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INFLUENCE OF HUMIDITY ON THE PRE–BREAKDOWN PHENOMENA IN ROD–PLANE GAPS UNDER IMPULSE VOLTAGES WITH LONG WAVETAILS

Dimitrios Gourgoulis and Constantine Stassinopoulos

Abstract. The purpose of the present work was to examine the effect of absolute humidity on the first and second corona discharges as well as on the dark period between them. It has been recognised that there is a lack of data regarding the effect of humidity on air breakdown under impulses with long wavetails and the present work forms part of a detailed statistical investigation of the discharge development in a medium length positive rod–plane gap. The influence of the absolute humidity on the initial stages of the discharge especially as the experiments and the analysis that followed showed that humidity acts interactively with other discharge parameters i.e. the wavefront and peak of the applied voltages, the gap length and the geometry of the tip of the rod.

1. Introduction

Normally corona inception characteristics have been studied at voltage levels below the minimum breakdown voltage and a common observation is that the inception voltage increases slightly as the humidity level rises and that, for a fixed voltage level the time to corona inception appears to increase [1–3]. These increases have been explained adequately from the frequency of electron production inside the critical volume [2]. The aim of the present study is the investigation of the effect of humidity on the breakdown mechanism of medium length rod–plane gaps (75 & 100 cm) under impulses with long wavetails (5000 μs) in atmospheric air. Besides humidity, other parameters taken were the geometry of the end of the rod and the front duration of the applied positive impulse voltage.

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The authors are with the Aristotle University of Thessaloniki, Department of Electrical & Computer Engineering, High Voltage Laboratory, Building D, Egnatia Str., Thessaloniki 540 06, Greece.

2. Experimental set–up

The experimental part has taken place in the High–Voltage Laboratory of the University of Thessaloniki. The gap consisted of a cylindrical brass rod with a diameter of 23 mm hanging over an earthed aluminium $2 \times 2m$ plane placed 80 cm above the floor of the laboratory. Three types of interchangeable rod tips have been used: a conical tip with a 30° end, a square – cut tip and a hemispherical tip.

A 4–stage, 560 kV, 1 kJ Marx generator produced impulse voltages with wavefront varying from 2 to 330 μs with wavetails around 5000 μs [4]. The voltages were measured via a capacitive divider and a digital oscilloscope [5, 6]. The spark gaps of the generator were located at a distance of around 5 m from the rod–plane gap, facing it at an angle. Absolute humidity in the laboratory was not interfered with artificially and during the present experiments it was found to vary normally between 5 and 20 gm^{-3}.

Information on the discharge was obtained by the oscillographic monitoring of the electric field at the centre of the plane. This was done during the determination of the U_{50} by the voltage level method [7] which was performed for breakdown probabilities from 0 to 1 and for various (6) values of absolute humidity per gap – impulse configuration. Each voltage level, differing by about 2–3 % from the previous one, consisted of 20 impulses at time intervals of around 45 s. By measuring the time of the inception of the first and second coronas from the oscillograms of the field at each applied impulse their respective inception voltages U_1 and U_2 were calculated. Unless stated specifically otherwise, the pre – breakdown phenomena mentioned were taken from voltages causing approximately 50 % breakdowns. All the inception voltages U_i (U_1 and/or U_2) were corrected for air density in accordance with IEC [7].

3. Experimental results

3.1 Influence of humidity on the first corona

It is believed that one of the ways humidity affects the 50 % breakdown voltage, is by influencing the first corona [8]. Thus the average values of the inception voltage of the first corona for every gap – wavefront configuration were related with humidity. This was done separately for cases when breakdown occurred U_{1b} and for withstand cases U_{1w}. This, for some of the applied waveshapes, is shown in Fig. 1, referring to a 75 cm long gap with a conical tip.

It was observed that there is an almost linear increase of both U_{1b} and U_{1w} with humidity, this behaviour was found to be more apparent for 75 *cm* gaps. Also, the difference between U_{1b} and U_{1w} tends to augment with humidity, this trend is more obvious for medium and long wavefronts. A similar trend was found for positive rod–plane gaps under impulse voltages with wavetails around 2000 μs [9].

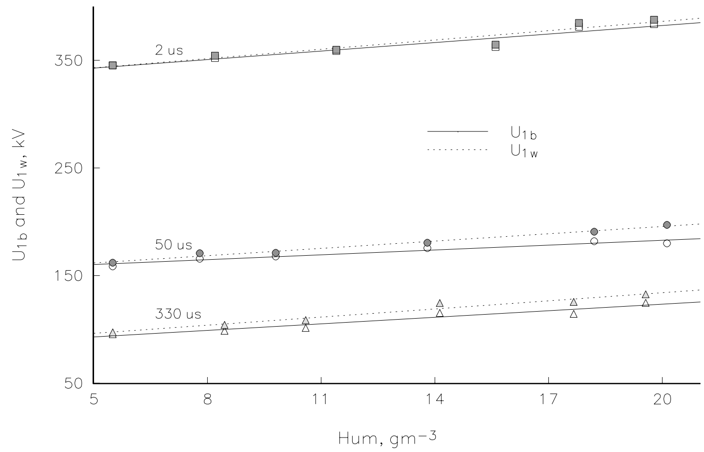

Figure 1. U_{1b} and U_{1w} versus humidity under U_{50} voltages, 75 cm gaps with conical tip.

Assuming that all the corona related parameters are stochastic in nature therefore following a normal distribution; the average values of the standard deviation of the first corona inception voltage as a percentage of its corresponding values, σ_{U_1}, were plotted against the front duration of the applied waveshape for high and for low values of the humidity and for both gap lengths. This is shown in Fig. 2 for 75 *cm* gaps.

From this figure it can be seen that higher humidity appears to cause smaller values for the average standard deviation, for the three tips of the rod. The tendency for smaller values of σ_{U_1} with increasing humidity becomes more marked for the 75 *cm* gaps and for longer t_f.

From the calculation of the linear regression of the inception voltages of the first corona on humidity its correlation coefficients were plotted against the slopes of the straight lines. For a square cut tip of the rod this plot appears in Fig. 3 and shows that the points form the shape resembling a ", ". Similar results have been obtained under impulses voltages with wavetails around 2000 μs [9].

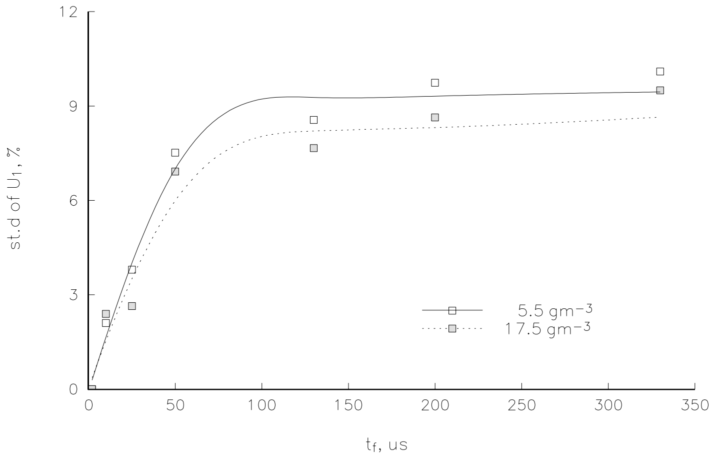

Figure 2. σ_{U_1} *versus* t_f*, under* U_{50} *voltages, 75 cm gaps with humidity as parameter.*

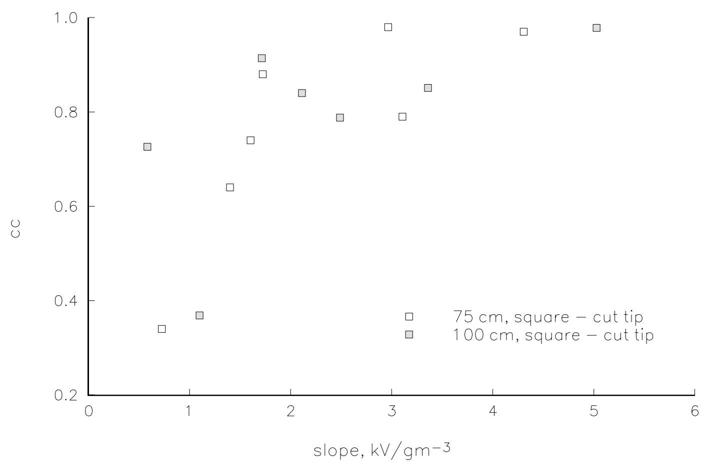

Figure 3. *Correlation coefficients of the linear regressions of* U_1 *on humidity versus the slopes of the straight lines with the gap length as parameter, square–cut tip.*

In Fig. 4 the slopes of these regression lines for conical and hemispherical tips were plotted against the front duration of the applied impulse wave-shape with the gap length as parameter. It was found that, in general, the inception voltages of the first coronas of the 75 *cm* gaps are more influenced by humidity (have bigger slopes) than those of the 100 *cm* gaps. Humidity seems to have a stable influence on the inception voltages of first corona irrespective of the front duration of the applied impulse waveshape. Exception to this behaviour are the gaps under 2/1700 μs displaying the biggest slopes than all the other cases. Besides it was found that gaps with conical tips display larger values of the slopes than gaps with hemispherical tips.

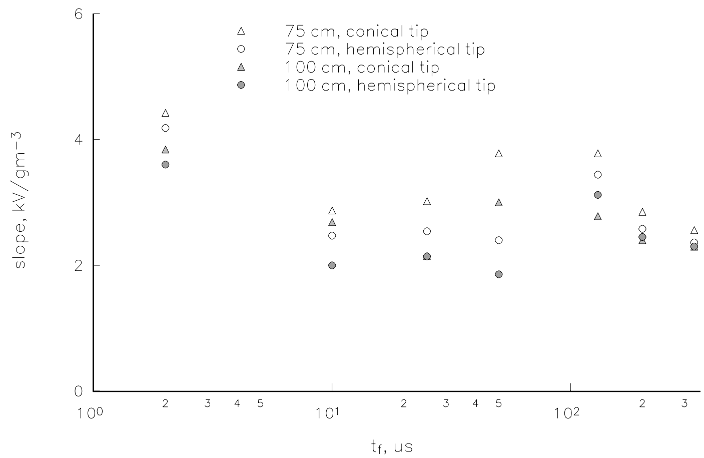

Figure 4. Slope of the linear regressions of U_1 on humidity versus t_f with the gap length and the tip of the rod as parameters.

3.2 Influence of humidity on the second corona

The average values of the inception voltage of the second corona U_2 measured under U_{50} voltages in 100 *cm* gaps, for every tip of the rod and for all the wavefronts were linked with the corresponding values of the absolute humidity. A typical plot appears in Fig. 5 referring to a 75 *cm* gap with square–cut tip. The correlation between U_{2b} and U_{2w} and humidity appears to be linear and it was found that both increase with increasing humidity. These curves show the same pattern as the corresponding curves relating U_1 to humidity (Fig. 1).

The average standard deviations of the inception voltages of the second corona σ_{U_2}, as a percentage of the corresponding values of U_2, for the three rod shapes were plotted against t_f with humidity as a parameter. A typical plot is shown in Fig. 6 for the 100 *cm* gaps. From this it can be seen that the influence of humidity on the distribution of U_2 depends on the front duration of the applied impulse waveshape. For impulses with t_f shorter than 50 μs increasing humidity causes σ_{U_2} to decrease whereas past 50 μs to increase (Fig. 6).

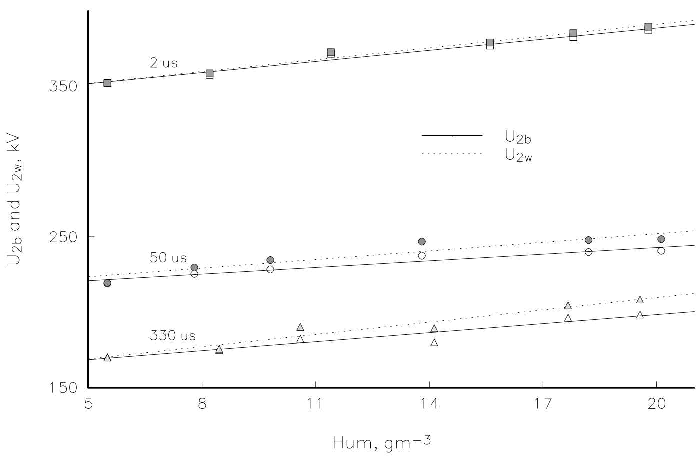

Figure 5. U_{2b} *and* U_{2w} *versus humidity under* U_{50} *voltages, 75 cm gaps with square–cut tip.*

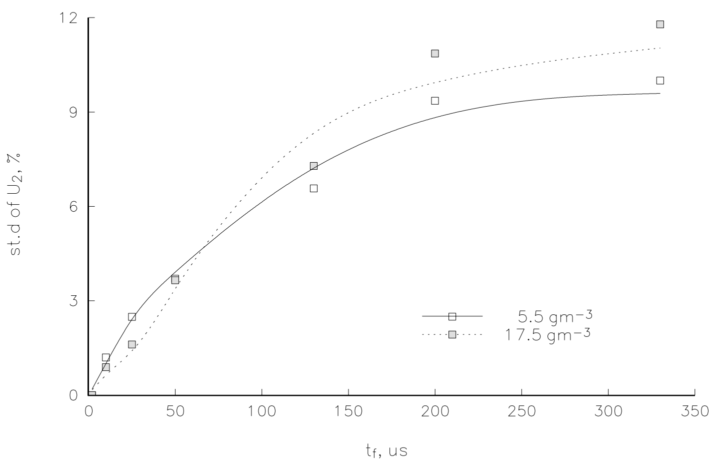

Figure 6. σ_{U_2} *versus* t_f*, under* U_{50} *voltages, with humidity as parameter, 100 cm gaps.*

The correlation coefficients of the linear regression of U_2 on humidity were plotted against the slopes of the straight lines (Fig. 7). From Fig. 7 it can be seen that the smaller values of the correlation coefficients correspond to the lowest slopes and that there is a tendency of correlation coefficients to increase with increasing slopes reaching values nearing unity for slopes of about 4 kV/gm^{-3}, for slopes over 4 kV/gm^{-3} the correlation coefficient has a tendency to remain constant.

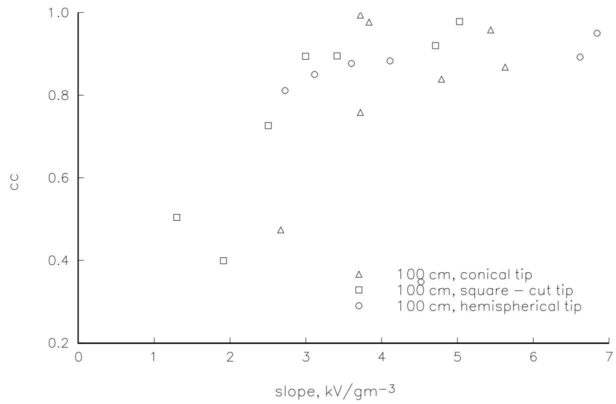

Figure 7. Correlation coefficient of the linear regressions of U_2 on humidity versus the slopes of the straight lines with the tip of the rod as parameter, 100 cm gaps.

Fig. 8 displays the influence of t_f on the slopes of the linear regression lines for conical and hemispherical tips with the gap length as parameter. From this figure it can be deduced that the second coronas for wavefronts with t_f for 130 and 200 μs have larger values of slopes, because, it is assumed, that humidity bears a greater influence on them. No distinct influence of the gap length and the tip of the rod on these slopes has been detected.

In Fig. 9, referring to 100 cm gaps, the correlation coefficients of the linear regressions of the corona inception voltages U_1 and U_2 on humidity were plotted against the slopes of the corresponding straight lines. It can be seen that for both coronas the small values of the correlation coefficients belong to lines with low slopes (around 1 – 2 kV/gm^{-3}). For higher slopes there is a tendency for the correlation coefficients (both for the first and second coronas) to increase approaching unity for slopes around 3 – 4 kV/gm^{-3}, for slopes higher than 5 – 7 kV/gm^{-3} and for second coronas only, the values of correlation coefficients tend to remain constant.

Comparing figures 4 and 8 it can be seen that the slopes of the straight lines of the linear regression of U_2 on humidity were in general larger than the corresponding slopes of U_1; this is negligible for both short and long t_f but not for intermediate front durations denoting that second coronas are more influenced by humidity than the first.

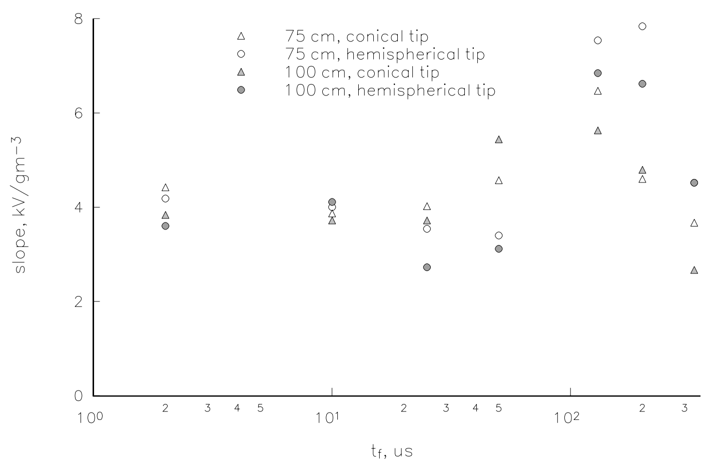

Figure 8. *Slope of the linear regressions of U_2 on humidity versus t_f with the gap length and the tip of the rod as parameters.*

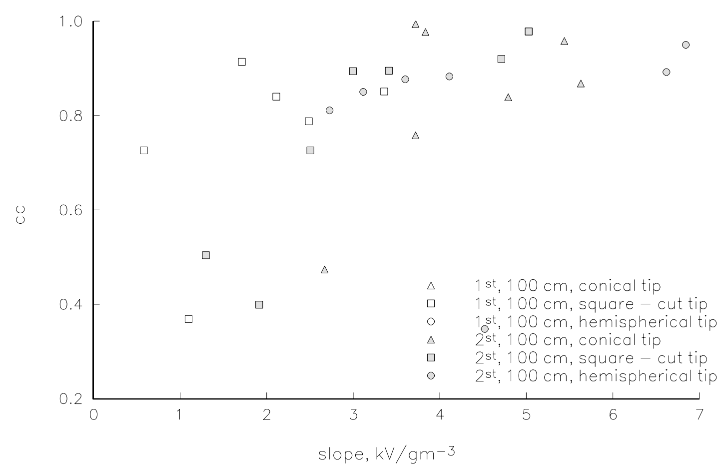

Figure 9. *Correlation coefficient of the linear regressions of U_1 and U_2 on humidity versus the slopes of the straight lines, 100 cm gaps.*

3.3 Influence of humidity on the dark period

During the present experiments there was always a dark period, t_d, between the first and the second corona. For every tip of the rod and gap length the average values of t_d, under U_{50} voltages, were plotted against t_f with humidity as parameter. Typical plots appear in Figs. 10, 11 and 12 the vertical bars representing the corresponding standard deviations of t_d.

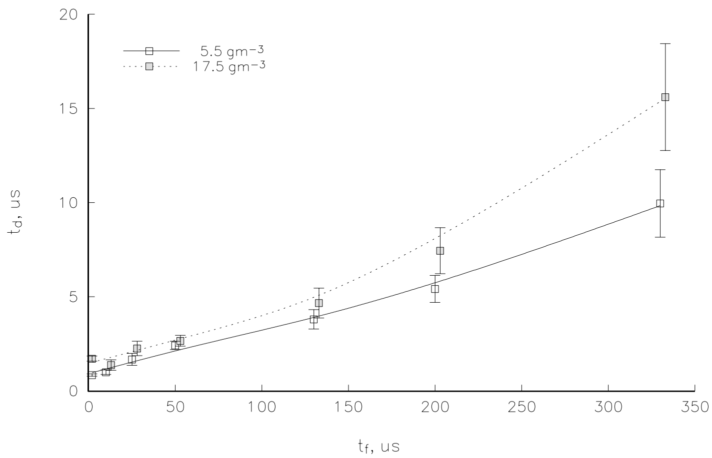

Figure 10. t_d versus t_f, 75 cm gaps with conical tip, under U_{50} voltages, with humidity as parameter.

From these figures it can be clearly seen that t_d increases with t_f. Concerning the influence of humidity, it is deduced that as humidity increases t_d attains bigger values. This agrees with previous findings for rod - plane gaps [9] and sphere – plane [10] under positive impulses.

The above mentioned behaviour of humidity depends both on t_f and on the tip of the rod. In particular, for gaps with conical and square–cut tips (Figs. 10 and 11) the influence of humidity is larger for values of t_f over 130 μs with the largest difference in t_d as humidity increases to appear for $t_f = 330$ μs; for fast wavefronts no influence of humidity is discernible. For hemispherical tips (Fig. 12) the influence of humidity is in evidence only for values of t_f around 130 – 200 μs.

Concerning the influence of humidity and of t_f on the corresponding σ_{t_d} (μs) (Figs. 10, 11 and 12), it is evident that σ_{t_d} increases both with humidity and with t_f.

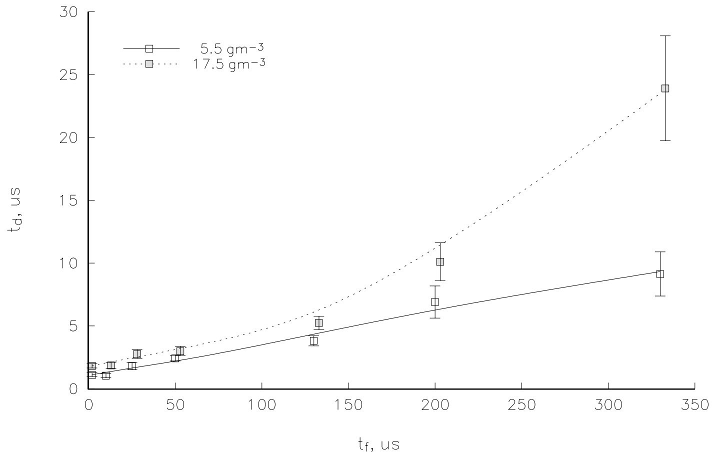

Figure 11. t_d *versus* t_f*, 75 cm gaps with square–cut tip, under* U_{50} *voltages, with humidity as parameter.*

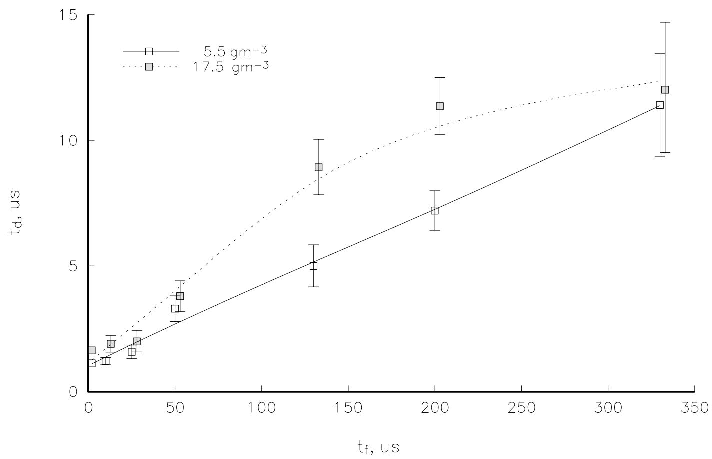

Figure 12. t_d *versus* t_f*, 100 cm gaps with hemispherical tip, under* U_{50} *voltages, with humidity as parameter.*

4. Discussion

The detachment of electrons from negative ions is the main mechanism of free electron production in the critical volume [2,11] and since the number of these electrons per unit volume and time is equal to the ratio of the negative ion density to their mean life time, it follows that the influence of humidity on corona inception can be both inhibitory and facilitating [9]; however, in the present case (Fig. 1) increasing humidity results in higher U_1.

The influence of humidity on the first corona in conjunction with the t_f is similar to the one that relates humidity to the inception of the first corona under impulses with wavetails around 2000 μs [8, 9]. Under intermediate t_f humidity influences a lot the first corona because of the greater importance of primary electrons since neither the times are long enough (long t_f) nor the field values high enough (short t_f) for an electron to be readily found [8].

Concerning the second corona increasing humidity results in higher values for U_2 (Fig. 5). This denotes that the reduction of the space charge injected by the first corona with increasing humidity [2,3,12] is not sufficient to lead to smaller U_2. Thus the inhibitory action of increasing humidity on the inception of the second corona both through the reduction of the length of the first corona streamers [13] and through the increased minimum electrical field needed for their stable propagation [14] overcome its facilitating action through the reduction of the amount of the positive space charge injected by the first corona.

Much information is provided both by the slope and by the correlation coefficient of the linear regression of U_i, (U_1 or U_2) with humidity. A high value of the correlation coefficients means that humidity influences corona in a fairly uniform manner, on the contrary a low correlation coefficient indicates that corona inception is affected by humidity in more than one ways. Also a high slope of U_i versus humidity denotes, obviously, a strong influence of humidity on the corona inception voltage.

From Fig. 9 it can be seen that for both coronas the small values of the correlation coefficients belong to lines with low slopes (around 1 – 2 kV/gm^{-3}) indicating that Ui is influenced by many contradictory factors. Then there is a tendency for the correlation coefficients (both for the first and the second coronas) to increase with increasing slopes approaching unity for slopes around 3 – 4 kV/gm^{-3}, this means that U_i is influenced by humidity a lot and in a uniform manner. For lines with slopes higher than 5 – 7 kV/gm^{-3} and for second coronas only, the values of correlation coefficients tend to remain almost constant, indicating that U_2 is largely influenced by many factors that are not contradictory to each other.

To understand why the second corona is more influenced by humidity (Figs. 4, 8 and 9) the parameters that determine the second corona's creation must be remembered. Gallimberti and Stassinopoulos [15] have shown that the start of the second corona is mainly related to the electric field in the stem region of the first corona. This field depends on the applied impulse, on the conductivity of the stem and on the choking effect of the positive space charge that is injected by the first corona.

Humidity does not act on the first parameter but has a big influence on the other two. As was shown by Allen et al. [16] increasing humidity tends to increase the stem conductivity resulting in reduced electrical field along the streamer stem. Besides although the positive space charge reduces, for the same applied voltage, the reduction of the streamers' length with increasing humidity leads to a bigger choking effect on the electrical field thus requiring a higher voltage to be applied in order for the second corona to start [8]. Thus, while humidity influences the first corona only through the availability of the initiatory electron, on the second corona its influence focuses on the amount and position of the space charge. Therefore humidity has a bigger action on the inception voltage of the second corona than on the first.

It was found (Figs. 10, 11 and 12) that for all the tips of the rod t_d increases with increasing t_f. This might be explained by the fact that as t_f increases the slower rate of rise of the voltage in conjunction with the slower drift of the positive space charge that was injected by the first corona lead to longer times in order for the electrical field to attain values high enough for the inception of the second corona [9].

It can be deduced that since in most cases examined during the present investigation, increased humidity causes longer dark periods (Figs. 10, 11 and 12), the main effect of humidity on corona in the gaps examined seems to be the shorter streamer length rather than the decreased amount of space charge.

5. Conclusion

Increasing humidity has inhibitory action on the inception of both the first corona and second corona. The inhibitory action of increasing humidity on the inception of the second corona becomes stronger for front duration around 130 and 200 μs.

For both coronas the smallest values of the correlation coefficients correspond to the lowest slopes of the linear regressions of U_i on humidity. Further, there is a tendency of the correlation coefficients to increase with increasing slopes forming a ", " shaped curve. For second coronas only and for very high slopes correlation coefficients tends to remain almost constant.

The inception of the second corona was found to be more influenced by humidity than the first.

For every gap length and for every tip of the rod t_d and σ_{t_d} increase with increasing wavefront duration and humidity.

As far as the first and second coronas are concerned, the behaviour of 75 and 100 cm long rod–plane gaps under positive impulse voltages is not influenced considerably by the increase of the wavetail from around 2000 μs to 5000 μs half time duration.

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