Experimental study of gas dynamics caused by spark discharge near wall

E V Dolgov, N S Kolosov, I A Moralev and A A Firsov*

Joint Institute for High Temperatures (JIHT RAS), 125412, Moscow, Russia

* af@jiht.org

Abstract. Experimental research of the high-speed flow caused by the decay of the thermal cavern after spark discharge located on the wall in ambient air is performed using schlieren technique. Parametric investigations include varying of discharge length in a range of 3-7mm and energy in a range of 60-200mJ. It was found that the rise of discharge energy results in insignificant increase of the size of disturbance height. For tested spark gaps at fixed total energy impact the maximal height of disturbance corresponds to minimal length of discharge (3mm). The results obtained are in a good qualitative and quantitative agreement with the simulation data previously published by the authors.

1. Introduction

The spark electrical discharge has been thoroughly investigated [1] and is actively used in various fields of technical applications, including ignition in internal combustion engines and generation of NOx for biomedical applications, etc.

Recently, an interest was arisen for a long (3-40mm) pulsed (100ns-5μs) spark discharge due to its ability in generation of gasdynamic perturbations potentially beneficial for a flow control and mixing intensification [2]. In several publications, the results of studies on the features of the spark discharge thermal cavern decay were presented: it was shown that large-scale jet flows are formed in the direction perpendicular to the channel due to the spark channel bends during the decay of the long spark discharge [3]. The effect of discharge shape (bending) on pattern of the gasdynamic perturbations was shown by using additional electrodes to distort the shape of the discharge, and also by numerical simulation [2].

One of promising directions of the use of gasdynamics caused by a spark discharge is development of plasma actuators for suppression of a transonic buffet - the normal shock wave oscillations that takes place in transonic flow around a wing at high Mach number or high angle of attack [4-6]. The spark discharge acted as a vortex generator in the boundary layer on a flat surface [4-5], and in the work published in paper [6] the spark discharge was combined with protrusions on the wing surface to create a directed transverse action. In paper [4], it was shown that the spark discharge near the surface leads to the formation of a jet of a rather complicated shape: after the shock wave has run away, the thermal cavern is significantly modified in geometry - a gas flows from the ends of the discharge channel to the center. Then the region of the low-density hot gas moves into plane perpendicular to the initial position of the spark, into a wide sector of about 180 degrees in the form of a half of toroid, the center of which takes a gas from the surrounding area. In paper [5], it was shown experimentally that such a discharge on the surface of the wing can lead to decrease the buffet amplitude. By the numerical simulation it was shown an entire suppression of the oscillations of the shock wave upon action by a pulse-periodic spark discharge.
There is a practical interest to study very short nanosecond (~100ns) discharges due to potential applications for airflow control, including applied aerodynamics problems (flow around various bodies) and problem of combustion/ignition of lean mixtures. In paper [7], it was shown that the decay of a thermal cavern of a nanosecond spark discharge with a spark gap of 1 mm results in the transfer of active particles into the surrounding volume by a distance of ~10 mm from the discharge axis. To use the discharges for aerodynamic applications, it is important to optimize the discharge parameters in terms of the flow control authority, the effect on the airflow pattern depending on the discharge parameters, such as interelectrode distance and energy deposition [8]. In this paper, the major focus is made on the experimental parametric study of structure and dynamics of gas perturbations caused by the long spark discharge.

2. Description of experimental setup

Electrical scheme and voltage-current measurements

Electrical scheme of experiment was modified in comparison to another one used in our previous experiment [2] for increasing the operating voltage and improving of discharge jitter. Principal electrical scheme is presented in Fig. 1,a. Main capacitor C1 (1.1-4.4nF) was charged using power supply U0 (8-16kV) through ballast resistance R1=10 MΩ which limits the charging current. Two spark gaps were connected inline, first one (1) was an externally triggered spark gap with operating voltage 4-10kV, second discharge gap (2) consists of two copper electrodes flush-mounted into ceramic BN (boron nitride) plate with spark gap 3, 5 or 7 mm. Resistance R2=1.7Ω was used to increase of resistive component of scheme during discharge pulse and reduce current oscillations caused by stray inductance. Resistive voltage divider based on R3=200 MΩ and R4=100 MΩ was used to increase the operating voltage range for spark gap (2). All lines of discharge circuit were as short as possible. Voltage U on spark gap was measured close enough to discharge using high voltage probe Tektronix P6015A, and discharge current was measured using Pearson current monitor mod.411. Maximum current and voltage amplitudes were the following - U up to 18 kV, and I up to 700 A. Typical voltage and current on time dependencies are presented in Fig.1,b for 5mm spark gap and energy E=100mJ.

![Electrical scheme and voltage-current measurements](image)

Figure 1. a - principal electrical scheme of experiment, b – typical voltage and current on time dependencies (5mm spark gap and energy E=100mJ)
Schlieren system details

Schlieren visualization of gas-dynamic disturbances caused by the discharge was performed using a highly sensitive shadow device tuned as a schlieren system. The shadow device consists of two lenses with a diameter of 150 mm with a focal length of 1.5 m and a swivel mirror that facilitates the adjustment of the system. The infrared laser source is installed in the focus of first lens, and the Foucault knife-edge is located in focus of second lens, and behind the edge the Basler acA2000-340km camera is installed. The experimental system was synchronized using an optical pulse generator, which gives high accuracy of synchronization of various equipment involved in the experiment. To prevent the camera from overexposing by discharge an interference filter is installed in front of the camera. This filter passes only a narrow range of wavelengths, into which the laser light of the shadow system with a wavelength of 812 nm. Laser pulse duration of 92 ns actually determines the exposure of our shadow device. After the camera exposure starts, a spark discharge breakdown is initialized, and then with an adjustable delay relative to the discharge, the laser pulse is activated. Because the electric circuit for triggering the discharge has a certain jitter, the real delay between the discharge and the laser pulse was measured directly by recording the pulse of the discharge current and the pulse from the IR (infrared) radiation detector.

For one breakdown of the discharge in the experiment, one frame of the shadow shooting was obtained. To obtain the dynamics of a thermal cavity, the experiment was repeated many times. At the first stage, it was necessary to choose the optimal position of the Foucault knife (see Fig.2) to observe a clear picture of the thermal cavity expansion and the development of jet instability caused by the operation of spark discharge. We tested the vertical and horizontal position of the knife, at an angle of 45° and shooting in the absence of a knife (direct shadow method). Because optical deviations in the vertical plane are considered in this experiment, the vertical position of the knife provides limited information about the plane passing through the middle of the spark channel. In this case, the disturbance on one side of the secant plane were darkened and lightened on the other, while the best picture was observed in the illuminated region which corresponds to the side part of thermal cavern. An attempt was also made to visualize the experiment in the absence of a knife, i.e. direct shadow method. Due to the strong gradient of the thermophysical parameters of air in the spark region in the time interval 0 - 20 μs, the disturbance that arises can be visualized by this method. At later times, the gradient decreases and the boundary of instability becomes less distinguishable. Then the knife was set in position at an angle of 45 degrees. It is clearly seen that in this case the cavity boundary was sharp only in a thin region close to the electrode. Also two horizontal positions of the edge knife were tested. Best images were obtained using bottom horizontal position of the knife. Using such settings of schlieren system the experiments were visualized over the all range of delay interval.

![Figure 2. Typical schlieren images. Energy = 100mJ, spark gap = 5 mm, delay 20 μs; a - vertical knife; b - no knife; c - 45° knife; d - horizontal knife.](image-url)
To accelerate the processing of a large number of shadow images obtained in the experiment, and to reduce the systematic error of data processing, a computer program was prepared that simplifies image analysis. The algorithm of the program was next: an array of images was loaded into the program, for the first of them a line perpendicular to the wall was selected manually, and dissecting the image of the thermal cavity, approximately in half (see Fig. 3,a). Along this line, the intensity profile of the shadow picture was maid (see Fig. 3,b). Local maxima corresponding to the contact of the thermal cavity with the wall (1), the upper boundary of the thermal cavity (2) and the position of the shock wave (3) are clearly visible on the obtained intensity profile. The first two local maxima were detected by the program and the size of the thermal cavity was determined as the distance between these maxima. The obtained distance was recorded in the memory, and the process was repeated for all obtained images. In addition to the images, a file with a list of shooting delays relative to the discharge breakdown was loaded into the program. For all images with the same delay (3-5 pieces), the averaging procedure was performed, and the obtained dependence of the average size of the thermal cavity on time was displayed on the screen and loaded to the text file.

![Figure 3. Typical schlieren image during post processing - a; and b - intensity profile along the vertical line in image (a): 1 – wall surface, 2 – cavity boundary, 3 – shock wave](image)

3. Results of experiments and discussion

The study was performed for three spark lengths: 3, 5 and 7 mm. For each length, the spark input energy was varied: \(E=60, 100, 150\) and \(200\) mJ. The upper value was limited due to the spontaneous breakdown of the spark gaps. But from the preliminary numerical modelling [9], higher energy input does not lead to the significant increase of the induced flow structures intensity. For all considered cases, the evolution of the cavern was analyzed at the time delay in a range from 0 to 10 µs with a step of 2 µs and up to 100 µs with a time step of 10 µs. The quantitative data on the flow structure were extracted from shadow images. The main analyzed parameter was the distance from the top of the hot cavern to the wall. The dynamics of the cavern top position for three values of energy release is shown in Fig. 4, a. It can be seen that the increase of the pulse amplitude leads to the increase of the total cavern boundary displacement: at a fixed delay \(t=100\) µs the maximum height of the disturbance is obtained for \(E=200\) mJ. Still, the effect of the energy input on the disturbance magnitude decreases at high energy values: increase of energy from 60 to 200 mJ leads to the increase of final cavern height from 3.6 to 5.5 mm.

Figure 4, b shows the cavern boundary dynamics for \(E=60\) mJ and three various interelectrode gaps. One can see that the decrease of the discharge length leads to the monotonous increase of the boundary velocity, with the maximal value obtained at \(d=3\) mm. Based on this parametric study, one can conclude that the optimal actuator parameters in the studied parametric space are the minimal interelectrode distance \((d=3\) mm\) and relatively low energy input on the level of 50-60 mJ. The observed data were compared to the previously obtained modelling results [9]. It can be seen that the good quantitative correlation of the numerical and experimental results can be seen. This means that
the significant part of the electrical power, induced by the discharge, is indeed transferred into the heating at the submicrosecond time scale. Some difference between presented experimental and computational data could be explained by the fact that real discharge size is larger than spark gap.

The further analysis of the velocity field, induced by the surface spark discharge, will be performed using PIV (Particle Image Velocimetry) method. These measurements will verify the characteristic gas velocities inside the vortices, produced during the decay of the spark cavity.

![Figure 4](image.png)

**Figure 4.** Experimental data about dynamics of afterspark cavity boundary: a - variation of discharge energy for 5 mm spark gap. b - variation of spark gap at fixed discharge energy 60mJ.

Heat source means data of CFD (computational fluid dynamics) simulation [9]

4. Conclusions
The experimental study of the gas-dynamic perturbations caused by the decay of a thermal cavern after submicrosecond long spark discharge arranged near the surface in the ambient air at standard conditions was performed using schlieren technique. Parametric investigations included varying of discharge length in a range of 3-7mm and energy in a range of 60-200mJ. Spark discharge induces gas motion which could be analyzed by schlieren visualization of the boundary of thermal cavern. It was found that the rise of discharge energy at fixed spark gap results in low increase of the size of thermal cavern height. For tested spark gaps at fixed total energy impact the maximal height of the disturbance corresponds to minimal length of discharge (3mm). The results obtained are in a good qualitative and quantitative agreement with the simulation data previously published by the authors.

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