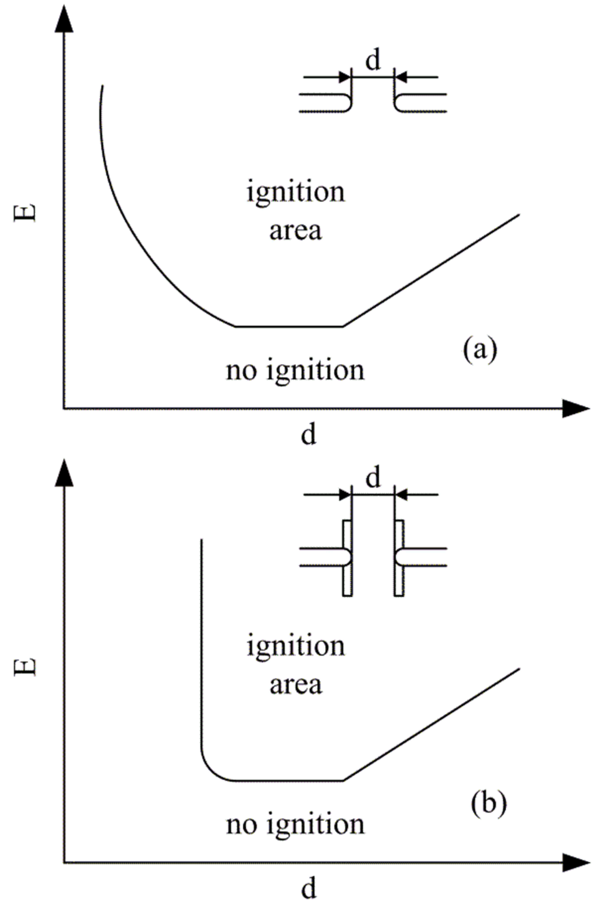

Figure 3: Minimum ignition energy as a function of spark distance gap for plain (a) and flanged (b) electrodes [1]

The geometry of the electrodes has a significant impact on the nature of the electrical discharge. Experimental and numerical studies [36] show that the dynamics of flame kernel growth vary for different geometries. The use of flanges with cylindrical electrodes causes vortices which trap the growing flame kernel for some time. This phenomenon results in higher gas temperature and lower spark ignition energy. The work [36] highlights the importance of viscosity in ignition, due to its impact on turbulences near the electrodes.

As regards discharge frequency, discharge time, according to [1] for the given flammable mixture there is the highest probability of ignition when the discharge frequency is at certain level. An increase in discharge time increases the ignition energy [1]. The work [11] presents studies into the influence of discharge time on MIE, with the most favorable spark duration for different propane concentrations hovering around 50 μs.

As regards the flammable mixture composition, the relationship between the amount of fuel and oxidizer has a significant impact on MIE. The ignition energy, while presented graphically as a function of fuel concentration, adopts the U-shaped form located in the flammability limits, with the minimum located around the stoichiometric mixture (Fig. 4). In the case of mixtures of most hydrocarbon fuels with air, MIE is on the rich side [1, 3, 9].

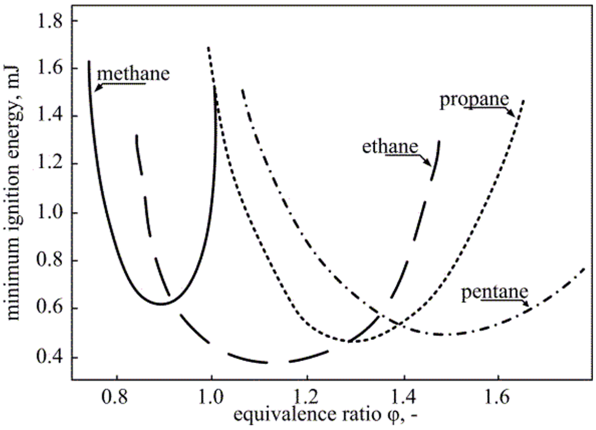

Figure 4: Ignition energy as a function of the equivalence ratio of the mixture of hydrocarbon fuels with air [7]

The authors of [1, 9] suggest MIE for rich mixtures is connected with the molecular mass of the fuel. For fuel molecules which are heavier than oxygen, MIE appears for $\varphi>1$ (φ is the equivalence ratio equal to the inverse of the excess air ratio $\varphi=1/\lambda$). For lighter molecules $\varphi<1$. The author of [1] explains that this is the result of the diffusion process. The diffusion factor is inversely proportional to the molecular mass, so the diffusion of heavier gas is lower than the diffusion of the lighter gas. In the case of heavy fuels, e.g. pentane, ignition favorable conditions exist for the rich mixture. The greater the offset from the stoichiometric composition, the lower the relative diffusion of the fuel.

The flow velocity of the mixture and its turbulence increase the energy required for ignition [1, 3]. The flow of the mixture blows out the spark. Also the spark needs to heat a greater volume of gas, so the MIE for a quiescent mixture is too low for flowing gases. This phenomenon intensifies with increasing velocity and turbulence intensity [3].

Pressure has a great impact on ignition energy. Lowering the pressure of the flammable mixture means greater energy of discharge for ignition is required [1, 3]. The authors of [3] introduce a concept of minimum ignition pressure (MIP), below which ignition is not possible due to the limitations of the ignition apparatus (spacing of electrodes), the reactor size or the value of the available discharge energy. As the pressure decreases, the quenching distance increases strongly, therefore MIP investigations require a large reactor to minimize the flame quenching effect. The researchers [3] explain this phenomenon by assuming that a certain spark energy can ignite a given mass of mixture. When the pressure is lower, the same mass has a greater volume, which results in the need to increase the electrode spacing to allow ignition to occur.

As regards temperature, increasing the temperature of the flammable mixture lowers the energy required for ignition [1, 3]. The relationship between ignition energy and ini-

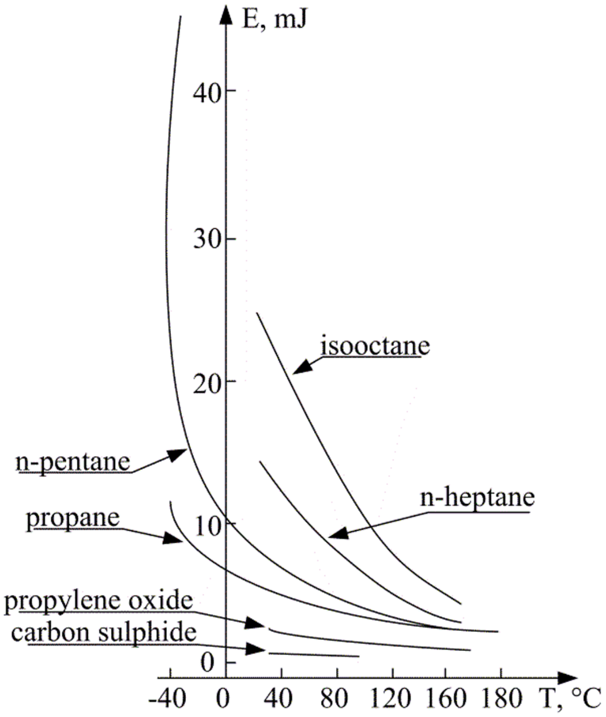

Figure 5: Dependence of ignition energy on the initial temperature of mixture [1]

tial temperature of the mixture is presented in Fig. 5.

Diluents—the share of inert gases in the flammable mixture has a significant influence on MIE. Generally, the presence of inert gases narrows the flammability limits and causes a great increase in MIE [1]. Experiments presented in [15] demonstrate substantial differences in mixture behavior while the $O_2/(O_2+\text{diluent})$ ratio is constant, but the diluents vary. It is connected with different conditions of heat transfer. When the $O_2/(O_2+\text{diluent})$ ratio is 0.21 and the inert gas is helium instead of nitrogen, MIE increases. If the inert gas is argon, MIE decreases. According to [3], MIE generally increases with increasing diffusivity, but argon is an exception. The authors of [3] suggest that humidity has a minimal influence on ignition energy and probably can be neglected. This was experimentally confirmed in studies [16] where the authors did not observe any significant impact of humidity on the MIE of a hydrogen-air mixture in the range 0-90%.

6. Ignition as a statistical phenomenon

Over the years, MIE was considered as a single threshold value based on the research presented in [15, 19]. However, over time, the literature started to present suggestions that ignition is strongly connected to probability of occurrence. According to [1, 10, 35] in boundary conditions the ignition may occur or not, leading to overlapping ignition/no-ignition areas and preventing the determination of a threshold value. As mentioned earlier, there is no explicit method of MIE determination based on one value of probability (E582 does not include any statistical criteria), which leads researchers to use various values (or to not mention it at all) and to discrepancies in results [6, 12, 13, 15]. This aspect of MIE studies led to attempts to use statistical analysis methods to analyze the results of MIE experimental investigations [6, 8, 13, 14, 24, 37–39]. It is postulated that the appropriate way to analyze the ignition phenomenon is logistic regression, as described in [6, 8, 13, 14, 24, 39]. It is used when the variable is described by the dichotomous scale, as in the case of MIE: ignition/no-ignition. According to [13], for a given spark energy (E_{spark}), the probability of ignition can be calculated using the following formula:

$$P\left(E_{spark}\right) = \frac{1}{1 + exp(-\beta_0 - \beta_1 E_{spark_i})} \tag{5}$$

where β_0 and β_1 are estimated by maximizing the likelihood function, which describes the spark energies and the binary results (ignition/no-ignition).

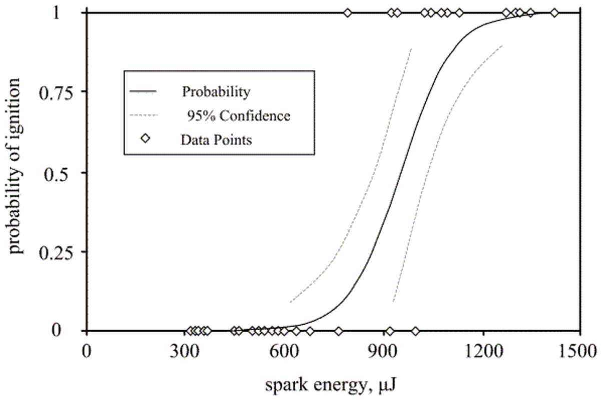

Figure 6: Logistic probability distribution and 95% confidence intervals for the 5% H_2/12% O_2/83% Ar mixture ignition [13]

As an example of the result of statistical analysis, the ignition probability distribution is shown in Fig. 6.

7. Summary

Safety is paramount when using gaseous fuels, hence the interest in ignition research. Minimum ignition energy is a significant parameter in the context of hazard assessment. Experimental investigation into the MIE of gases was considered in this paper. The authors collected a significant amount of experimental data from recent studies and described the most influential factors of MIE. The statistical nature of the ignition phenomenon is also mentioned. MIE, as a strongly probabilistic quantity, has to be analyzed with statistical methods, because it is not a single threshold value as was postulated for many years.

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Appendix

Table 1: Summary of the experimental conditions for previous MIE studies. Part 1.

mixture	ignition apparatus	parameters				ignition criterion	MIE calculation	probability as MIE criterion	Ref
		capacitance, pF	concentration	pressure, atm	temperature, $^\circ$C				
methane /air	capacitance sparks, flanged electrodes, gaps: 0.1 .. 10mm, 0 .. 15 kV	1.9 .. 1280	7 .. 30%	0.2 .. 1	25		stored in capacitor		[15]
methane /air	capacitance sparks,spark gap dist: 2.2 mm	19.0 .. 63.9	stoichiometric	1	22	pressure	E=$C_0{}^2V_0{}^2/2C_B$, because of varied breakdown voltage ,	80%	[7]
ethane /air	capacitance sparks, spark gap dist: 2.2 mm	19.0 .. 63.9	stoichiometric	1	22	pressure	E=$C_0{}^2V_0{}^2/2C_B$, because of varied breakdown voltage ,	80%	[7]
ethane /air	capacitance sparks, flanged electrodes, gaps: 0.1 .. 10 mm, 0-15 kV	1.9 .. 1280	4 .. 40%	0.2 .. 1	25		stored in capacitor		[15]
ethane /air	spark gap dist: 1.0 .. 1.3 mm, 5.4 .. 6.8 kV, capacitance sparks, UV radiation	4.6 .. 14.0	8%		22+/- 2	acoustic (pressure venting), visual		100 tries	[24]
ethane /air	gap: 1.2 mm, capacitance sparks, spherical electrodes		8%	1	21	visual	stored in capacitor		[2]
ethane /air	gap: 1.0 .. 1.3 mm, capacitance sparks, spherical electrodes, voltage up to 10 kV	4.8	8%	1	22+/-2		stored in capacitor	over 5000 tries	[21]

Table 2: Summary of the experimental conditions for previous MIE studies. Part 2.

mixture	ignition apparatus	parameters				ignition criterion	MIE calculation	probability as MIE criterion	Ref
		capacitance, pF	concentration	pressure, atm	temperature, °C				
propane/air	capacitance sparks, flanged electrodes, gaps: 0.1 .. 10 mm, 0 .. 15 kV	1.9 .. 1,280	4 .. 30%	0.2 .. 1	25		stored in capacitor		[15]
propane/air	capacitance sparks, spark gap dist: 2.2 mm	19.0 .. 63.9	stoichiometric	1	22 .. 125	pressure	$E=C_0^2V_0^2/2C_B$, because of varied breakdown voltage	80%	[7]
propane/air	capacitance sparks, flanged electrodes, spark gap dist: 2 mm, ASTM E582	14.0 .. 28.6	3.5 .. 8.0 %	1	25	visual	stored in capacitor	5%	[6, 8]
propane/air	spark gap dist: 1.5 .. 1.9 mm, 8.0 .. 10.0 kV, capacitance sparks, UV radiation	8.0 .. 46.0	5.2%		22+/- 2	acoustic (pressure venting), visual		100 tries	[24]
propane/air	gap: 1.7 mm, capacitance sparks, spherical electrodes		3.7 .. 6.7 %	1	21	visual	stored in capacitor		[2]
propane/air	gap: 1.5 .. 1.9 mm, capacitance sparks, spherical electrodes, voltage up to 10 kV	9.5	5.2%	1	22+/-2		stored in capacitor	over 12000 tries	[21]
propane/air	capacitance sparks, 11.25 l vessel, gap: 3.3mm, stainless-steel rods, diam.: 3.2 mm, voltage 1 .. 15 kV, 1,180 l vessel, 7.7 .. 8 kV, gap: 10 mm	30 .. $1 \cdot 10^6$; (0.5 .. 1)$\cdot 10^6$	12.1 .. 3.5%; 2.1 .. 4%	1; 0.82-0.99	20, 22.9 .. 35.3	visual, pressure, temperature	stored in capacitor	20%	[9]

Table 3: Summary of the experimental conditions for previous MIE studies. Part 3.

mixture	ignition apparatus	parameters				ignition criterion	MIE calculation	probability as MIE criterion	Ref
		capacitance, pF	concentration	pressure, atm	temperature, °C				
propane /air	capacitance sparks, tungsten wires, diam. 0.3 mm, 30° half angle cone end, steel rods, diam. 3 mm, 45° half angle cone end, gaps: 0.5 .. 3.5 mm		3.0, 3.2, 3.5%	1	25	visual	stored in capacitor	50%	[11]
propane /air	capacitance sparks, tungsten wires diam.26 μm .. 0.5 mm, steel wires diam. 0.8 and 1 mm, 1.35 .. 5.6 kV, flowing mixture (laminar flow)		2.9, 3.2, 4%	1	25	visual	stored in capacitor	50%	[10]
propane /air	inductance sparks, nickel, spherical electrodes (diam. 0.5mm), gap: 0.5 .. 2.0 mm, 4 .. 8 kV		φ=0.6, 0.7, 0.8			visual		50%	[12]
butane /air	capacitance sparks, spark gap dist: 2.2 mm	19.0 .. 63.9	stoichiometric	0.75	22-125	pressure	$E=C_0^2V_0^2/2C_B$, because of varied breakdown voltage	80%	[7]
pentane /air	capacitance sparks,, spark gap dist: 2.2mm, ,	19.0—63.9	stoichiometric	0.75	22-125	pressure	$E=C_0^2V_0^2/2C_B$, because of varied breakdown voltage ,	80%	[7]
hexane /air	capacitance sparks,, spark gap dist: 2.2mm,	19.0—63.9	stoichiometric	0.75	22-125	pressure	$E=C_0^2V_0^2/2C_B$, because of varied breakdown voltage	80%	[7]

Table 4: Summary of the experimental conditions for previous MIE studies. Part 4.

mixture	ignition apparatus	parameters				ignition criterion	MIE calculation	probability as MIE criterion	Ref
		capacitance, pF	concentration	pressure, atm	temperature, °C				
hexane /air	11.25 l vessel, gap: 3.3 .. 6 mm, stainless-steel rods, diam.: 3.2 mm, voltage 1 .. 15 kV, capacitance sparks	$30 .. 1\cdot10^6$	1 .. 6.8%	1	20	visual, pressure, temperature	stored in capacitor	20%	[9]
heptane /air	capacitance sparks, spark gap dist: 2.2 mm	19.0 .. 63.9	stoichiometric	0.75	22 .. 125	pressure	$E=C_0{}^2V_0{}^2/2C_B$, because of varied breakdown voltage	80%	[7]
hydrogen /air	capacitance sparks, flanged electrodes, gaps: 0.1 .. 10 mm, 0 .. 15 kV	1.9 .. 1,280	7 .. 90%	0.2 .. 1	25		stored in capacitor		[15]
hydrogen /air	spark gap dist: 0.4 .. 0.75 mm, 2.7 .. 5.0 kV, capacitance sparks, UV radiation	3.6 .. 10.4	22%		22+/- 2	acoustic (pressure venting), visual		100 tries	[24]
hydrogen /air	capacitance sparks, gap: 0.5, 1, 2, 3, 4 mm, tungsten electrodes	4.3 .. 471.8	10, 14, 22, 30, 40, 50 %	1	25	visual (aluminium foil rupture)	stored in capacitor, residue energy verification		[16]
hydrogen /air	gap: 0.45 .. 0.7 mm, capacitance sparks, spherical electrodes, voltage up to 10 kV	4.41	22%	1	22+/-2		stored in capacitor	over 3,500 tries	[21]
hydrogen /air	1180 l vessel, 7.7 kV, gap: 10 mm, capacitance sparks	$0.5\cdot10^6$	8 .. 10%	0.99	28.6	visual, pressure, temperature	stored in capacitor	20%	[9]

Table 5: Summary of the experimental conditions for previous MIE studies. Part 5.

mixture	ignition apparatus	parameters				ignition criterion	MIE calculation	probability as MIE criterion	Ref
		capacitance, pF	concentration	pressure, atm	temperature, °C				
acetone /air	gap: 1.5 .. 3.6 mm,capacitance sparks, spherical electrodes, voltage up to 10 kV ,	16.0	6.5%	1	22+/-2		stored in capacitor	over 2500 tries	[21]
propane /hydrogen /air	stainless-steel rods, diam: 3.2 mm, 1,180 l vessel, 7.7 8 kV, gap: 10 mm, capacitance sparks	$(0.5\ ..\ 1)\cdot10^6$	1 .. 2.5/4 .. 10%	0.82 .. 0.99	22.9 .. 31.0	visual, pressure, temperature	stored in capacitor	20%	[9]
hydrogen peroxide/ hydrogen oxide	capacitance sparks,, flanged electrodes, gap: 5.1 .. 16.3 mm ,	34 .. 179	35.1 .. 50.44 .. 100%	0.03 .. 0.26	68 .. 108	pressure	stored in capacitor	100 tries	[22]
hydrogen /nitrous oxide	capacitance sparks, flanged and plain electrodes, gap: 1.5 .. 4.0 mm, 0 .. 10 kV	3 .. 30, 15 .. 250	φ=0.15, 0.2, 0.25	0.15 .. 0.25	25	visual, pressure, temperature	difference between stored and residual energy	50%	[23]
methane /nitrous oxide	gap: 2 .. 6 mm, capacitance sparks, voltage 30 kV, turbulent conditions	$0.5\cdot10^6$	2 .. 5%,	0.99	20	visual, pressure, temperature	stored in capacitor		[17]

Table 6: Summary of the experimental conditions for previous MIE studies. Part 6.

mixture	ignition apparatus	parameters				ignition criterion	MIE calculation	probability as MIE criterion	Ref
		capacitance, pF	concentration	pressure, atm	temperature, °C				
ammonia /nitrous oxide	gap: 2 .. 6 mm, capacitance sparks„ voltage 30 kV, turbulent conditions,	$0.5{\cdot}10^6$	5.3 .. 67.5%	0.99	20	visual, pressure, temperature	stored in capacitor		[17]
hydrogen /oxygen /argon	capacitance sparks, gap: 2 mm, gap: 1.5 mm, gap: 1 mm, voltage 0 .. 15 kV, 50 GΩ resistors, tungsten, conical electrodes, (base diam. 6.35 mm, cone angle 53°, tip radium 0.8 mm),	3 .. 30	5%/12%/83% , 6%/12%/82% 7%/12%/81%			visual, pressure, temperature	difference between stored and residual energy	50%	[13, 14]
hydrogen /oxygen /argon	long capacitance sparks„ voltage up to 30 kV, variable gap: 1 .. 10 mm, tungsten, hemispherical electrodes (radius 3.2 mm) ,	5 .. 20	6%/12%/82 %			visual, pressure, temperature	difference between stored and residual energy	50%	[13, 14]
hydrogen /oxygen /argon	capacitive sparks, gap: 1 .. 2mm, voltage 0 .. 15 kV, 50 GΩ resistor	3 .. 30	7%/21%/72%			visual, pressure, temperature	difference between stored and residual energy		[35]