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EVALUATION OF HUMIDITY CORRECTION FACTOR FOR DC DISRUPTIVE DISCHARGE VOLTAGES

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Abstract: The authors studied disruptive discharge voltages corrected by the humidity correction factors for direct voltage given in the third edition of IEC 60060-1 standard. The humidity correction factor given in the previous IEC standard was determined on the basis of actual measurements of disruptive discharge voltage for direct voltage with a rod–rod gap.

Rod-rod gaps are prescribed as the standard gaps for measuring DC disruptive discharge voltages in air. Standard voltage values have been determined for such standard gaps, and therefore such gaps can be used for carrying out calibration of non-approved measuring systems. In such calibration of a non-approved measuring system, the DC disruptive discharge voltages measured with the standard gaps must be corrected for atmospheric conditions by means of atmospheric correction factors, of which high reliability is required.

The atmospheric correction was performed on the measured values using the humidity correction factors given in the current IEC standard, and the corrected disruptive discharge voltage values were evaluated.

This paper reports the results of a study in which DC disruptive discharge voltages in air were measured using the rod-rod gaps that are the standard gaps for such measurement. Finally, the measurement result and the IEC reference value are used, and the humidity correction parameter *k* for our measured disruptive discharge voltages is estimated.

1 INTRODUCTION

Rod-rod gaps are prescribed as the standard gaps for measuring DC disruptive discharge voltages in air. Standard voltage values have been determined for such standard gaps, and therefore such gaps can be used for carrying out calibration of non-approved measuring systems. In such calibration of a non-approved measuring system, the DC disruptive discharge voltages measured with the standard gaps must be corrected for atmospheric conditions by means of atmospheric correction factors (an air density correction factor and a humidity correction factor), of which high reliability is required.

This paper reports the results of a study in which DC disruptive discharge voltages in air were measured using the rod-rod gaps that are the standard gaps for such measurement, and the measurement results were used to examine values corrected with the altered humidity correction factor in the new IEC standard, and the soundness of the application ranges (atmospheric conditions, gap length, etc) for the humidity correction factor. Note that since no difference for actual application can be discerned between the current and the previous standard as regards the air density correction factor, that factor is not considered here.

2 EXPLANATION OF CORRECTION FACTOR AND DISRUPTIVE DISCHARGE VOLTAGE FOR AIR GAPS

The disruptive discharge of external insulation depends upon the atmospheric conditions. In the latest version of IEC 60060-1, the humidity correction factor k_2 for DC disruptive discharge voltage is altered. A description of such alteration and a discussion of related items in the latest standard are set forth below, together with the relevant content of the previous standard [1][2].

2.1 Atmospheric correction factors for direct voltages

The atmospheric correction factor K_t is expressed by equation (1). Dividing by K_t corrects a measured discharge voltage value U_{mes} into a disruptive discharge voltage at standard reference atmosphere, $U_{0,mes}$, as in equation (2).

$$K_t = k_1 \times k_2 \tag{1}$$

$$U_{0,mes} = U_{mes} / K_t \tag{2}$$

The air density correction factor k_1 and the humidity correction factor k_2 are expressed by equations (3) and (4) respectively.

$$k_1 = \delta^m \tag{3}$$

$$k_2 = k^w \tag{4}$$

where δ is the relative air density. *m* in equation (3) and *w* in equation (4) are determined by the parameter *g*, which in turn is determined by the minimum discharge path *L* (m), the relative air density *δ*, the parameter *k*, and U_{50} (kV) [1][2]. When the disruptive discharge voltage for voltage is measured with a standard gap, the values of *m* for air density correction and of *w* for humidity correction are both taken to be 1.

In the latest standard, the parameter *k* in equation (4) has been altered from the previous IEC standard. The equations for *k* in the previous standard and in the current standard are given in equations (5) and (6) respectively, where *h* is the absolute humidity.

Previous IEC standard:

$$k = 1 + 0.014\,(h/\delta - 11) \quad \text{for } 1\ \text{g/m}^3 < h/\delta < 13\ \text{g/m}^3 \tag{5}$$

Current IEC standard:

$$k = 1 + 0.014\,(h/\delta - 11) - 0.00022\,(h/\delta - 11)^2 \quad \text{for } 1\ \text{g/m}^3 < h/\delta < 15\ \text{g/m}^3 \tag{6}$$

The difference is shown in Figure 1. In this figure, the vertical axis indicates the correction parameter *k* and the horizontal axis *h*/*δ*. In this figure, the vertical axis indicates the parameter *k* and the horizontal axis *h*/*δ*. Also, curve Eq.(5) and original data are the curves described in the IEC Ed.2 [1] and curve Eq.(6) is defined in the IEC Ed.3 [2].

In this paper, we used a humidity correction factor k_2 calculated from the parameter *k* in equation (6).

2.2 Disruptive discharge voltage U_0 for air gaps

The IEC reference value U_0 – disruptive discharge voltage for direct voltage under standard atmospheric conditions – is given by equation (7) [3].

$$U_0 = 2 + 0.534 \times d \quad (\text{kV}) \tag{7}$$

where U_0 is in kilovolts and *d* is the gap spacing in millimetres.

Equation (7) is valid for gap distances d between 250 mm and 2500 mm and for a humidity range *h/δ* between 1 g/m^3 and 13 g/m^3.

3 EXPERIMENTAL PROCEDURES AND RESULTS

3.1 Overview

The phenomenon of DC discharge in air is affected by the atmospheric environment. The DC disruptive discharge voltage in air increases linearly with the absolute humidity.

However, variation occurs in the disruptive discharge voltage value, with a particular absolute humidity as boundary, and a deviation of around 15% may occur between individual measurements, even with the same level of absolute humidity [4]. Under the atmospheric conditions that permit application of atmospheric correction, it is not possible to perform correction to within ±3% of the

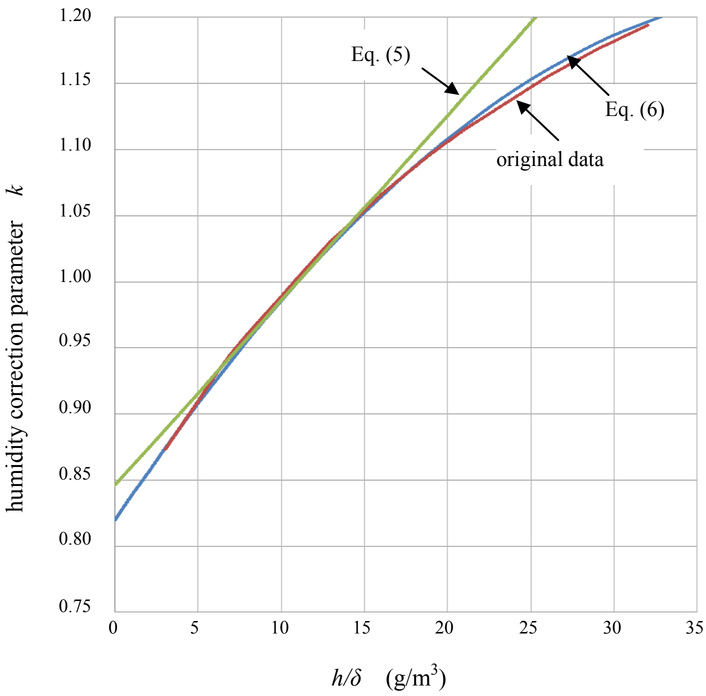


Figure 1: Comparison of parameter *k* between previous IEC standard and current one

standard value unless the difference between the highest and lowest measured disruptive discharge voltages is within 6%.

Accordingly, we verified the relation between the measured disruptive discharge voltage U_{mes} and h/δ in the case of DC positive polarity, so as to examine the limit for application of atmospheric correction – that is, the absolute humidity at which variation in the disruptive discharge voltage starts to occur. Following that, we checked for deviation from the IEC reference value U_0, by verifying the relations between the humidity correction factor k_2, the parameter h/δ, and the value $U_{0,\mathrm{mes}}$, which was U_{mes} corrected for atmospheric conditions.

3.2 Experimental procedures

The tests were carried out in two laboratories. The test conditions at one laboratory were as follows.

The direct voltage generator used had Cockcroft-Walton circuits and a maximum generated voltage of 1800 kV. The voltage was applied to positive polarity and raised so that the time interval between 75% and 100% of the discharge voltage was about 1 min. The rod electrodes were 15 mm square section rods. The rod-rod gap was arranged so that the length of the voltage application rod was 1000 mm and that of the earthed rod was 2000 mm, as shown in Figure 2 [5].

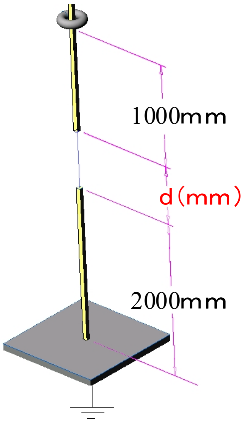


Figure 2: Arrangement of rod-rod gap

At the other laboratory, a direct voltage generator with a 300 kV voltage doubler-rectifier circuit was used. The same rod-rod gap as in Figure 2 was used. The discharge voltage U_{mes} was measured for gap length 250 mm and 300 mm.

3.3 Influence of *h/δ* on U_{mes}

Figure 3 shows the measurement results for the (uncorrected) disruptive discharge voltage U_{mes}. In this figure, the vertical axis represents the discharge voltage and the horizontal axis h/δ. For gap length 500 mm and gap length 750 mm, h/δ and U_{mes} were found to have a linear relationship in the range $h/\delta < 20$ g/m^3. With $h/\delta > 20$ g/m^3, the tendency differed from that with $h/\delta < 20$ g/m^3 and the disruptive discharge voltage fell markedly. Numerous results were obtained with gap length 250 mm and 300 mm. They appear to indicate that although there is large variation in the measured disruptive discharge voltages, the tendency is similar to that with 500 mm and 750 mm.

3.4 Comparison of $U_{0,\mathrm{mes}}$, U_{mes} and U_0 with regard to k_2 and *h/δ*

Figures 4 (a) to (d) show the results of comparing the $U_{0,\mathrm{mes}}$ disruptive discharge voltages, which are the measured disruptive discharge voltages U_{mes} converted to standard atmospheric conditions via the atmospheric correction factor (equation (2)). Also shown in those figures are the measured disruptive discharge voltages prior to atmospheric correction. The horizontal axis represents h/δ, and also indicated along that axis is the humidity

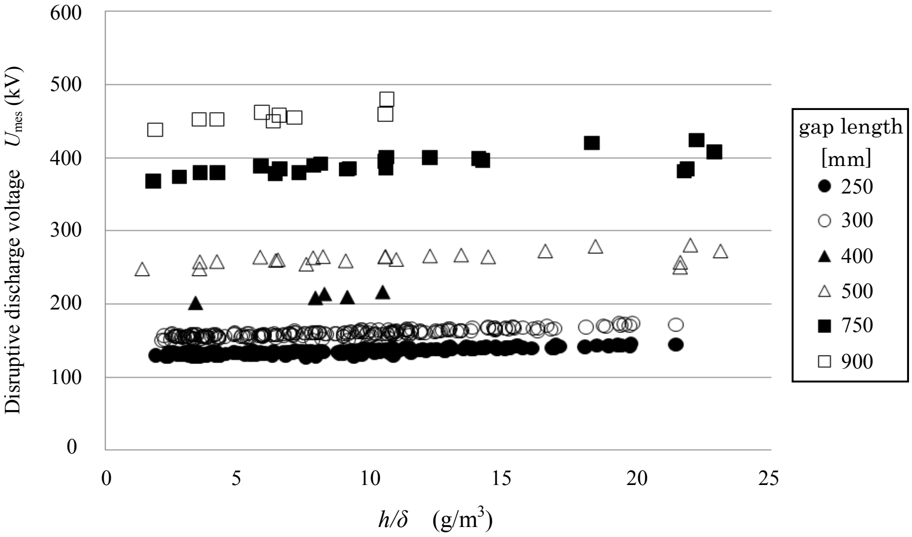


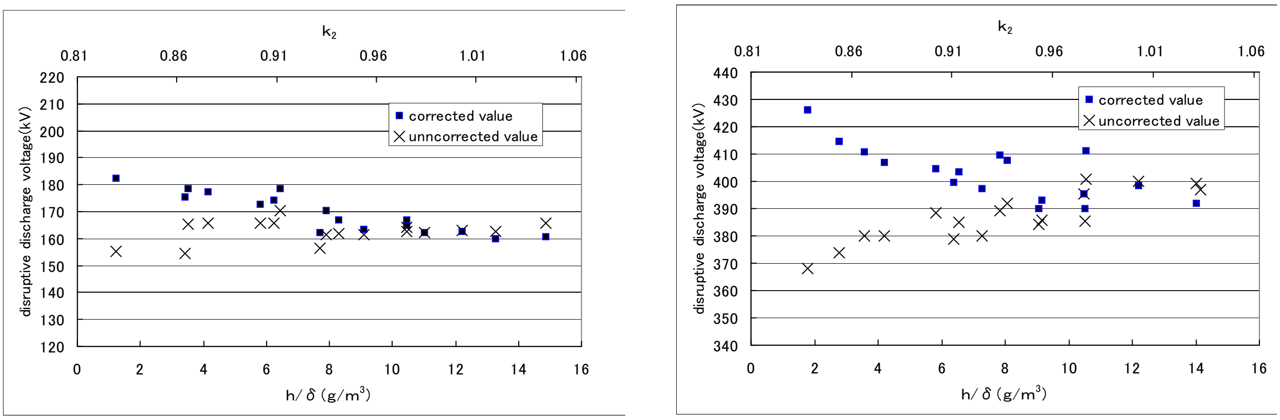
Figure 3: Relation between U_{mes} and h/δ for rod-rod gap lengths

correction factor k_2, which was derived from equation (4), taking into account the h/δ application range (1 g/m^3 < h/δ < 15 g/m^3) for equation (6).

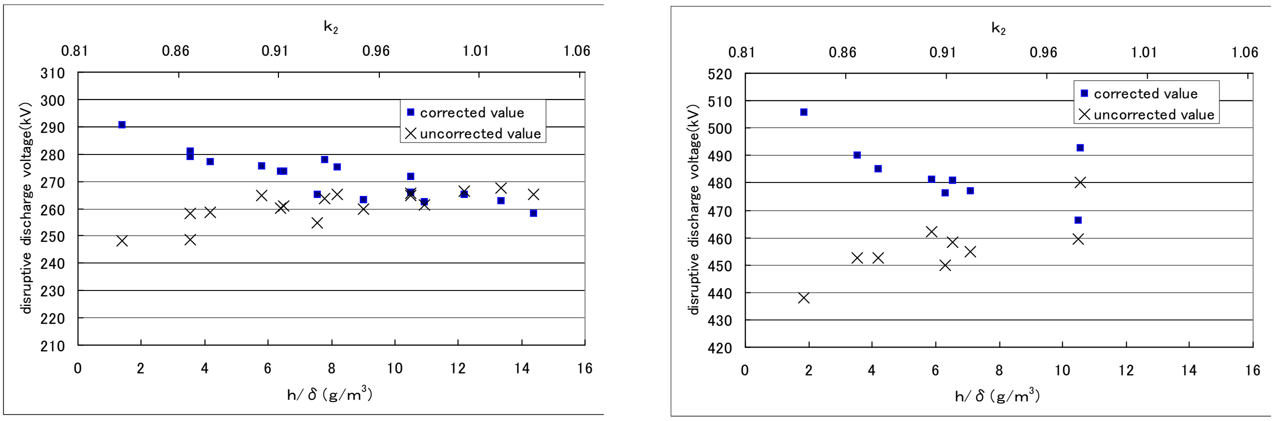
Pursuant to the results in Figure 3, Figure 5 shows the relation between h/δ and the deviation σ_{mes} (see equation (8)), which is given by dividing the difference between U_{mes} and U_0 by U_0.

$$\sigma_{\text{mes}} = (U_{\text{mes}} - U_0) / U_0 \times 100\ (\%) \qquad (8)$$

The σ_{mes} value is observed to have a proportional relationship with h/δ, the largest difference between them approaching 10%. Also, the results for the range exceeding 20 g/m^3 are found to have large variations between measurements.



(a) d=300 mm (c) d=750 mm



(b) d=500 mm (d) d=900 mm

Figure 4: Comparisons of U_{mes} and $U_{0,\text{mes}}$ for the parameter h/δ (1 g/m^3 < h/δ < 15 g/m^3)

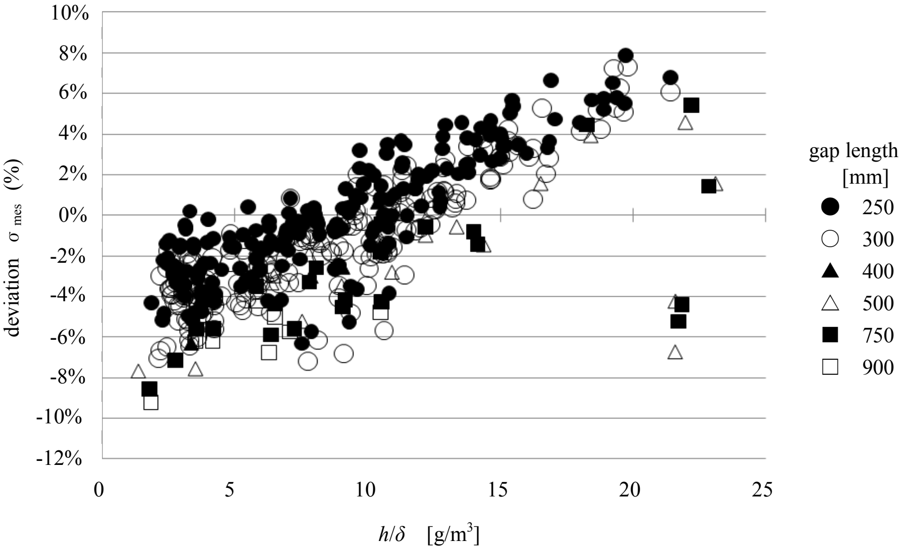


Figure 5: Relation between the uncorrection σ_{mes} and the parameter h/δ

As opposed to that, Figure 6 shows the relation between h/δ and the deviation $\sigma_{0,mes}$ (see equation (9)), which is given by dividing by U_0 – which is $U_{0,mes}$ corrected for humidity according to equation (6) – the difference between $U_{0,mes}$ and U_0.

$$\sigma_{0,mes} = (U_{0,mes} - U_0) / U_0 \times 100\ (\%) \qquad (9)$$

From this it can be seen that an adequate correction effect is obtained in the region where h/δ is high (10 g/m^3 < h/δ < 20 g/m^3). On the other hand, in the region where h/δ is low (1 g/m^3 < h/δ < 4 g/m^3), deviation such that $\sigma_{0,mes}$ exceeded 5% was observed. Also, the deviation in the regions with long gap length was small compared with the deviation in the regions with short gap length. Thus, the deviation was found to be dependant on the gap length.

4 DISCUSSION FOR HUMIDITY CORRECTION FACTOR

As a result of this investigation of atmospheric conditions (especially humidity correction), it was found that equation (7) is valid for the range where humidity is higher (10 g/m^3 < h/δ < 20 g/m^3) than with standard atmospheric conditions. However, it was also found that in the range where h/δ is low – particularly in the regions with short gap length – large deviation is exhibited.

Assuming $m = 1$ for equation (3) gives:

$$k_1 = \delta \qquad (10)$$

which will be determined by the air temperature and air pressure. If it is further supposed that ideal atmospheric correction is performed, then:

$$U_{0,est} = U_0 = 2 + 0.534 \times d \qquad (11)$$

Hence, with $U_{0,est}$ denoting the measured correction disruptive discharge voltage:

$$U_{0,est} = U_{mes} / (k_1 \times k_{2,est}) \qquad (12)$$

It then follows that:

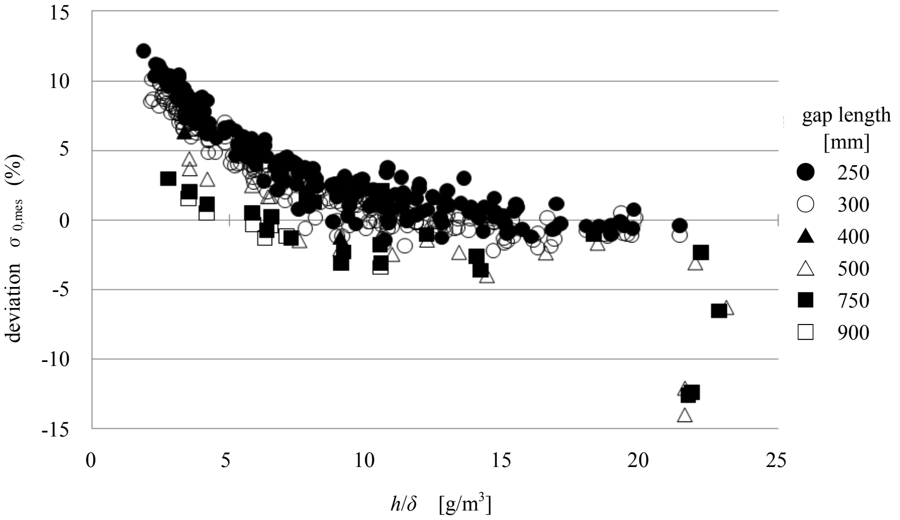


Figure 6: Relation between the correction $\sigma_{0,mes}$ and the parameter h/δ

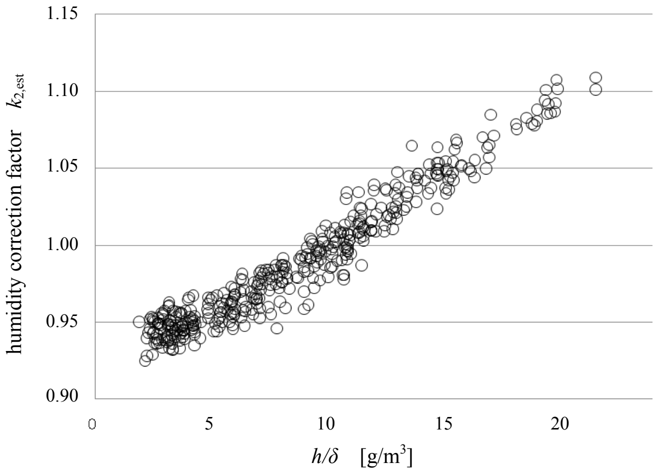


Figure 7: Distribution of the estimated humidity correction factor $k_{2,est}$ to the parameter h/δ

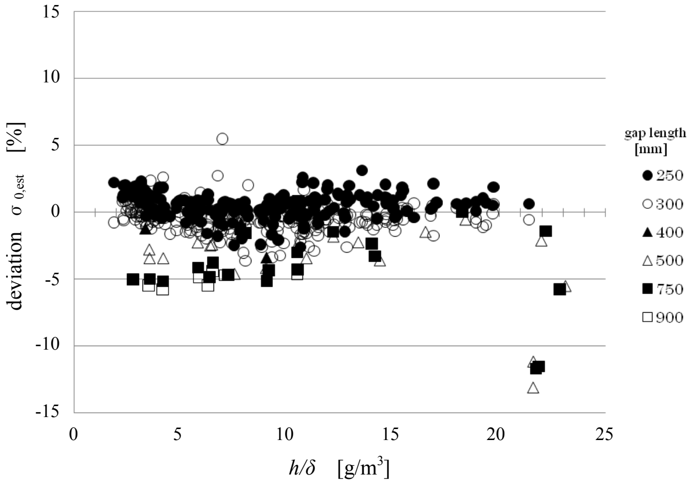


Figure 8: Relation between the deviation $\sigma_{0,est}$ and the parameter h/δ

$$k_{2,est} = U_{mes} / (k_1 \times U_{0,est}) = U_{mes} / (\delta \times U_0) \quad (13)$$

Figure 7 shows the distribution of the factor $k_{2,est}$ obtained from the disruptive discharge measurement results (U_{mes}). In this figure, the vertical axis represents the $k_{2,est}$ value and the horizontal axis h/δ. Also, when w in equation (4) is 1, $k_{2,est} = k_{est}$. Comparing the characteristics in Figure 7 with those in Figure 1, the forms of the curves will be seen to differ.

Fitting these curves into an equation of similar type to equation (6), we derive equation (14) for the parameter k_{est}:

$$k_{est} = 1.01 + 8.83 \times 10^{-3} \times (h/\delta - 11) \quad (14)$$

Then, distribution of the deviation $\sigma_{0,est}$ (refer to equation (15)) given by the estimated k_{est} to h/δ is shown in Figure 8.

$$\sigma_{0,est} = (U_{0,est} - U_0) / U_0 \times 100\ (\%) \qquad (15)$$

It was found that more or less satisfactory correction was effected across the broad humidity range where 1 $g/m^3 < h/\delta < 20\ g/m^3$. However, some cases where the deviation $\sigma_{0,est}$ exceeded 5% were observed in the ranges with long gap length. It may be desirable to add a correction parameter for gap length so as to deal with such cases.

5 CONCLUSION

Using the standard gap prescribed by the IEC standard, disruptive discharge voltage for positive direct voltage in air was measured for gap lengths ranging from 250 mm to 900 mm. Atmospheric correction was then performed on the measured values using the humidity correction factor given in the latest IEC 60060-1, and the corrected disruptive discharge voltage values were evaluated. With a measurement method using the rod-rod gaps used for measuring direct high voltage, it was found that correction using the humidity correction equation prescribed in the new IEC standard sometimes produced voltage values lower than the standard voltage by 10% or more in the low humidity regions.

The correction factors necessary for performing accurate correction were sought through repeated experiments. As a result, correction accurate within almost ± 5% became possible across all the humidity regions.

Also observed were characteristics that indicate that the discharge voltage depends on the gap length, albeit to a slight extent.

6 REFERENCES

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