Contact angle measurements of sessile drops deformed by a DC electric field
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Abstract - Sessile water drop geometries on various surfaces have been studied with and without exposure to electric fields with the aim to understand the phenomena involved in the generation of the sound emission from wet high voltage transmission lines. It has been demonstrated that noise can be reduced by the application of certain coatings to the high voltage conductors. Various coatings/treatments have been evaluated with respect to contact angle measurements under a wide range of conditions including discharge levels.
In the experiments presented water drops of well-controlled volume were placed on horizontal stainless steel and aluminium surfaces which had undergone a variety of treatments, singly and in combination: sandblasting, glass bead blasting, and hydrophobic and hydrophilic coatings. The surfaces mentioned formed the lower electrode of a parallel plate discharge gap. Contact angles were determined by first producing an electronic image of the drop which was then assessed by means of software developed in this study.
It has been shown that the voltage at which instability, resulting in ejection of a fine jet of water of a few μm with increasing electric field, is reached depends strongly on the initial shape of the water drop and thus on the contact angle which, in turn, is controlled by the surface properties.
This work demonstrated that the instability voltage was roughly doubled if the surface conditions changed from hydrophobic to hydrophilic.

Keywords: Contact angle, high voltage transmission lines, acoustic emission, drop instability.

1. INTRODUCTION

After precipitation high voltage transmission lines emit excessive levels of noise. The major component of ‘wet’ weather noise to be suppressed is a fixed frequency (100 Hz in Europe and 120 Hz in North America) hum called tonal noise and perceived as particularly annoying especially at night and when it can be the dominant noise in the locality. The early study of acoustic emission from high voltage lines was done in 1969 [1]. Former investigations [2, 3] demonstrated that tonal emissions from high voltage transmission lines were directly linked to the presence of water drops on the conductors and their periodic (2f) deformation. This interpretation has recently been scrutinized in depth (see [4, 5]). It has been shown that the essential role of oscillation drops is that of injecting electrical charge carriers into the immediate surroundings of the conductor. The periodic moment of these charges will eventually lead to the sound emission [5]. At high local field strengths (> 20 kV/cm) the drop deformation can lead to instability accompanied by water ejection, loss of charge and sound emission. The drop elongates in the direction of the electric field and becomes unstable at a critical field strength.
Clearly the surface field strength on the drops plays a decisive role, which, in turn, is largely determined by the drop shape which is strongly influenced by the surface properties of the substrate. For instance, with a hydrophilic substrate the water drop contact angle is small and sessile drops have a very shallow contour; this implies lower surface field strengths, thus less deformation and a lower level of sound emission as well as lower discharge activity. In these studies it was shown that a model line with a strongly hydrophilic surface had – after cessation of precipitation – only 4 % of the integrated discharge current of the untreated/hydrophobic line, taken over a 20 minutes drying period of the lines.
The work presented here is based on the characterization of the drop contact angle for different conductor surfaces with and without application of voltage. Although alternating current (AC) is the most common form of electrical energy transmission, studies with direct current (DC) were used to elucidate the process involved in the acoustic emission from overhead high voltage lines; specifically details of the deformation of water drops in the electric field in dependence on drop size, surface condition and field strength were investigated.

2. INSTABILITY OF WATER DROPS IN AN ELECTRIC FIELD

The phenomenon of water drop deformation and instability in an electric field is well documented. Lord Rayleigh [6] found a stability criterion, later refined by Sir Geoffrey Taylor [7] for spherical drops, which connects the applied electric field, drop radius and surface tension. The critical electric field strength for drop instability of an uncharged free-floating drop is [8] given as:

\[ E_{cr} = 447 \frac{\gamma}{r} \]

where \( r \) is the drop radius and \( \gamma \) the water surface tension.

Experimental investigations have shown that with the increase of the applied voltage, instability is reached, a Taylor cone is formed and the drop starts to vibrate. As a consequence of the pointed drop shape eventually attained there is a field enhancement at the apex which leads to axial extension of the drop. In this way, the apex angle decreases and this produces further field enhancement and deformation which has to be balanced by the surface tension. When the field enhancement due to deformation produces so high a force at the apex that it can no longer be balanced by surface tension, instability is reached, i.e. the drop is ruptured and a fine water jet/droplet is ejected.

3. METHODS TO MEASURE CONTACT ANGLES

The contact angle is the parameter used to characterize different surfaces and to classify the shape of a water drop resting on a horizontal surface with and without application of an electric field. In all the experiments described here static contact angles were measured, since we did not have the equipment to measure advancing and receding contact angles.

The first step of the measurement was to place a water drop of defined volume on the solid sample surface, which was always exactly horizontal. To apply reproducible uniform volume drops of deionised water, calibrated micropipettes were used; in general, the volume of the water drop used here was in the range of 20-100 \( \mu l \). Drop shape was recorded with a high speed framing camera, images were then processed by a computer and stored. In the investigations carried out to date, the drop shape is then automatically evaluated in terms of contact angle as represented by the angle between the substrate surface and a tangent from the edge to the contour of the drop.

The uncertainty in the measurements depends on the light-dark contrasts of the drop picture, in particular at the air-liquid-solid triple point, and on the method used for the evaluation. An error of 3-4° must be assumed, which can still be accepted, since the experiments were carried out in a system where perfect surface uniformity and cleanliness could not be guaranteed.
At this stage two methods, depending on the degree of drop picture quality, for contact angle measurements were used: manually and using a software. The problems encountered in different experimental methods are described in the following. In general, it is easy for the program to find the drop profile, but hard for it to find the correct baseline, which may be obscured in the image; furthermore the specimen may be somewhat irregular. Conversely, it is easy for a person to locate the baseline but fitting a tangent to the drop profile is more difficult.

The assumption one can use in some cases is that the drop profile is represented by a portion of a circle of defined radius and centre. When this assumption is true it is much easier to find the contact angle manually, because one needs only to measure with a ruler the length of the chord and the height of the drop. Then with a simple relation \( \theta = \arcsin \left( \frac{4sh}{s^2+4h^2} \right) \), where \( s \) is the length of the chord, \( h \) is the height of the drop and \( \theta \) is the contact angle) one can find the value of the angle.

If the assumption that the drop profile is a portion of a circle is not applicable, one still has the choice to assess the contact angle by drawing the tangent to the drop surface and measuring the angle formed between solid surface and the tangent by means of a goniometer. In this case it is easily understandable that the measurements are strongly subjective and a larger error is expected.

Measuring contact angle with a software has the big advantage that it enables one to determine contact angles on solids rapidly and easily. Many companies in the world sell systems [9] which provide a number of features that make the procedure for contact angle measurements easy and versatile. In the study only approximate values of contact angles are required so that investment in costly systems would not be justified. So, for a more rapid but also a more economic method to analyze the image of a drop and, therefore, to assess contact angle, a suitable software has been developed here. The program, a Matlab script, permits hands-free measurements using image acquisition and image processing techniques. First the program reduces the grey-scale image of the drop to a set of equations describing the periphery, and then it obtains the intersection of the baseline with the tangent. The different steps in the processing technique are presented in Fig. 1.

![Figure 1. Measurement of contact angle using image processing techniques.](image)

A comparison between the methods described above for the case of a 20 μl water drop on sandblasted aluminium surface, where the circle approximation of the drop also applies, is presented in Fig. 2.

The results show that the measurement using the software produces a lower uncertainty (about 2°), while a larger error is encountered in measurements made manually. However, the mean value seems to show no significant difference for different methods.
4. DROP EVAPORATION ON SANDBLASTED ALUMINIUM AND STAINLESS STEEL SURFACES

In the first test series the evaporation of drops on sandblasted aluminium and stainless steel surfaces was investigated without the influence of an electric field. Many authors state that contact angle measurements are strongly influenced by the time \( t \) between positioning the drop on the surface and making the measurement [9, 10]. Furthermore, since a drop does not behave symmetrically in the electric field, the contact angle was separately

![Figure 2](image1.png)

**Figure 2.** Comparison between different contact angle measurement methods

![Figure 3](image2.png)

**Figure 3.** Contact angle versus time for 20, 50 and 100 \( \mu l \) drops on sandblasted Al and stainless steel surfaces
determined at the left and at right sides; the average of the left and right values is presented here. Pictures were recorded at room temperature of 20°C and 40% relative humidity. The contact angle was measured with both methods, i.e. manually and using the program. Fig. 3 illustrates the decrease of contact angle with time for three drop volumes (10, 50 and 100 μl) for a rough/polished surface (sandblasted aluminium) and a smooth/polished surface (stainless steel). Although it has been found that the contact angle decreases with decreasing drop size, as demonstrated in [11], this experiment shows that a 100 μl water drop seems to have a smaller contact angle than a 10 μl one. This is mainly due to the non-uniformity of the analyzed surfaces, which contributes also to a large hysteresis.

Within a few minutes the loss of volume due to evaporation – manifesting itself in a decrease of contact angle – is quite evident with both surfaces and with all drop sizes. At this point it can be stated that with both stainless steel and sandblasted aluminium surfaces, the time t elapsed until the contact angle is measured should be less than 2 minutes, in order not to influence the results significantly, in accord with [6]. This is a good choice, because the experiments with electric fields are carried out within 1.5 minutes including deposition of the drops and taking the normal security steps required before starting an experiment using high voltage. Moreover, in the present experiment the temperature of the electrodes on which the drops were positioned did not change during application of high voltage.

5. LABORATORY INVESTIGATIONS WITH AN ELECTRIC FIELD

In the next test series the behaviour of single drops during an increase of the applied electric field was studied.

![Figure 4](image-url)"
Two parallel metal plates of defined dimensions and shapes (6.5 cm diameter, 90° Rogowski profile) were arranged with 1 cm gap. The upper electrode was always stainless steel without any treatment, while the lower one was varied to test different surfaces and coatings available. After each measurement the lower electrode was rubbed down with ethyl alcohol to restore uniform starting conditions. The arrangement of Fig. 4, supplemented as required by a framing camera, was used to study drop deformation and instability.

Deionised water drops of 30, 50, 80 and 100 μl were deposited on the lower electrode in the central region. The high DC voltage was produced by a stabilized HV power supply controlled by a function generator. To have sufficient time to record water drops sequences up to instability, a special function with voltage linearly increasing with time was programmed as represented in Fig. 4. With the function chosen, 60% of the maximum voltage amplitude (U) was reached in 2 s, and then the voltage was increased up to the breakdown voltage in 14 s. To record rapid drop deformation and the development and consequences of instability, a high speed (up to 10000 fps) digital framing camera was used. In this test series single drops were recorded with 2000 frames per second, for a duration of 16 seconds. The water drops were always illuminated indirectly, to avoid rapid evaporation.

6. PROCEDURE AND MEASUREMENTS

The electrodes were variously prepared for each measurement: stainless steel polished, aluminium sandblasted, and aluminium glass beads blasted. Furthermore, coatings were obtained for assessment from commercial and institutional sources; for confidential reasons the name of the sources cannot be disclosed. A commercial hydrophobic coating based on silica and a TiO₂ powder was applied to all the substrates. The contact angle for different surface states (untreated, hydrophobic and hydrophilic) of the electrodes in the absence of high voltage are presented for a 50 μl drop in Table 1.

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>Treatments</th>
<th>Contact angle [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>untreated</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>hydrophobic</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>hydrophilic</td>
<td>15</td>
</tr>
<tr>
<td>Sandblasted Al</td>
<td>untreated</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>hydrophobic</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>hydrophilic</td>
<td>~0</td>
</tr>
<tr>
<td>Glass beads blasted Al</td>
<td>untreated</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>hydrophobic</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>hydrophilic</td>
<td>~0</td>
</tr>
</tbody>
</table>
By definition, a water drop on a hydrophobic surface has a large contact angle. The deformation of such a drop of 80 μl in the electric field in the parallel plate configuration is illustrated in Fig. 5. The growing axial elongation of the drop with increasing field is quite evident (intentionally the sequence has not been taken into instability).

Figure 5. Deformation of a 80 μl water drop by the electric field. Aluminium surface sandblasted and subjected to a proprietary hydrophobic treatment. Gap spacing was 10 mm. The sequence was terminated before reaching instability (> 10 000 V).

The voltage at which instability occurs depends clearly on the conductor surface and on the drop size (Fig. 6). The results underscore that the critical global electric field at first instability is higher when the drop is flatter (lower contact angle) and, correspondingly, it is lower with a greater contact angle. Fig. 6 illustrates also that the decrease of instability voltage with increasing drop volume in the range 30…100 μl is approximately linear with both hydrophobic

Figure 6. Instability voltage in dependence of drop size for various treatments of a sandblasted aluminium substrate
and untreated treatments. The non-linearity of the hydrophilic curves is probably due to the difficulty for the program in measuring small contact angles. The deformation of the drop by the electric field brings an evident change in contact angle. Figures 7 and 8 show variations of contact angle as functions of voltage and drop size for a stainless steel electrode which was untreated or made hydrophilic.

**Figure 7.** Variation of contact angle versus applied voltage for different drop sizes for an untreated stainless steel substrate

**Figure 8.** Variation of contact angle versus applied voltage and drop size for a strongly hydrophilic treatment of a stainless steel substrate. Note that the deformation sets in at about twice the voltage for the sample in Fig. 7

One can see that the contact angle decreases as the electric field distorts the drop. The drop has initially a higher contact angle, which then becomes somewhat smaller with increasing
deformation of the drop. A comparison between the cases analyzed shows that variation of the contact angle has a similar tendency for both hydrophobic as well as hydrophilic surfaces.

7. INTERPRETATION AND DISCUSSION

These investigations provided details on the instability of water drops in an electric field in dependence of drop size, surface condition and field strength. In fact, the instability controls the size of surviving drops on wet high voltage transmission lines, which contributes to sound emission.

It was observed with all surfaces analyzed that the drop changed its shape becoming more pointed with increasing voltage but flatter at the base, which meant that the contact angle decreased considerably. This behaviour began at ca. 6 kV for hydrophobic as well as for untreated surfaces, then the decrease of contact angle was nearly linear with increase in voltage; while with ultra-hydrophilic surfaces it became only significant above about 16 kV (see Figs. 7 and 8).

Clearly the instability voltage depends on the contact angle, as shown in Figs. 6, 7 and 8. An evaluation of the entire series of contact angle measurements leads to the plot in Fig. 9, in which it is observed that with a decrease of contact angle from about 90° (hydrophobic surface) to about 5° (strongly hydrophilic) the instability voltage roughly doubles for a 100 μl drop. For 80 and 50 μl drops the same behaviour was observed, while for a 30 μl drop the instability voltage increased even by a factor of 3.

8. SUMMARY AND CONCLUSIONS

(1) A new set up for detailed optical investigation of drop deformation was used and have proved its capability to yield significant information on the parameter dependence of deformation of water drops in an electric field.
(2) A tool written in Matlab to evaluate automatically the water drop contact angle was successfully developed, giving an uncertainty of about 2°.
(3) The instability voltage at which a water drop elongates in the direction of the electric field was demonstrated to increase strongly with a reduction in zero-field contact angle and to decrease with increasing drop volume.

9. ACKNOWLEDGEMENTS

Constant help and support provided by the CONOR team (T. H. Teich, M. Semmler and U. Straumann) is much appreciated, and so is the continued feedback from Prof. Klaus Fröhlich. Financial support of the work by EnBW (Germany), APG (Austria), Illwerke AG (Austria), PSEL (Switzerland) and BUWAL (Switzerland) is gratefully acknowledged.

10. REFERENCES