Hot Gas Kernel Expansion Shape Caused by Contact-Break Discharges on Cadmium and Zinc Cathodes in a Hydrogen-Air Mixture

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1 Introduction

Due to the high interest in hydrogen technologies, hydrogen explosion safety is still in the focus of research. Contact-break discharges, that occur even at low voltages and currents, represent a potential ignition source and are therefore of upmost importance. The focus in literature, however, is on static electrodes and higher voltages, different gases or larger scales of the discharge setup and hot gas kernel size [1], [2], [3], [4]. In this work the focus is on dynamic electrodes and voltages and currents in the range of 40 V and 40 mA, respectively. Contact-break discharges and the resulting hot gas kernel expansion in a hydrogen-air mixture with a hydrogen volume fraction of 21 vol.% between a tungsten anode and a cadmium or zinc cathode are investigated by means of high-speed schlieren imaging. The experimental research is extended by a 3D numerical model meant to analyze the hot gas kernel expansion and characteristics depending on the discharge channel position.

The idealized process of a contact-break discharge can be split into four phases [5]. First, there is an electrical and mechanical contact between the anode and the cathode while voltage is applied. In the second phase, the two contacts are separated. Due to the small electrode gap, i.e. few micrometers, only small discharges can form. These small discharges cannot lead to ignitions but support the formation of longer discharges. Therefore, these are called preprocesses [5]. With further increase in electrode distance these preprocesses transition into a larger main discharge in the third phase. It was observed that the radiation of the plasma at the start of these larger discharges is dominated by the cathode material. Hence, they are assumed to be metal vapor discharges [5]. The main discharge brings energy into the surrounding gas, heating it up and leading to the formation of a hot gas kernel. Further heated by the main discharge, this hot gas kernel expands and depending on several parameters, an ignition can

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then occur in phase four. However, the actual transition from discharge driven to chemically driven hot gas kernel expansion is not well understood. While cadmium is an established material for testing explosion protected electrical equipment [6], the current investigation was extended to zinc in order to find material independent relations.

2 Measurement Setup

The experimental contact device, which is used to create the contact-break discharges, consist of a rotating disc-shaped cathode, made of either cadmium or zinc and a wire made of tungsten with a diameter of 200 µm. The wire is removed from the rotating cathode surface by a linear motor at a speed of about 0.008 m/s. The cathode is rotated at a speed of 5 turns per minute. The investigated gas mixture consists of 21 vol.% hydrogen and air, in accordance with the international standard IEC 60079-11:2023 [6]. Parallel to the recording of the images, the electrical parameters of the discharges are recorded by means of an oscilloscope. Voltage and current are supplied by a constant current source with a voltage limitation. Typically, constant currents are set between 40 mA and 100 mA while the voltage is limited to values between 20 V and 40 V. For the measurement of the hot gas kernel, the schlieren technique was used [7], [8]. The schlieren setup consists of a light source (EQ-99X-FC-S by Hamamatsu Photonics), a collimating lens, the explosion chamber with the test gas and the experimental contact device, a focus lens, a knife edge and a high-speed camera (Fastcam Nova S by Photron). With the knife edge, changes in the refractive index of the gas, caused by changes in density mainly caused by changes in temperature, become visible [7], [8]. This way it is possible to measure the hot gas kernel by its temperature change.

3 Experimental Results

The examples of schlieren images in figures 1 and 2 were recorded with a high-speed camera and are post-processed with background correction. They are structured as follows: On the right edge of the image, the cathode can be seen. In the middle of the cathode a trench is visible which forms over time, due to mechanical abrasion and vaporization of cathode material during the discharges. On the left, the anode wire made of tungsten is visible. The tip of the wire is irregularly shaped, due to accumulations of cathode material during the experiments. The edge of the hot gas kernel is marked with dashed lines.

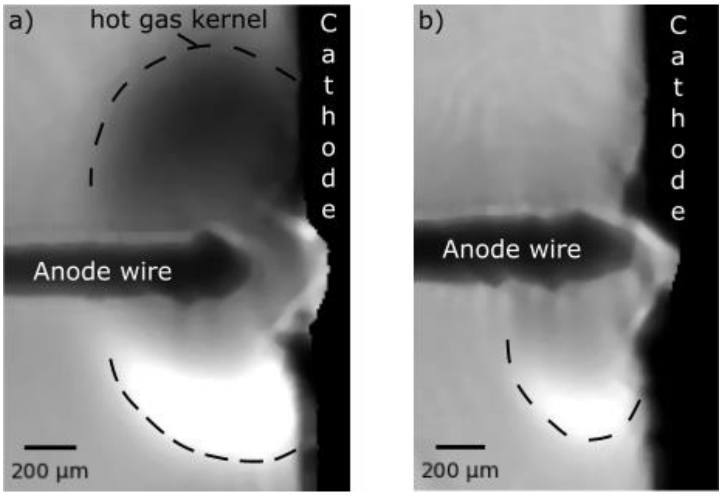

Figure 1: The hot gas kernel expansion for cathodes made of cadmium. a) A symmetrically expanding hot gas kernel is formed with similar expansion velocities above and below the anode wire. b) The hot gas kernel expands only below the anode wire. The applied maximum voltage and constant current were 40 V, 40 mA and 20 V, 80 mA, respectively.

Due to the effect of the knife edge in the schlieren setup, the hot gas kernel appears darker above and brighter below the anode wire.

The expansion of the hot gas kernel follows in general two distinct forms relative to the anode wire: a symmetric and a one-sided hot gas kernel. However, combinations of these two types are also possible, resulting in an asymmetric expansion.

In figure 1 a), the hot gas kernel expands on both sides of the anode wire in a half circular or elliptical shape. The expansion velocities above and below the anode wire are nearly equal. This kind of expansion is therefore referred to as symmetric expansion with the anode wire as axis of symmetry. In figure 1 b), the expansion is only one-sided, below the anode wire. Above the anode wire, no hot gas kernel expansion is visible at all. The form is estimated as quarter circle or ellipse. In contrast to the symmetric case, this one is referred to as one-sided expansion.

The same investigation was done for cathodes made of zinc. Similar to the cadmium investigation, the expansion forms, symmetric and one-sided, as well as their combination, asymmetric, could be observed. As depicted in figure 2 a), the hot gas kernel forms around the anode wire and expands with similar expansion velocity above and below the anode wire. The form is again a half circle or ellipse. In figure 2 b), the hot gas kernel expands mostly below the anode wire. Only a small part is visible above the anode wire. The discharge between the electrodes is still visible. The trench in the middle of the cathode is not visible for the zinc cathodes due to a smaller number of measurements. A factor could also be the differences in material parameters like melting point and hardness between cadmium and zinc.

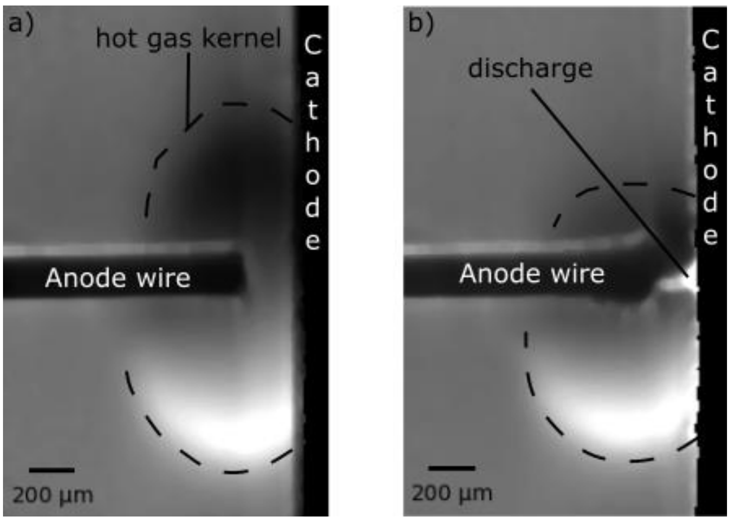

Figure 2: The hot gas kernel expansion for cathodes made of zinc. a) The hot gas kernel expands above and below the anode wire with similar expansion velocities. b) The hot gas kernel expands mainly below the anode wire. The expansion above the anode wire is slower. The applied maximum voltage and constant current were 40 V, 70 mA and 30 V, 90 mA, respectively.

In general, the observed shapes of expansion are similar for both cadmium and zinc cathodes. Further, both types of expansion were observed for different electrical parameters. However, close to the ignition limit, i.e. for low currents and voltages, ignitions mainly followed asymmetric or one-sided hot gas kernel expansions, leading to the assumption that these types of expansion present the more ignitable case.

4 Numerical Model

During the discharge-driven expansion phase, the hot gas kernel expansion is influenced by several factors such as electrode losses, surface conditions, discharge position, or gas composition. The electrode losses, considering a fixed gas composition, were previously analyzed in a 2D axially symmetric numerical model detailed in [9]. However, due to the imposed symmetry, this model is only partially adequate to study the influence of the surface conditions or certain geometric variations, e.g., discharge position, on the hot gas kernel expansion. Another limitation of this numerical model was the treatment of the fluid as a static medium, i.e. no fluid dynamics equations were solved. This limits the energy distribution computation to thermal conduction only.

To assess the influence factors that lead to the experimentally observed gas kernel asymmetry, a 3D conjugate heat transfer model with laminar flow is developed. This model features a cylindrical tungsten (W) anode with a conical tip with a length of 500 µm and a diameter of 200 µm. The cadmium cathode block has a width and length of 1000 µm, a height of 500 µm and presents in the middle a narrow trench with a depth of 100 µm.

A cylindrical heat source, representing the discharge in a static manner, is positioned at a 45° angle between the anode and cathode. The discharge has a height of 150 µm and a diameter of 50 µm. Unlike the model from [9], the 3D model presented in figure 3 a), does not consider an anode movement and maintains a fixed discharge length during the entire simulation time. The discharge input power is set according to experiments and presented in figure 3 b). The heat transfer coefficients on the anode/cathode-gas interface (h_{AG}, h_{CG}) used in this model are calculated from the ratio of the thermal conductivity of the gas $\lambda(T)$ and the thickness of the thermal boundary layer δ_T, i.e., $h = \lambda(T)/\delta_T$ and are presented in figure 3 c).

The surrounding fluid domain is modeled as a sphere with 1000 µm radius. The fluid is considered to be a gas mixture of air and hydrogen with 21 vol.% hydrogen. Additionally, the presence of 20 vol.% cadmium metal vapor in the discharge and 10 vol.% in the surrounding gas are also considered. The temperature-dependent material properties for these two domains are set according to the percentage of cadmium metal vapor as in [9].

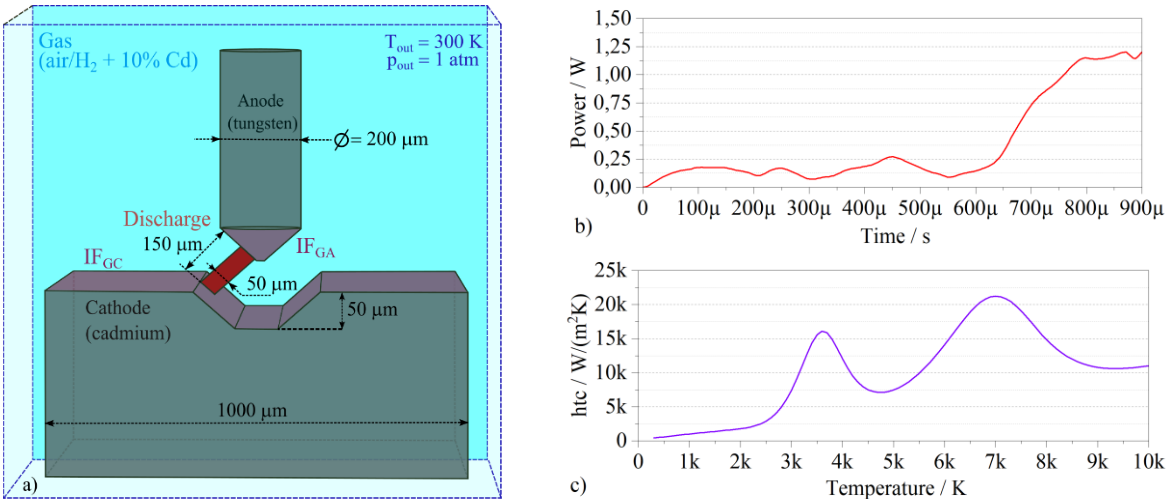

Figure 3: a) 3D Geometry and boundary conditions of the computational model; b) temporal variation of the power input for the discharge and c) the heat transfer coefficients used at the fluid-solid interface.

The main advantages of the new developed 3D model are that (1) it allows the analysis of 3D surface variations without being restricted to geometrical symmetry and (2) it implements the fluid equations including the energy distribution by convection. However, similar to the 2D model, this model does not consider chemical reactions during the gas kernel expansion. Also, local thermodynamic equilibrium (LTE) is assumed in both the discharge and the surrounding gas region.

The model is implemented in COMSOL Multiphysics and combines two physics interfaces, “Heat Transfer in Solids and Fluids” which solves for the heat balance equations derived from the principle of conservation of energy and the “Laminar Flow” which solves for the mass and momentum continuity equations for weakly compressible flow. The two interfaces are coupled through the “Nonisothermal Flow” interface. In this manner, conduction is used for heat transfer in solid materials and both conduction and convection are considered for heat transfer in the fluid. The model uses a transient solver with a simulation time of 900 µs.

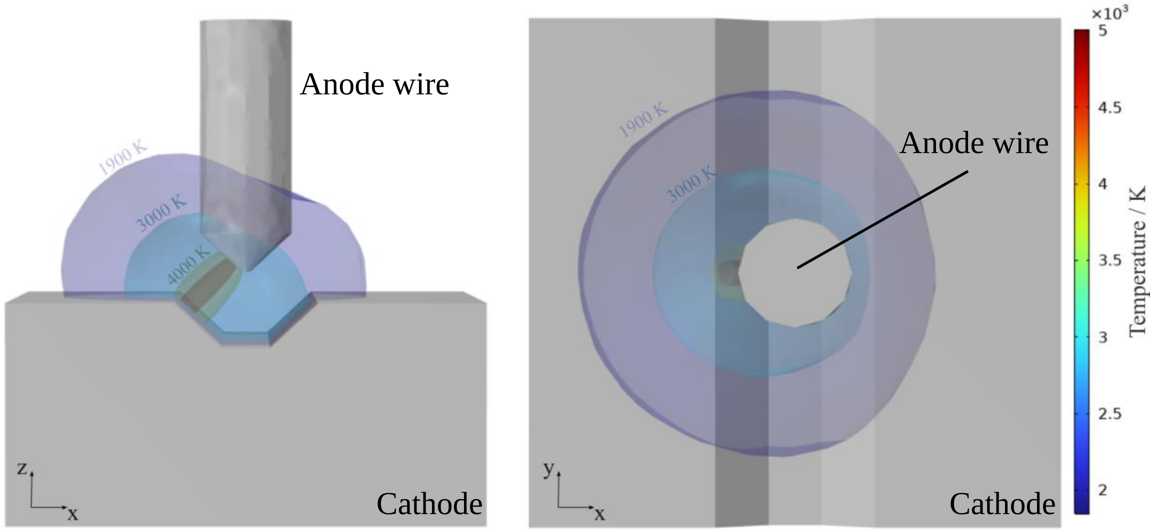

Figure 4: Temperature distribution inside the hot gas kernel surrounding the discharge. The isotherms of the hot gas kernel for 1900 K, 3000 K and 4000 K are depicted in purple, blue and green respectively. The discharge is shown in brown between the electrodes.

The preliminary results, depicted in Figure 4, show the hot gas kernel expansion for a discharge positioned at the edge of the trench at 900 µs. The isotherm of the adiabatic flame temperature (1900 K) along with two other temperatures (3000 K and 4000 K) is plotted to offer a rough visual comparison with the experimental results. From the numerical model, it can be observed that the hot gas kernel expansion is asymmetric with a stronger flow development towards the upper left region. This behavior is expected due to the position of the discharge and the surface variations that the flow encounters due to the trench walls on the right side.

This model is limited by the static behavior of the anode and the cathode. A more accurate description of the model would be achieved by including the dynamic movement of the anode and the corresponding changes in the shape of the discharge.

5 Conclusion and Outlook

The examples shown in this work illustrate the basic idea of the hot gas kernel expansion for the used cathode materials cadmium and zinc. In general, the hot gas kernel expands either symmetric on both sides of the anode wire, only one-sided or in a combination of these two expansion types, leading to an asymmetric expansion, with one side expanding faster than the other. These expansion types appear to be independent of the cathode material. Further, it appeared in investigations of the electrical ignition limits that asymmetric and one-sided hot gas kernels were more ignitable than symmetric ones, due to the appearance of mostly asymmetric or one-sided hot gas kernels. However, this is a first estimation and needs more statistical proof.

The results from the modelling approach were able to partially reproduce the observed asymmetry in the shape of the hot gas kernel, as observed in the experiments. However, to get the full image of the hot gas kernel expansion, the numerical model needs further adjustment. Future research will take a detailed look at how the discharge position, surface variations and the heat transfer coefficients influence the hot gas kernel expansion, as well as expand the simulation for zinc cathodes.

Acknowledgement

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