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Precise triggering of electrical discharges by ultraviolet laser radiation for the investigation of ignition processes

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ABSTRACT

Ignitions caused by low energy electrical discharges represent a potential risk in explosion protection. However, the random nature of such discharges poses a major obstacle to experimental investigations. In the present paper we propose a means of triggering the discharge by ultraviolet radiation from a pulsed laser. Thus, a sufficient number of free electrons is generated in the spark gap to initiate a discharge. Through this method we achieve a precise timing and a high reproducibility of the discharge. Therefore, the proposed approach opens a new possibility for the detailed investigation of ignition processes through electrostatic discharges.

1. Introduction

The assessment of the consequences of electrical discharges plays an important role in the evaluation of explosion protected devices as well as safety-relevant processes. Especially in the chemical and process industry it is of paramount importance to avoid the ignition of combustible gas mixtures by such discharges. Despite their relevance for the operation of a wide range of plants, the current standards and regulations regarding this safety risk are based mainly on empirical data. This results in the necessity for consideration of relatively large safety factors during the design of explosion protected devices [1–4]. Consequently, the limits of operation for chemical processes and the protective measures taken may be overly conservative in certain cases. Thus, a more fundamental understanding of the ignition process caused by electrical discharges would contribute to pave the way towards standards that are based on scientific findings. This would enable wider ranges of operation for some chemical processes without an increase in the explosion risk. Further, economic benefits are expected due to a possible reduction of the design and production costs of explosion protected devices [4].

The minimum ignition energy (MIE) of a combustible is a useful characteristic for the assessment of explosion risks. While in the context of forced ignition, the MIE is often defined as the energy where an ignition occurs with a probability of 50% [5,6], this risk cannot be tolerated for safety-relevant ignition processes as they could occur in the frame of explosion protected devices. Thus, the MIE is defined as the energy which leads to the ignition of the most ignitable mixture of a burnable gas with air in one of 100 trials [3,7]. It is important to note that the MIE is not only a function of the combustible mixture but also of the method used to obtain it [2,8,9]. For instance, the MIE of hydrogen is larger when laser ignition is employed than when the ignition source is a short electrical discharge [10]. Therefore, a standardized method for the measurement of MIEs was developed which utilizes electrical discharges [11].

For the reasons given above the analysis of the physical and chemical processes underlying ignitions by electrical discharges gained the attention of researchers during the last decades. Concerning experimental investigations, usually a procedure is followed that involves the usage of high voltage capacitive model discharges [7,12]. In this arrangement, electrical discharges occur between two electrodes if the voltage across the gap exceeds the gaseous breakdown limit potential, which is given by Paschen's law [13]. However, the time instance and formation of the discharge is a random process where the probability of a discharge increases as the voltage is increased. More precisely, the exact timing of the discharge is determined by the presence of a sufficient number of free electrons in the electric field between the electrodes. These electrons are accelerated by the electric field and lead, finally, to the formation of an electron avalanche if the field strength is large enough (which is called the Townsend [14] mechanism). If during this event impact ionization dominates the recombination reactions and the number of electrons exceeds $10^6 \ldots 10^8$, a streamer forms [15]. In this case, the gap is bridged by a conductive channel and a gas discharge occurs.

However, the analysis of the ignition event requires the exact synchronization of the measurement equipment such as cameras and lasers with the time instance of the occurrence of the discharge. Therefore, the discussed randomness of the discharge process constitutes a major challenge for its observation via experimental techniques. Often, for the

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investigation of very fast processes taking place at time scales of microseconds or less single-shot techniques are employed [16–18]. In the context of electrical discharges, the breakdown occurs within some nanoseconds. Further, the discharge duration for the pure breakdown is on the order of tens to hundreds of nanoseconds and up to milliseconds for arcs [15]. However, the intrinsic delays of the measurement equipment are usually much longer. More specifically, for CCD cameras it is often on the order of microseconds and for pulsed lasers, e.g. Nd:YAG lasers it is hundreds of microseconds. Therefore, obviously the measurement devices cannot be triggered by the discharge itself if the fast temporal scales shall be resolved. Instead some means of pre-triggering is mandatory.

Several solutions to this problem have been proposed in the past. One proposal is the generation of discharges using high voltage pulses as done by Lee and Shepherd [19], Randeberg et al. [20], and Ono et al. [21]. Therein, a short voltage pulse is superimposed to a constant voltage which itself is below the breakdown potential. This pulse is intended to initiate the breakdown whereas the added amount of energy is considered to be negligible. While the discharge is accurately triggered using this procedure, a drawback is the modification of the discharge conditions such as the voltage and current waveform with respect to the un-triggered discharge. Recently, Zhong et al. [22] compared this method to a technique where one of the electrodes was rapidly moved which lead to a well timed discharge. However, a drawback of the latter approach is that the precise distance of the electrodes during the discharge is a priori unknown. As a result, the alignment of the measurement equipment is not possible or at least complicated. There is also a type of discharge, called nanosecond repetitively pulsed discharge, which consists only of the transient voltage phase and allows for easy synchronization with measurement equipment. A typical duration of this discharge is 10ns while its repetition frequency is usually 10 kHz. It has been studied in detail both experimentally [23–26] and numerically [27,28] in the context of IC engine ignition and aviation high altitude ignition processes. However, due to its repetitive property, it is not applicable to safety-relevant ignition processes where single discharges are commonly examined.

Another method is the slow increase of the voltage across the gap, starting at a voltage sufficiently smaller than the natural breakdown voltage [21,29]. When the voltage exceeds the breakdown voltage, a discharge occurs. Afterwards, the power supply is shut off to prevent further discharges. Whereas the conditions of the spark are well-defined in this approach, its timing precision remains unclear. Furthermore, Shepherd et al. [30] proposed the usage of a manually or electronically controlled high voltage switch. Hereby, the discharge circuit can be closed at the desired time instance. However, this concept is rarely used and its timing accuracy is not reported in the given reference.

Finally, in another context it was proposed to utilize the well-known fact that ultraviolet (UV) radiation increases the probability of a discharge [31]. This effect was used by Langer et al. [32] to virtually fix the breakdown voltage in experiments that determine the minimum ignition energy of burnable gases. The reported results demonstrated important advantages of this method compared to the above discussed approaches. Namely, the UV light adds only a minuscule amount of energy to the setting. Further, the location of the discharge is well defined since electrodes remain fixed is space. However, in the study of Langer et al. [32] a continuous UV light source was used which did not allow for triggering of discharges.

In section 2 of the present paper, we propose the initiation of discharges through UV light to facilitate the precise timing of discharges for the investigation of ignition processes. The efficiency of this new approach in the context of ignition studies is compared in section 3 to the triggering of discharges by a slow voltage increase. Finally, the conclusions are given in section 4.

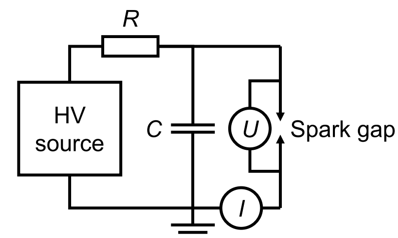

Fig. 1. Schematic of the proposed electrical set-up.

2. Proposed experimental set-up and procedure

A schematic of the electrical set-up used for the investigation of low energy electrical discharges is shown in Fig. 1. It consists of a high voltage source (FUG HCP 35–35000), a charging resistor R, a capacitor C (3–30 pF, Jennings CADC-30-10S), and the spark gap. The resistance R is chosen to be 1 GΩ in order to prevent continuous or secondary discharges once a discharge has occurred. The voltage across the spark gap can be measured with a high voltage probe (U, Tektronix P6015A). Further, the spark current can be measured with a current transformer (I, Bergoz CT-B5.0). Both signals are recorded by a high bandwidth oscilloscope (Yokogawa DLM6054). Moreover, the high voltage source can be controlled externally by a waveform generator (Agilent 33510B). This capability was needed to enable the comparison with the method of generating discharges by a slow voltage increase (see section 3.1).

Fig. 2 outlines the geometry of the electrodes and the relative path of the laser beam. The electrodes were tungsten rods with round tips and a diameter of 2.4 mm. A pulsed Nd:YAG laser (InnoLas SpitLight 1200) omitting UV light was used for the purpose of triggering electrical discharges. It was operated at the fourth harmonic, giving a wavelength of 266 nm. The beam had a Gaussian profile with a $1/e^2$ width of $d = 6.5mm$. The pulse length was 7 ns–10 ns.

Two photos of the most important parts of the set-up are presented in Fig. 3. The electrodes are positioned in the center of the cylindrical vessel and are not visible in the top view due to the top electrode holder. They are shown in the side view image. The dimensions of the vessel are 140 mm in diameter, excluding the flanges, and 110 mm in height. A purple line indicates the laser beam path from the bottom of the image towards the center.

The experiments were carried out in air or in an 8.0 vol % ethene/air mixture at room temperature (21.5 °C ± 1.0 °C) under atmospheric conditions ($1\text{bar} \pm 40$ mbar). For the experiments in air, the gap length L was 1.5 mm ± 0.1 mm while for the experiments in the ethene/air mixture it was 1.2 mm ± 0.1 mm. The relative humidity of the mixture inside the test vessel was not greater than 0.3%.

The time accurate triggering of a physically well-defined discharge is the crucial issue of the experimental procedure proposed herein.

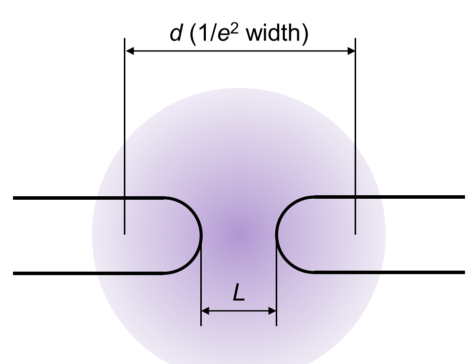

Fig. 2. Electrode geometry and laser beam emitting UV light. The beam is oriented perpendicular to the plane of the sketch.