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Published: 01/01/1973

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Link to publication

Citation for published version (APA):
DISTRIBUTIONS OF THE SPOTDIAMETER FOR SINGLE- AND MULTI-CATHODE DISCHARGES IN VACUUM

by

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Distribution functions of the spot diameter for single- and multi-cathode discharges in vacuum

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January 1973

TH-Report 73 - E - 32
ISBN 90 6144 032 7

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1. Introduction.

Throughout the last decades attention was drawn to the determination of the size of the cathode-spot and current density in a vacuum discharge. The conditions several investigators used show a wide difference as well as the results obtained for the current density [given e.g. by 1, 2, 3]. Therefore it is customary to use the term average current density of the cathode spot, disregarding the parameters by which this current density is influenced.

Only few data are available giving the relation between current density in cathode-spot and surface condition [2, 3]. For this reason investigations were set up in this field. The results show that the behaviour of the discharge varies with surface conditions. Making use of this effect the cratersize of a metal vapour discharge can be determined accurately. At a given current value there appears to be a fairly large variation in diameter according to a distribution function which is symmetrical. The peak value of these distribution functions (i.e. the most probable value of the diameter) is a linear function of the current. Investigations of a multi-cathode discharge show the behaviour of the partial discharges to be governed by the same laws. These results may contribute to an explanation of the large variation in current density as found in the literature. A theoretical model based on Joule heating explains some of the phenomena observed [4].

2.1. The experimental vacuum breaker.

In order to investigate the current density in a cathode-spot of a metal vapour discharge in vacuum use is made of an experimental vacuum breaker made of stainless steel. The breaker had demountable flanges provided with high potential bushings. The electrodes consist of a base of O.F.H.C. copper on which a high-purity copper sheet is brazed (fig. 2.1.1).

The impurities present in this copper sheet were less than 8 p.p.m. Prior to mounting in the breaker the electrodes were treated as follows: degreasing in a freonbath, and degassed in vacuum (pressure < \(10^{-5}\) Torr.) for 30 minutes at 700°C. After assembling the electrodes the breaker was evacuated and baked out for twelve hours at a maximum temperature of 250°C.
The pressure obtained, after cooling down to room temperature was less than $10^{-8}$ Torr.

The average opening-speed of the electrodes was $1.5 \text{ msec}^{-1}$, the anode acting as the movable electrode. The maximum distance between electrodes reaches 6 mm.

### 2.2. Electrical circuitry.

The experiments were carried out in the following circuit (fig. 2.2.1).

![fig: 2.2.1. the circuit.](image)

- **VB**: vacuum breaker.
- **MB**: master breaker.
- **$T_1$, $T_2$**: thyristors.
- **$R_S$**: shunt.
- **$R_T$**: variable resistance.
- **SB**: storage battery.

A storage battery was used as d.c. power supply.

$R_T$ is a variable resistance $(68 \cdot 10^{-2} \Omega / 77 \cdot 10^{-6} \text{ H})$.

Thyristors $T_1$ and $T_2$ serve to reduce the time the current is flowing through the closed contacts of the vacuum breaker.

To prevent damage of the prepared contacts the contact force was kept to a minimum. It proved then necessary to limit the time of current flow prior to arcing in order to reduce excessive melting.
The switching sequence is as follows:

Having closed the breaker (V.B.), the master breaker (M.B.) is switched in and thyristor $T_1$ is ignited. After about $5 \times 10^{-3}$ sec. the contacts of the vacuum breaker separate. By firing thyristor $T_2$ the discharge extinguishes and the current is interrupted by tripping the master breaker.

The various devices used are triggered by a six channel delay unit. The current was measured with a low inductive shunt, having a resistance $R_S$ of $10,256 \times 10^{-3}$ $\Omega$. The discharge voltage was measured directly. Both current and voltage are recorded on a dual beam oscilloscope (Tektronix 556) with a polaroid camera.

2.3. The influence of the cathode surface on the behaviour of the discharge.

In order to examine the role of cathode surface conditions, experiments were made using surfaces treated as follows:

1. Polished (Roughness $< 2$ Ru $^3$)
2. "Half" polished (Roughness 2 à 6 Ru)
3. Roughened (Roughness 9 à 13 Ru).

The cathode consists of four progressively finer polishing phases. Using only the two first phases we obtain a "half" polished surface on which we observe a number of rounded smooth undulations.

Using emery paper (no. 600) a surface is obtained showing numerous sharp ridges, oriented in a parallel direction.

Having treated these cathode surfaces in the different ways mentioned, experiments were carried out.

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3) The surface roughness amounts to one Ru if the average distance from the roughness profile to the centre line equals $25 \times 10^{-6}$ mm.
After assembly, the breaker was incorporated in the circuit and with each cathode surface one single test was performed. The current level in the discharge initiated at contact separation was of the order of 47 amps. The measurements were performed under identical circumstances. The track on the cathode surface due to the discharge was examined under a microscope.

On a polished electrode, the surface is affected strongly over a small area (3.5 mm$^2$ in $12.10^{-3}$ sec.). In this area (fig. 2.3.1), the spots touch or overlap each other. There are no individual spots visible.

The lower limit of the discharge voltage is 19 Volt (fig. 2.3.2). The high frequency components in the voltage recording have a peak to peak value of 4 Volt. They show a regular character.

On a contact surface roughened with emery paper the discharge tends to follow the irregularities on the surface (fig. 2.3.3), as is well-known [7].

The area over which the discharge has run is much larger than on a polished surface. The trace area (70 mm$^2$ in 5.5 msec.) is composed of microscopic craters, mostly relatively far away from each other. The intermediate parts are not affected. Using a larger magnification (fig. 2.3.4) it appears that the motion of the discharge is clearly discontinuous.

A close observation shows that the craters are mostly situated on the rims of ridges and generally on places where presumably sharp edges were found before a crater was formed (fig. 2.3.5).

Positions of craters on a roughened surface.

fig:2.3.5.
The lower limit of the discharge voltage is 16 - 17 Volt (fig. 2.3.6). The high frequency component of this signal is irregular, having a lower frequency than found on a polished contact surface (compare fig. 2.3.2 with fig. 2.3.6).

On a half polished cathode surface the trace of the discharge shows on the one hand as on a polished surface and on the other hand as on a roughened surface. Fig. 2.3.7 shows areas with many spots overlapping each other as well as individual spots. The lower limit of the discharge voltage is 17 Volt (fig. 2.3.8). The shape of the high frequency voltage component corresponds with the behaviour of the discharge voltage as found on a polished contact (fig. 2.3.2). Table 1 summarizes the results.

**TABLE 1.**

<table>
<thead>
<tr>
<th>Cathode surface conditioning</th>
<th>Discharge voltage (V)</th>
<th>Current Value (A)</th>
<th>Behaviour of the discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>polished</td>
<td>19</td>
<td>~ 4</td>
<td>48.7</td>
</tr>
<tr>
<td>half polished</td>
<td>17-(13)</td>
<td>~ 4</td>
<td>47</td>
</tr>
<tr>
<td>roughened with emery paper</td>
<td>16-17</td>
<td>~ 3</td>
<td>47</td>
</tr>
</tbody>
</table>

2.4. **Conclusions.**

There is most probably a correlation between the movement of the discharge and the roughness of the cathode surface. Measurements show that on a smooth surface the discharge affects a small area only; this area increases on a rougher surface. The track, caused by the discharge on the rough surface, is composed of mostly individual spots; the movement has a discontinuous character.
By increasing the roughness of the surface and keeping the discharge current constant, the discharge voltage decreases; on a polished surface it is 19 Volt, on a roughened surface 16-17 Volt. There appears to be a correlation between the high frequency voltage and the movement of the discharge.

3. The current-density in the cathode spot.

The current density in the cathode spot of a copper vapour discharge in vacuum can be obtained from the tracks on the cathode surface, using roughened electrodes.

The preparation of the contact was as follows.

After polishing the surface unidirectional ridges were obtained, using emery paper (no. 600). After this treatment the electrodes were baked out and assembled in the breaker. The system in total was baked out again.

During a certain time a discharge with a prescribed current level was produced between the contacts. The cathode was dismounted and the surface photographed through a microscope. With this the diameter of the individual, almost circular spots was measured.

Fig. 3.0.1 shows a typical example of such a crater.

The bottom is shown here as a white spot. The walls are in appearance dark. The way in which the diameter of the crater has been measured is illustrated by fig. 3.0.3 (compare [3], [5]).

The determination of the diameter of a crater has to deal with two main difficulties:

a. The craters having a small size are difficult to discern from their surroundings, which is highly irregular on that scale.

b. At larger values of crater-dimensions, one has to be careful in deciding whether the crater observed is a single one or actually is consisting of several craters, overlapping one another.

Some practical experience in this respect leads to minimize these possible sources of error.

In the range of measurements carried out by varying the current from 20 up to 230 ampères one can distinguish two types of discharges:
1. The single-cathode discharge (21.5 - 105 amperes)  
2. Multi-cathode discharge (> 105 amperes)  

3.1. The single-cathode discharge.

From literature it is known that for a copper cathode a single discharge can appear up to 150 A [6]. In our current range (21.5 - 105 amperes) the diameter of a large number of individual spots was measured for seven different current values. Fig. 3.1.3 and fig. 3.1.4 show some photomicrographs of the cathode surface on which a discharge has run during a certain time. The results of the measurements are given in fig. 3.1.1 and 3.1.2. Table 2 shows the total number of measurements (N) for a given value of the discharge current (I) and the value of the diameter (d) that correspond with the peak of the distribution curve (the most probable diameter).

**TABLE 2.**

<table>
<thead>
<tr>
<th>I (amp)</th>
<th>N (number)</th>
<th>d (10^-6 meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.5</td>
<td>323</td>
<td>3.7</td>
</tr>
<tr>
<td>38.5</td>
<td>160</td>
<td>4.0</td>
</tr>
<tr>
<td>54.4</td>
<td>200</td>
<td>6.0</td>
</tr>
<tr>
<td>66.3</td>
<td>209</td>
<td>7.3</td>
</tr>
<tr>
<td>71.0</td>
<td>180</td>
<td>8.5</td>
</tr>
<tr>
<td>87.0</td>
<td>170</td>
<td>10.0</td>
</tr>
<tr>
<td>105.0</td>
<td>205</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Observing the measuring results of the single-cathode discharge the following conclusions can be drawn.
- The distribution curves when plotted on a single logarithmic scale are symmetrical in respect to their peak values (fig. 3.1.1 and fig. 3.1.2).

- At a given value of the current there is a fairly large variation in the diameter of the craters; however a most probable value of the diameter can be defined (the peak of the distribution curve).

- The distribution curves determined are reasonably similar.

- The relation, between the most probable diameter of the crater and the discharge current is linear and satisfies the following equation:

$$d = 1,125 \cdot 10^{-7} \cdot I$$

where

- $d$ measured in meters

and

- $I$ in ampères (fig. 3.1.3).

In case of the most probable diameter of the spot the current density in the cathode spot is inversely proportional to the discharge current according

$$J = \frac{10^{10}}{I} \text{ amp./cm}^{-2}$$

The relation is shown graphically in fig. 3.1.4.

3.2. **Multi-cathode discharge.**

For current values beyond $10^5$ amp. measurements were carried out at two current levels i.e. 127 and 230 amp.

**The 127 ampère discharge.**

The 127 amp. discharge was split up. Inspection of the traces showed that first one discharge was present and, after splitting, two partial discharges appeared.
Fig. 3.2.1 is a sketch of the cathode trace. In area A the initial single discharge split up and one partial discharge remained in area B.

From both areas a large number of individual spot-diameters were measured. Fig. 3.2.2 and fig. 3.2.3 show the distribution curves measured in area A and area B respectively. The distribution curve, measured over area B (only one partial discharge), resembles the distribution curve for a single cathode discharge. The distribution curve measured over area A (initial discharge) is different; it has no symmetry. This is apparently due to the fact that the two traces observed are partly overlapping each other.

Therefore we can assume this distribution to be composed of two separate distributions which we can determine, taking into account they are symmetrical as in the case of a single discharge. If we subtract from the measured non-symmetrical distribution curve a symmetrical distribution having the same maximum peak value of \(7.10^{-6}\) m, we find a new distribution with a most probable diameter of \(12.10^{-6}\) m.

We can assume that this diameter \((12.10^{-6}\) m) is related to the most probable diameter of the discharge before division took place. If we extrapolate the time which shows the relation between the most probable diameter and the current in the discharge (fig. 3.1.1), we find for a 127 A discharge a most probable diameter of \(14.10^{-6}\) m.
The most probable diameter measured over area B (only one partial discharge) is \(8.10^{-6}\) m. If we apply the curve of fig. 3.1.3 on this partial discharge, the current was 70 amp. The partial discharge in area A having a most probable diameter of \(7.10^{-6}\) m, the current will then be 60 amp.

This means a total current of the two partial discharges of 130 amp., which agrees with the measured value.

The 230 ampère discharge.

Almost immediately after initiation, the discharge divides. The traces were overlapping each other. Two areas were found of which we were certain that on each only one discharge had occurred. From both areas the distribution of the spot diameter was measured. The results are plotted in fig. 3.2.4 and fig. 3.2.5.

The results are: One curve with a most probable diameter of \(8.10^{-6}\) m (i.e. about 70 A) and another non symmetrical curve which can assumed to be composed of two symmetrical curves; one having a most probable diameter of \(9.10^{-6}\) m (80 A), the other with a most probable diameter of \(14.10^{-6}\) m (125 A).

A reconstruction of the splitting process is that the discharge at first divided into two partial discharges (current levels 105 and 125 ampères) and later on had split up into three partial discharges (two 80 amp. discharges and one 70 amp. discharge).

Taking measuring errors into account, it is very well possible that the average current after splitting is the same in every partial discharge.

Conclusions.

The most probable diameter of a partial discharge in a multi-cathode discharge agrees with the diameter of a single cathode discharge. In other words by studying a single cathode discharge one can learn something of the behaviour of a partial discharge in a multi-cathode discharge also.
4. Summary.

- The roughness of the cathode surface affects the movement of the discharge. On a smooth contact the discharge only moves in a small area. On a rough contact the area on which the discharge moves is much larger and clearly discontinuous.
- At increasing roughness of the cathode surface and the same current in the discharge, the discharge voltage decreases. This also applies to the high frequency components.
- At a given current value in the discharge there is a fairly large variation in the diameter of the spots. The distribution function on a semi logarithmic scale being symmetric in respect to the peak value, the different distribution function showing a fair agreement with each other.
- There exists a linear relationship between the most probable diameter and the current in the discharge, the current density therefore being inversely proportional to the current.
- It appears that a partial discharge of a multi-cathode discharge has the same spot-diameter as related to a single cathode discharge.
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Fig. 2.3.1.

100 μ. —

Fig. 2.3.2.

$+1\, V \: 4V/div$

$+1\, I \: 19.5 \: A/div$

$+V_o$

$+I_o$

$t \: 2.10^3 \: sec/div$
Fig. 2.3.3.
Fig. 2.3.4.

100 μ. ———

Fig. 2.3.6.

+V 4V/div

+I 19.5 A/div

\( t = 10^{-3} \) sec/div
Fig. 2.3.7.
100 μ.

Fig. 2.3.8.

+V 4V/div

+I 19.5 A/div

+V₀

+I₀

t = 10⁻³ sec/div
fig: 3.0.1.

fig: 3.0.2.
O 21.5 ampere discharge
X 38.5 ampere discharge

diameter ($10^{-6} \text{ m}$)
fig: 3.1.3.

current density ($10^6$ ampere/m$^2$)

current (ampere)

fig: 3.1.4.

current density ($10^8$ ampere/cm$^2$)

current (ampere)
Fig. 3.1.3.
38.5 ampère
100 μ.

Fig. 3.1.4.
66.3 ampère
100 μ.
127 ampere discharge
(measured over area A)
230 ampere discharge (measured over area A)

fig: 3.2.5.