高氣壓下에서 SF_6混合가스 (SF_6/N_2)의 絶緣破壞에 대한 硏究

論　文
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A Study on the Electrical Breakdown in Pressurized SF_6/N_2 Mixtures

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Abstract

The effective ionization coefficient in SF_6/N_2 mixtures was attempted to derive from the pure gases. Measurements of static breakdown voltage were made under the uniform field at pressures up to 4 bar in order to compare with the results obtained from this assumption. The relative performance of SF_6/N_2 mixtures to pure SF_6 was also investigated.

The effect of surface roughness on discharge thresholds in SF_6/N_2 mixtures was calculated employing the simplified model and mesurements of breakdown voltages for a gap with an artificial protrustion were also made.

The experimental results show that the effective ionization coefficient in gas mixtures can not be reliably estimated from the values measured for the pure gases. Therefore, basic parameters for SF_6/N_2 mixtures must be measured by investigation of the mixtures themselves. The relative performance of mixtures to pure SF_6 could be considered with the values of pR.

1. Introduction

SF_6 is used as an insulating medium for compact substation components and gas-insulated cables because of its high dielectric strength. However, recent studies have shown that because of the rapid variation of the effective ionization coefficient $\bar{\alpha}$ with the parameter E/p(E= electric field, p=pressure), is extremely sensitive to local field enhancement owing to electrode surface imperfactions[1] or to the presence of contaminant particles[2], so that the ideal Paschen-value electric strength may not be achieved in practical systems. But, on the other hand, non-attaching gases do not show such sensitivity to electrode roughness[3]. As a result, by adding a common gas such as nitrogen to SF_6, the resultant effective ionization may have a reduced sensitivity to electrode irregu-larities and particle contamination.

There is little information to date on the direct measurement of the effective ionization coefficient $\bar{\alpha}_m$ in SF_6/N_2 mixtures. However, it has been assumed[4],[5] that $\bar{\alpha}_m$ is obtainable from data for the individual pure gases, and with this assumption it is possible to attempt to calculate the breakdown voltages.

In this paper the breakdown strengths in various mixtures of SF_6 with nitrogen for smooth electrodes were calculated and compared with measured values. The effect of surface roughness on discharge thresholds in SF_6/N_2 mixtures was also calculated employing the simplified model.

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Measurements of breakdown voltages for a gap with an artificial protrusion were also made.

2. Experimental Apparatus and Techniques

The general apparatus and associated high voltage supply have been fully described previously[6]. Stainless-steel Bruce profiled electrodes of overall diameter 120mm were used with gap spacings limited to<20mm in order to exclude the possibility of avalanche development outwith the normally uniform region of the test gap.[7] Highly polished steel spheres of 500μm radius were placed on the surface of the lower electrode.

The applied voltages was initially set at approximately 80% of the anticipated breakdown level and thereafter raised at about 500 volts per second until a breakdown occurred. A minimum of 25 breakdowns were recorded for each condition.

In order to obtain the required gas mixture the following procedure was adopted. The test vessel was evacuated, and then filled first with SF_6 to the highest partial pressure to be investigated. Nitrogen was then added until the total pressure desired was obtained.

3. Breakdown Criterion

Adopting the assumption made by Baumgartner[8] the effective ionization coeffecient $\bar{\alpha}_m$ for mixtures may be expressed in terms of the individual coefficients of the pure gases as follws

$$\frac{\bar{\alpha}_m}{P}=\left(\frac{\bar{\alpha}}{P}+\phi\cdot\frac{\alpha}{P}\right)\Big/(1+\phi) \qquad (1)$$

where $\bar{\alpha}$=effective ionization coefficient of SF_6

α=ionization coefficient of nitrogen

$\phi=p_2/p_1$

p_1=partial pressure of SF_6

p_2=partial pressure of nitrogen

p=total pressure

Using the relations

$$\frac{\bar{\alpha}}{p_1}=\bar{\beta}\cdot\frac{E(z)}{p_1}-\frac{\bar{K}}{Z(p_1)} \qquad (2)$$

for SF_6[9] and

$$\frac{\alpha}{p_2}=A\ \exp\left[-Bp_2/E(z)\right] \qquad (3)$$

for nitrogen[10],

the value of $\bar{\alpha}_m/p$ for SF_6/N_2 mixtures is given by

$$\frac{\bar{\alpha}_m}{p}=\frac{1}{(1+\phi)}\cdot\left[\left(\bar{\beta}\cdot\frac{E(z)}{p}-\bar{K}\frac{1}{Z(p_1)}\right)+\phi\cdot A\cdot\exp\left(\frac{-Bp}{E(z)}\right)\right] \qquad (4)$$

where $\bar{\beta}$=27.8 (kV)

z=distance from the base surface of an electorde

$\bar{K}$=246 (barmm)

$Z(p_1)$=compressibility factor

A,B= constants having values of 6.6×10^2 (bar mm)$^{-1}$ and 21.5 kV (bar mm)$^{-1}$ respectively.

Following the practice established in a number of recent publications[12],[13],[14] concerned with the engineering applications of compressed gas insulation, breakdown thresholds were calculated using the simple streamer condition

$$\int\bar{\alpha}_m dz=k \qquad (5)$$

where k=streamer constant

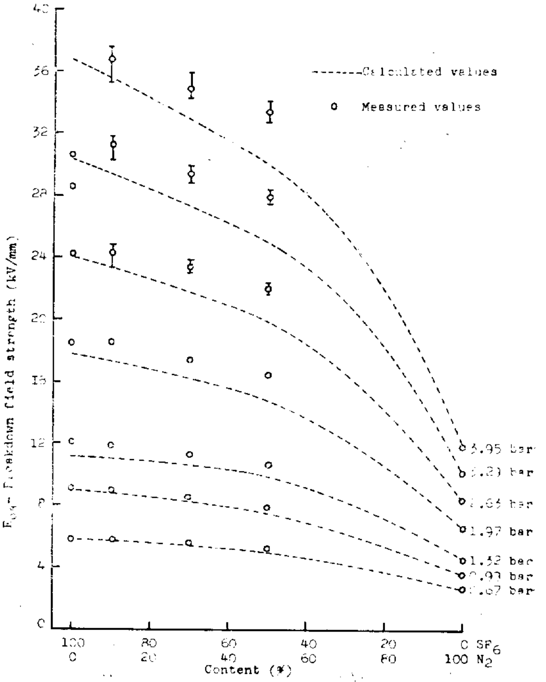

Fig. 1 Breakdown field stength in SF_6/N_2 mixtures with smooth electrodes

4. Results and Discussion

4.1 Breakdown with smooth elecroder

The breakdown voltages in SF_6/N_2 mixtures for uniformfield conditions with smooth electrodes may be obtained from equation (4) in which E(z) is replaced by E_0 (the macroscopic uniform field and equation (5) in the form $\bar{\alpha}_m d=k$. Figurel shows the results of these calculation as plots of E_{0s} against SF_6 content for total pressures up to about 4 bar. Also shown on figure 1 are the values of E_{0s} measured using lightly polished uniform field electrodes having a value of pR(R= height of protrusion) below the critical level[9].

The curves relating to total pressures of 0.67 and 0.99 bar drawn on figure 1 show that measurement and calculation are in good agreement for percentage SF_6 contents ranging from 100% down to 50%. As would be expected, the dielectric strength of the mixtures falls off with increasing N_2 content and is always below that of pure SF_6. This agreement between calculation and measurement indirectly supports the use of the breakdown criterion described in above section at least up to a pressure of about 1 bar.

However, at pressures above about 1 bar the measured values rise progressively above the calculated results for all mixture ratios. Such a trend can not be accounted for by localized enhancement or field emission since these would lower the breakdown fields below the calculated level. Therefor, it must be concluded that the calculations do not allow accurate prediction of the breakdown levels. The largest discrepancies were found for the mixture containing 50% SF_6, and for this mixture the maximum deviation occurred at a total pressure of ~4 bar where the measured point lies about 12% above the calculated value. For 90% SF_6, the differences between calculation and measurement were reduced to about 7% at most.

It is interesting to compare breakdown strengths for the various mixtures to the measured strength of pure SF_6 over the pressure range up to 4 bar. This comparison is shown in figure 2 where the ratio (E_{0s}-mixture)/(E_{0s}-SF_6) is plotted for the mixtures containing 50%, 70% and 90% SF_6. At low pressures all of the mixtures perform less well than pure SF_6. However, as pressures increase towards 4 bar the mixtures show an appreciable gain over pure SF_6. At 4 bar, the mixture containing 90% SF_6 breaks down with an applied field about 20% above that measured for pure SF_6 with the same electrodes.

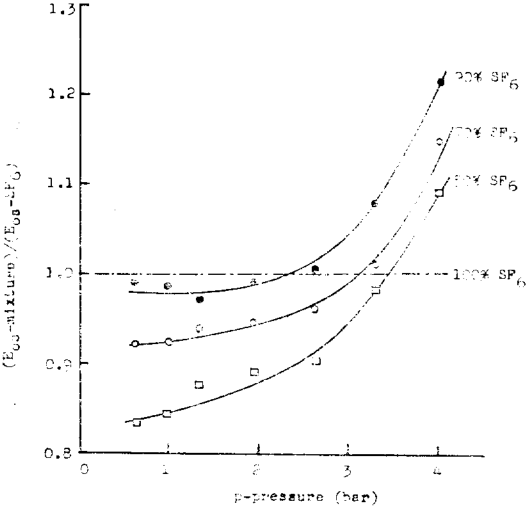

Fig. 2 Comparison of measured breakdown field strength between SF_6/N_2 mixtures and SF_6

4.2 Breakdown at high value of pR

The limiting value of E_0/p for a mixtures of SF_6 and N_2, (E/p) limϕ, can be calculated from equation (4) with $\bar{\alpha}_m/p=0$. Consequently, the theoretical value of the surface roughness factor for a gas mixture ζ_m can be defined in a manner similar to reference (9) and is given by

$$\zeta_m=Z(p_1)\cdot\left(\frac{E_{0s}}{p}\right)\Big/\left(\frac{E}{p}\right)_{\lim\phi} \qquad (6)$$

As a result, the variation of ζ_m and the normalised critical avalanche length U_{0m} as functions of pR for different values of mixture ratio ϕ can be calculated using the analysis due to Pedersen[15], employing the streamer breakdown criterion for gas mixtures described by equation (5). Figures 3, 4, and 5 show the results of these calculations.

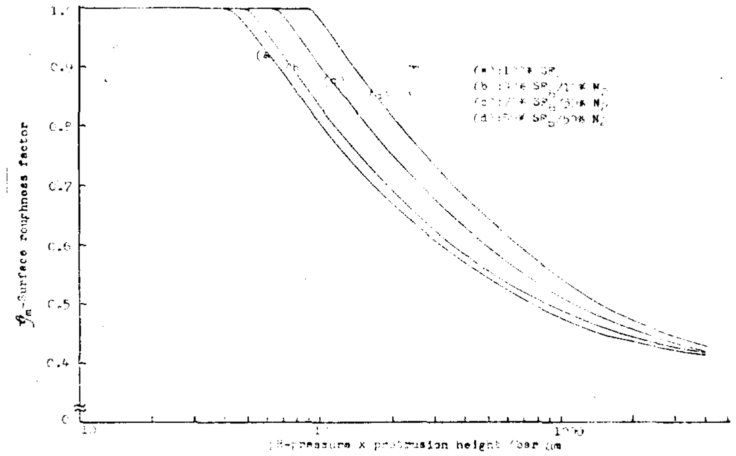

Fig. 3 Surface roughness factor for SF_6/N_2 mixtures

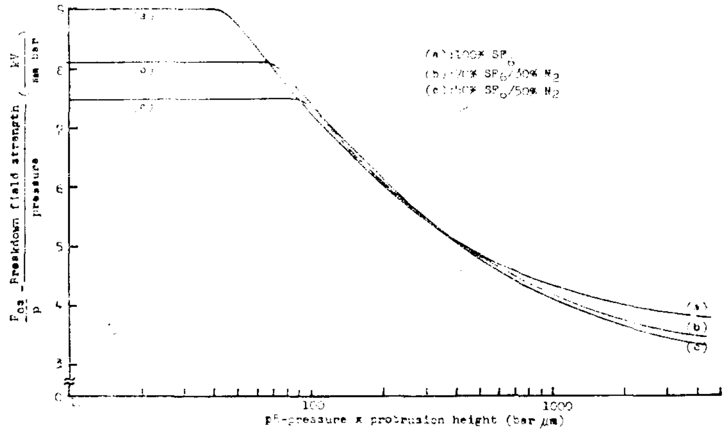

Fig. 4 Values of E_{0s}/p as a function of pR for SF_6/N_2 mixtures

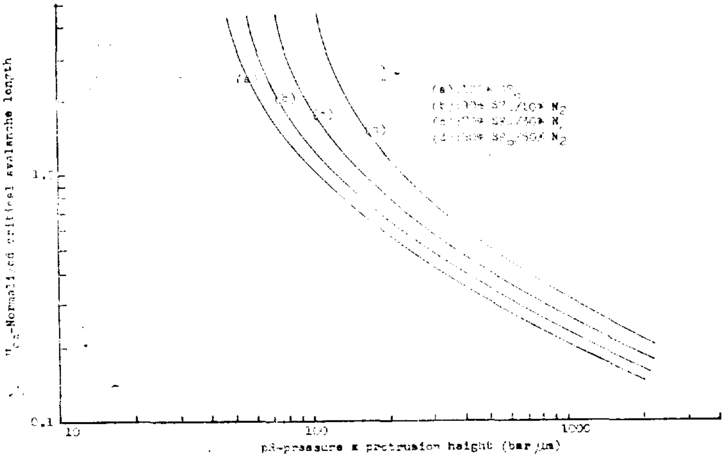

Fig. 5 Normalized critical avalanche length for SF_6/N_2 mixtures

Figure 3 presents the calculated values of ζ_m as a function of pR for the hemispherical protrusion model. It is evident that as the nitrogen content is increased from10% to 50% the critical value of pR rises from ~45 bar μ_m to~95 barμ_m. However, it is important to note that this increase in the calculated value of the critical level of pR depends greatly on the validity of the simple assumption that the streamer constant k can be calculated by linearly interpolating between 10.5 and 18. However, with this assumption it is clear that, as the percentage of nitrogen is increased, the theory predicts that the reduction in breakdown level due to roughness should decrease.

This effect is further described in figure 4, which shows the actual theoretical breakdown level for mixtures as a function of pR. Obviously, the point from which the breakdown strength is affected by pR, is extended with increasing nitrogen concentration. It is interesting to note that the $E_{0\phi}/p$ values for the 70% SF_6/30% N_2 and 50% SF_6/50% N_2 mixtures are higher than those for pure SF_6 over the range from about 70 bar μm and 100 bar μm respectively to about 400 bar μm. This predicts that that the dielectric strength of those mixtures is less sensitive to electrode surface irregularities than that of pure SF_6 over this range of pR, i.e. the calculation shows that in this region, the amount of nitrogen added to the SF_6 slightly increases the breakdown strength. Above about 400 bar μm, pure SF_6 becomesgradually superior to SF_6/N_2 mixtures.

Figure 5 presents the calculations of the normalized critical avalanche length U_{0m} as a function of pR, assuming the hemispherical protrusion model. The values are longer than those calculated for pure SF_6, and this effect increases with increasing concentration of nitrogen. The curve for a 50% SF_6/50% N_2 mixture (curve d) shows that U_{0m} for this mixture increases very rapidly if pR values less than 100 bar μm are considered.

It must be emphasised, however, that the calculations are likely to be progressively less accurate as pressures above about 1 bar are considered since, as shown in above section at these higher pressure the calculations did not agree particularly well with measurement for smooth electrodes; that is, in particular, the calculated values of $(E/p)_{lim\phi}$ did not agree with the measured values and in fact always lay below the measured values. From the results presented in figures 1 and 4 the measured and calculated limiting values are as follows:

Table 1. Limiting values for SF_6/N_2 mixtures

Mixtures $(E/p)_{lim\phi}$	90% SF_6	70% SF_6	50% SF_6
Measured	8.85	8.6	8.4
Calculated	8.65	8.13	7.5

Units: kV bar^{-1} mm^{-1}

The calculated curves of figure 4 can now be replotted using the measured values of $(E/p)_{lim\phi}$ and this ensures that the curves are correct at least at very low values of pR. These new, corrected curves, showing the predicted reduction in $E_{0\phi}/p$ as a function of pR for various mixture ratios, are shown in figure 6.

By comparing the completely theoretical curves of figure 4 with the empirically corrected curves of figure 6 it can be seen that above a pR value of about 500 bar μm both sets of curves predict that mixtures will behave less well than pure SF_6. Above the pR value of ~45 bar μm, the onset value for rougness effects in pure SF_6 gas, but below 500 bar μm both figures 4 and 6 suggest that mixtures offer advantages over pure SF_6. How ever, whereas the purely theoretical curves indicate that higher concentrations of SF_6 are advantageous the corrected curves clearly show that the improvement is most marked at lower SF_6 concentrations.

In order to present these calculated results more clearly, to identify the ranges of pR over which the mixtures are predicted to breakdown at higher values of $E_{0\phi}/p$ than pure SF_6, the curves of figure 6 were normalized by dividing the calculated $E_{0\phi}/p$ for the mixtures by the calcultaed $E_{0\phi}/p$ for pure SF_6. The results of this cal-

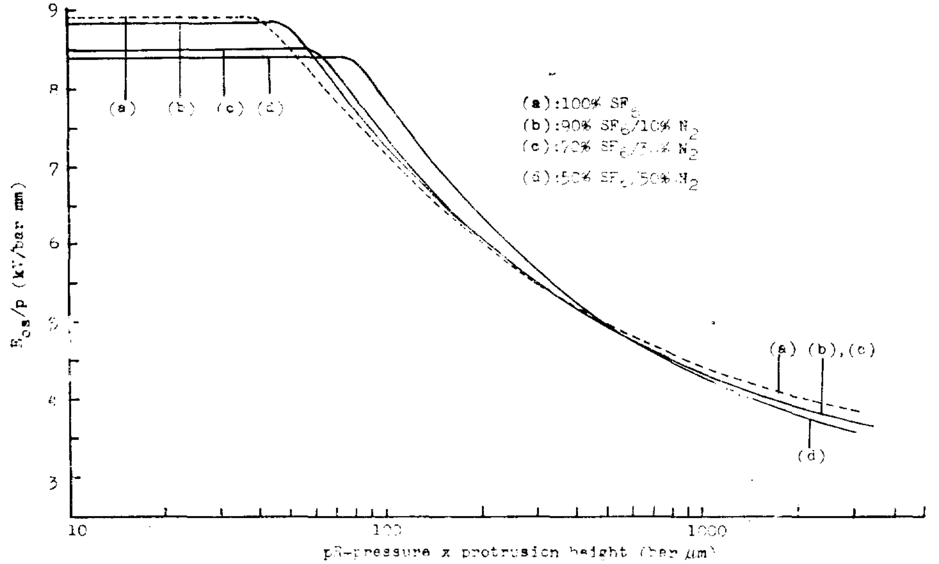

Fig. 6 Empirically corrected values of E_{os}/p as a function of pR for SF_6/N_2 mixtures

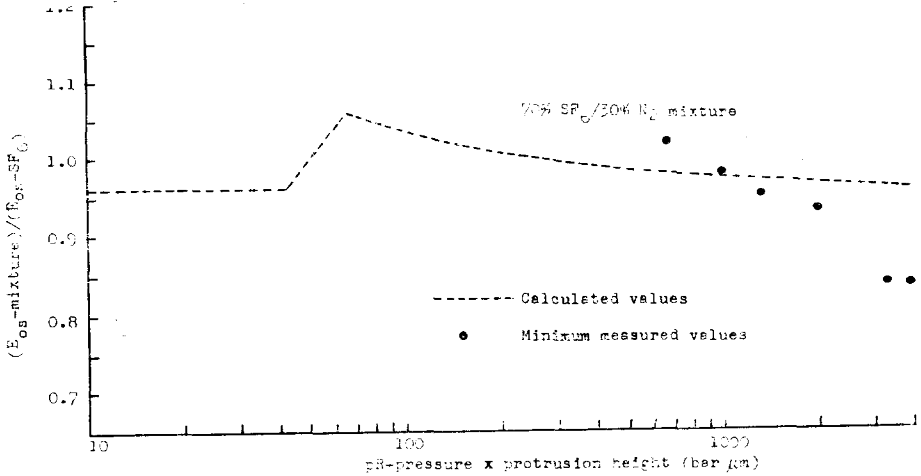

Fig. 7 The dielectric strength of SF_6/N_2 mixture relative to pure SF_6

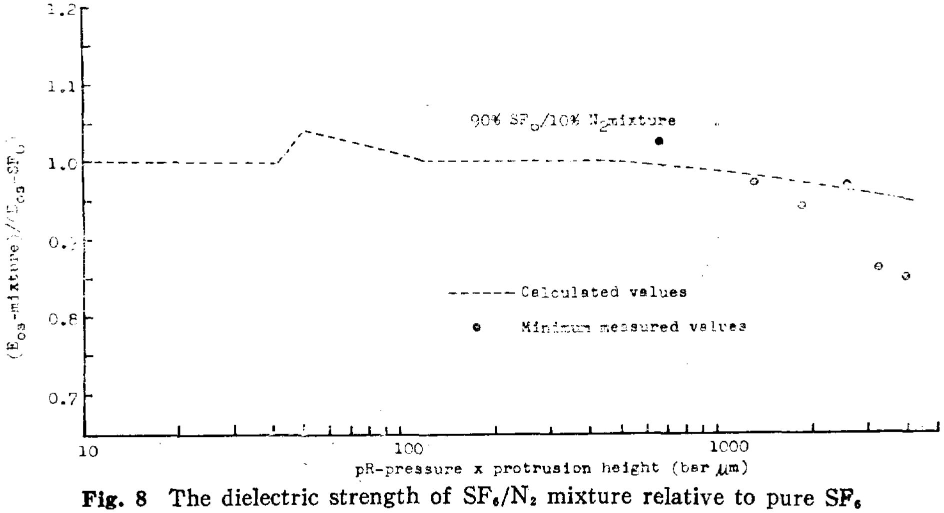

Fig. 8 The dielectric strength of SF_6/N_2 mixture relative to pure SF_6

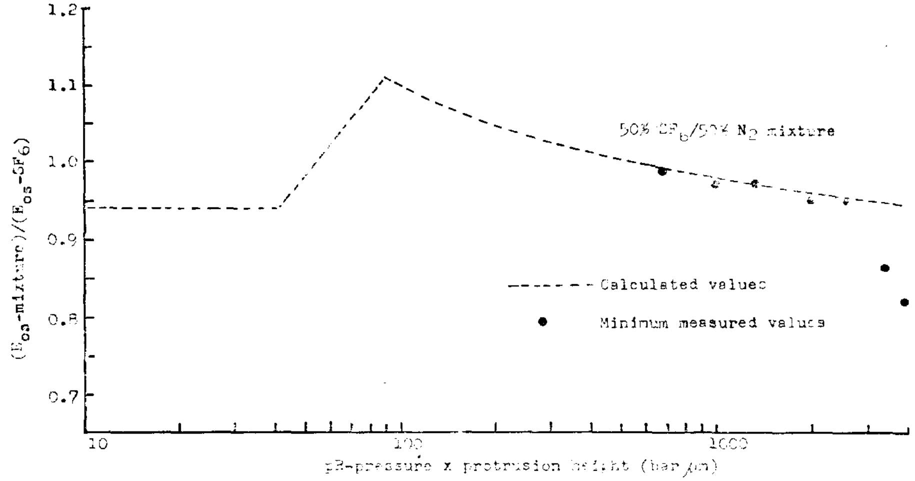

Fig. 9 The dielectric strength of SF_6/N_2 mixture relative to pure SF_6

culation are shown in figures 7,8 and 9 where the ratio (E_{0s}-mixture)/(E_{0s}-SF_6) is plotted as a function of pR. Also shown on these figures are measured values to be described later.

These figures show clearly that the theoretical relative performance of SF_6/N_2 mixtures should be discussed with reference to three distinct ranges of parameter pR.

Range (1): pR<45 bar μm The relative performance of the mixtures decreases with increasing N_2 concentration.

Range (2): 45<pR<300 or 400 bar μm Here the mixtures perform better than pure SF_6 and this effect becomes more marked as N_2 concentration increases.

Range (3): pR>400 bar μm At these high values of pR all mixtures are comparable and all perform less well than pure SF_6.

In order to obtain some measurements to compare with the predicted behaviour shown in figures 7,8 and 9 some tests were made at high values of pR with spherical protrusions. These results are plotted on identical figures. The measured ratio of (E_{0s}-mixture)/(E_{0s}-SF_6) evidently supports the prediction that, at pR values greater than a few hundred bar μm, the mixtures do not perform as well as pure SF_6.

5, Conclusions

For mixtures of SF_6 and N_2 the method adopted to estimate breakdown levels, and to calculate the influence of surface roughness on these levels, has not given particularly satisfactory agreement with measured values. This clearly shows that the effective ionization coefficient and streamer constant k can not be reliably estimated from the values measured for the pure gases. It must be concluded, therefore, that these basic parameters must be measured by investigation of the mixtures themselves.

Despite these limiations the general trend predicted by the calculations, that the relative performance of mixtures to pure SF_6 could be considered over three ranges of pR, proved to be of significance. At high values of pR (>400 bar μm) both theory and measurement were in agreement and the SF_6/N_2 mixtures performed less well than pure SF_6. However, at low values of pR (<45 bar μm) no agreement could be found between theory and calculation and, in particular, the measurements showed a very significant gain in performance as pressure increased to 4 bar. This was in complete contrast to the predictions of the theoretical model which always predicted a lower breakdown level for the mixtures.

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