Experimental investigation of the electrical characteristics of low-voltage contact-arcs in hydrogen-air mixture

Carsten Uber [a], Rajiv Shekhar [a,b], Udo Gerlach [a]
[a] Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, Braunschweig, Germany
[b] University of Queensland, Brisbane, Australia

1 Introduction

Low voltage discharges occurring between opening electrical contacts are a potential ignition source in flammable gas mixtures. For safe operation in hazardous areas equipment is approved according to an international standard. For deriving the limit values in the standard and if necessary in practice, a so called spark test apparatus (STA) is used [1], which generates these discharges between contacts in the gas mixture with the electrical energy of the test equipment. However, the results are unreliable and must be improved.

For this reason, electrical discharges between opening contacts in flammable gas mixtures are investigated. The relationship of the distance of the electrodes and the voltage of the discharge for different current values of a constant current supply is determined and plotted. Differences between igniting and non-igniting discharges of the first measurements will be shown. The measurement is very challenging because the short duration of the discharges (microseconds), small dimensions (micrometers) and low radiation.

The goal is to investigate the opening process in the STA in order to obtain a voltage-length curve of the discharge as well as the geometric distribution of its energy transfer into the gas. These relationships can be used for a simulation of the ignition to enable the long-term development of an alternative to the STA.

2 Background

The contact opening process to be examined begins with the sliding of the wire over the surface. Depending on the wear of the cathode, the roughness of the cadmium-surface differs. At the beginning there is electrical contact between the electrodes. When the wire reaches the groove, there is a distance of a few micrometers between the electrodes. When the wire moves from the edge, the electrical discharge takes place and according to the conditions also the thermo-chemical reaction takes place. A minimum roughness of the surface is required for the generation of such discharges [2]. The phases of the contact opening are shown in Figure 1.

Correspondence to: carsten.uber@ptb.de

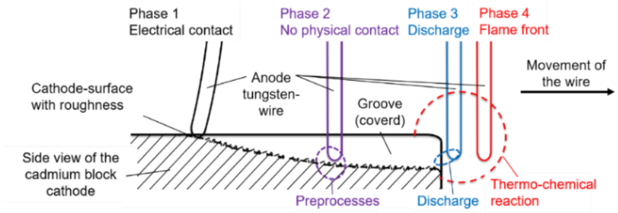

Figure 1: Movement phases of the contact arc

In the STA the wire slides with a typical velocity of about 0.2 m s^{-1} above the surface, which varies according to the geometry and roughness of the surface. In some situations, when the wire moves away from the slot edges, the electrodes separate with a low velocity of about 0.001 m s^{-1}. When the wire bounces from the edge, the strained wire speeds up to velocities up to 26.8 to 31.1 m s^{-1} [3].

In the first phase electrical contact takes place via the microscopic asperities of the surface, which can also be covered with impurities such as cadmium oxide. As the contact area decreases the current density increases. Molten bridges can then result and metal can evaporate explosively [4–6].

In the transitional phase, when the wire moves a distance of a few micrometers over the surface, some preliminarily processes take place, e.g. small discharges. When the wire moves away from the edge, the main electrical discharge, a "short arc" according to [7] is generated. The main component of this discharge is presumed to be metal vapour, since the wavelengths of the radiation correspond to the atomic lines of cadmium [2]. Electrical field enhancement, especially due to micro-roughness and areas with lower work function such as impurities can support the discharges.

At the beginning of the discharge the voltage across the contacts increases to the cathode fall voltage of 10 V [8]. As the electrode distance increases, higher voltage are necessary to maintain the arc [9]. For static electrodes and DC, Ayrton [10] and Nottingham [11] published an equation similar to equation (1).

$$V_{arc} = \mathrm{a} + \mathrm{b} \cdot l_{arc} + \frac{(\mathrm{c}+\mathrm{d}\cdot l_{arc})}{I^n} \qquad (1)$$

In this equation V_{arc} represents the voltage of the discharge, l_{arc} the length and I the current. a corresponds to the fall voltage, b, c, d, n are empirical constants. Additional dynamic influences for example by the influence of heat capacity are discussed in more recent literature [12].

This relationship is, on the one hand relevant for the simulation of the voltage from the movement of the electrodes on the other hand for the transmission of the electrical energy into the gas. At the same time the thermochemical reaction starts and if there is enough energy transferred into the relevant volume and also suitable conditions present, it leads to an explosion [13]. The minimum ignition energy of hydrogen-air-mixture with 21vol% of hydrogen is 17 µJ ± 2.3 µJ (measured between static electrodes [14]).

3 Experimental Setup

The main component in these experiments is the contact device, which generates electrical discharges at the same position in a chamber with hydrogen air mixture in order to observe them with a camera.

The contact device consists of a cathode, a cadmium block (30 mm x 10 mm x 10 mm) and the anode, a tungsten wire, which moves linearly over the surface. As in the spark test apparatus, the diameter of the wire is 200 µm and 11 mm long. The distance of the wire to the surface is adjusted in such a way, that the wire tip overlaps the block edge by between 0 and 1 mm, depending on the experiment.

In the experiment, the wire slides over the top of the cadmium-block and with a velocity of about 0.2 m s^{-1}. When the wire has moved over the edge, the wire accelerates to measured speeds of 1 to 2 m s^{-1}, when the wire is previously adjusted to a minimal non-measurable overlap. During this phase when moving from the edge the electrical discharge to be examined occurs.

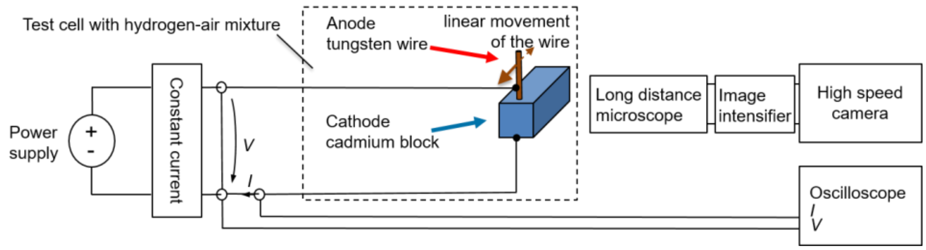

Figure 2: Experimental setup for generating incendive contact-arcs

The chamber with the contact device is filled with approximately 12 liters of 21vol% hydrogen-air mixture, according to gas group IIC of the IEC standard IEC 60079-11 [1]. The oscilloscope and the camera are triggered by an infrared diode, which detects the radiation of the explosion in the infrared range.

The electrical energy is supplied via a voltage source with constant current behavior (rectangular characteristic), where the desired current value can be set. The voltage and current curve was recorded with a digital storage oscilloscope Yokogawa DK9040L with a sampling rate of 5 GS/s (62.5 MS/s) together with a differential probe 50 MHz 1/100. A RLC meter GenRad 1689 Precision RLC Digibridge was used to estimate the parasitic electrical values of the circuit. The parasitic values with approximately $L \approx 4$ µH und $C \approx 25$ pF are very low and have a negligible influence on the ignition.

The images of the electrical discharges are recorded with a high-speed camera Photron SA5 and a long distance microscope Questar QM1. So pictures with 320 x 192 pixels are recorded and a section of about 1.4mm x 0.9mm is observed. The weak radiation of the electrical discharges especially at the ignition threshold, limits the frame rate of this images. In order to allow 100000 fps an image intensifier Hamamatsu C10880-03C was used. The images are assigned to electrical signal values via the recorded sync signal of the camera.

4 Results

For the experiments the electrode surface was conditioned by repeated contact cycles comparable to the standard IEC 60079-11 [1] (24 VDC, 100 mA, 95 mH inductance). It was shown that the investigated discharges are only possible after such a conditioning processes and the duration of preliminary processes and effective discharges increase with more conditioning processes (see Figure 3).

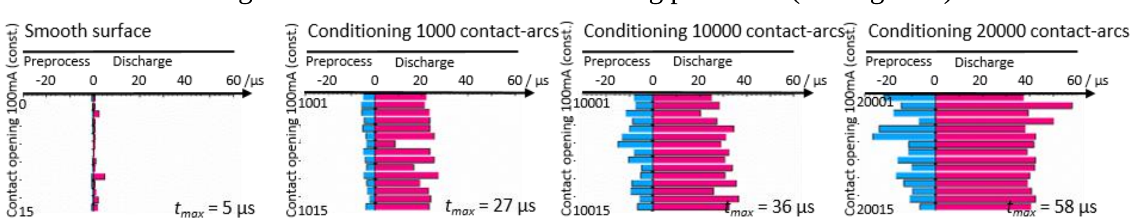

Figure 3. Diagram showing the duration of the preprocesses and effective discharges after different numbers of contact cycles for the conditioning

The main measurement series of igniting contact discharges, with a voltage of 30 V and currents of 250 mA, 200 mA, 150 mA, 100 mA and 70 mA was then performed. Figure 4 shows an example of the correlations. For the wire movement the lowest possible separating velocity is targeted (1 – 2 m s^{-1} measured) in order to minimize the influence of dynamic effects. The cadmium-surface is very worn and rough.

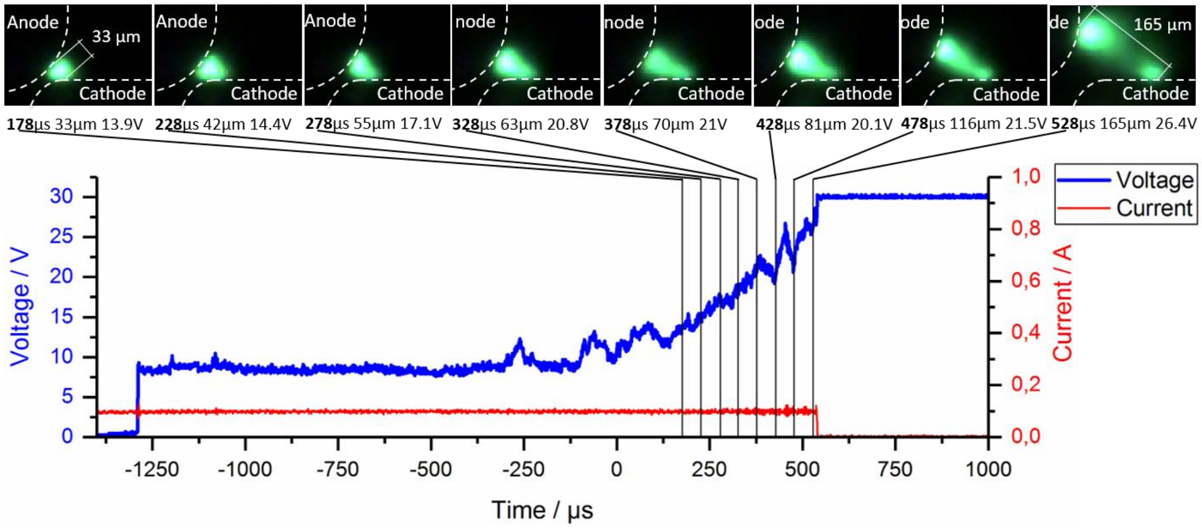

Figure 4. Image sequence and electrical curve of a contact discharge with ignition for a voltage of 30 V, a current of 100 mA in hydrogen-air mixture

For each current value 15 contact discharges were performed. During a contact process, every 10 µs an image is taken and producing about 70 measurement values per discharge. For the voltage of 30 V and the current of 100 mA the results of the measurement and also the fitted characteristic are shown in Figure 5 (Left). Figure 5 (right) shows the linear fitted curves for all current values of the measurement.

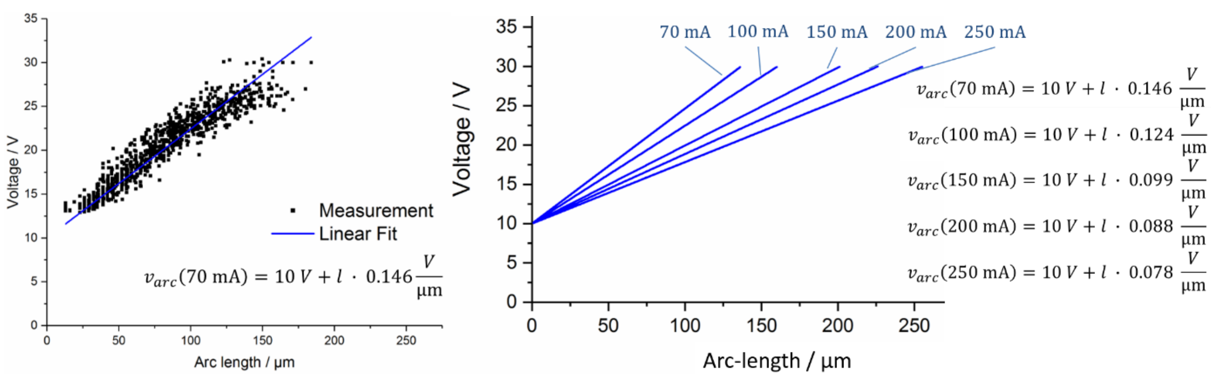

Figure 5. Left: Measurement values and fitted curve for contact discharges with ignition for a voltage of 30 V and a current of 100 mA; right: Voltage-discharge length characteristic for contact-arcs with ignition for a voltage of 30 V and current values from 70 mA to 250 mA

Compared with the measurements of [2], which could only be measured with a lower temporal and spatial resolution, the results are in the same range. The curves from 100 mA to 250 mA are similar. The now measured curve for 70 mA is more plausible, compared to the 74 mA curve from [2] with the noted deviation. Figure 6 (Left) shows both results. Figure 6 (right) shows the calculated VI-characteristic of the measurement. In addition the data of Zborowski [15] given for orientation, as this is one of the few comparable datasets from the literature. These data are only qualitatively comparable and calculated for the spark test apparatus in air based on data of Holm [16].

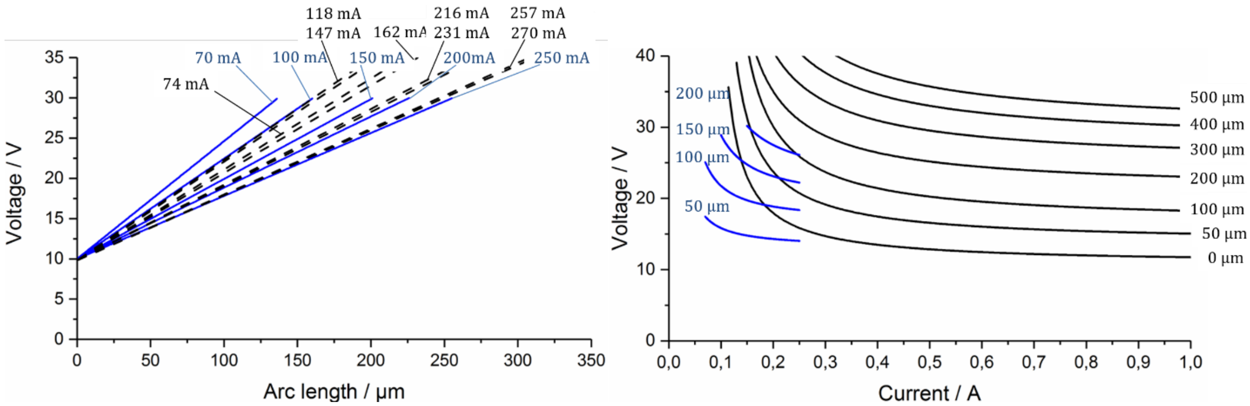

Figure 6. Left: Comparison of the measured curves to the results of Uber [2]; right: Calculated VI-characteristics (blue) in comparison to the data from Zborovsky [15] (black), calculated for the spark test apparatus in air.

5 Discussion

First investigations with discharges without ignition show that these discharges have a lower/flatter V-arc length characteristic (compare Figure 6). An example is shown in Figure 7. It is worth mentioning, that in the case of no ignition the duration of preliminary processes was less than 500 µs (duration, when the voltage is between 8.5 and 11 V) and for discharges with ignition the duration was about 1000 – 2000 µs. It should be noted, that because of the small number of experiments more investigation in this case is needed.

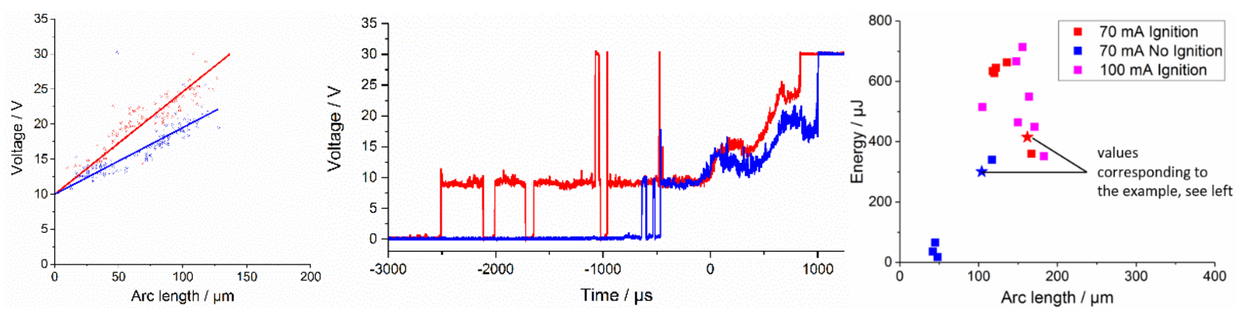

Figure 7. Left: V-arc length-curve with 30 V and 70 mA with an ignition (red) in comparison to without an ignition (blue); middle: Voltage-curve for an contact-arc with an ignition (red) in comparison to without an ignition (blue) ; right: Calculated net energy

The steeper increase of the V-arc length curve means that there is a higher voltage with the same spark length or electrode distance and because of this a higher power and energy available. The net energy for the examples as well as some other first measurements are calculated with the method of Johannsmeyer [7] and shown as a function of the electrode distance in Figure 7 (right).

These experiments show the first results of the electrical characteristics and the arc length with overall relationships and special conditions, which apply only to this situation. Further investigations are required for the confirmation as well as the transferability of these results to other electrode materials and gases. Also more accurate analysis of the physical and chemical processes is needed to apply a physical discharge model.

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