The Effect of Compressibility on Breakdown and Modification of the Surface Roughness Factor in Compressed SF_8

論 文
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Abstract

A pressure dependence in the value of Es/p at a constant pd is observed in sulphur hexafluoride at pressures in excess of about one bar. This is explained in terms of the non-idealgas behavior of SF_6 which has a significant influence on the interpretation of electrical breakdown of this gas. The criterions for breakdown at low pressures and in the presence of rough electrodes are modified to allow this phenomeneon.

1. Introduction

Breakdown thresholds in compressed sulphur hexafluoride under nominally uniform field conditions have been observed to depart from the values anticipated from sub-atmospheric measurements when expressed in terms of the experime rimentally determinable parameters of voltage, gas pressure and nominal gap geometry.

At pressures of a few bar these departures may be considered to be due to at least two different processes. Firstly, the extremely short critical avalanche lengths encountered at high pressures confine the development of the initial prebreakdown ionization to regions very close to the conductors and consequently any localised field enhancement created by surface irregularities becomes increasingly significant as pressure is raised thus leading to a lowering of the discharge threshold below those expected from low-pressure cata where nominal gap geometry may be assumed(1)(2)(3). Studies on this matter will be presented in the subsequent papers. Secondly, under conditions where the nominal gap geometry has been preserved by using hignly polished electrode surfaces discharge thresh-olds at high pressures have observed to increase those expected from low-pressure data(4). Therefore it is evident that both phenomena must be considered in order to describe fully the breakdown mechanism in compressed SF_6. In this paper the results taken under the latter conditicns are analysed.

2. Apparatus and Experimental Techniques

The stainless steel pressure vessel is approximately 670mm high and 500mm in diameter and is designed for use at pressures up to 4 bar. In the present experiments, a pair of stainless steel uniform field electrodes made to the Bruce profile were mounted along the vertical axis of the vessel. These were of 180mm overall diameter and could be operated with gap spacing of up to 60mm.

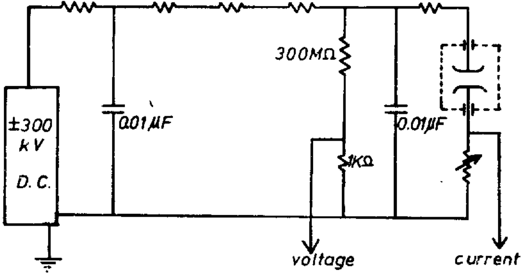

Fig. 1. High voltage circuit

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The experimental vessel and associated high voltage supply are fully shielded by aluminium housing.

The output from the d.c. generator was connected to the smoothing circuit illustrated diagrammatically in figure 1. The voltage applied to the test gap was measured using a resistance divider and a digital voltmeter. The Solartron type LM 1867 digital voltmeter has a maximum resolution of 1 part in 30,000 and an accuracy of ±0.0033% of full scale.

The temperature of the gases inside the vessel was measured using a digital thermometer probe (United Systems Corporation Model 502—17s).

The two electrodes were finely polished with 0.1μm diamond paste and showed surface roughneese of 0.04μm C.L.A. and 0.1μm C.L.A.

As the present maximum pressure is about 4 bar, the value of pR=0.4 barμm p=pressure, R=maximum height of a protrusion) in the present work clearly satisfies the condition that pR=45 barμm$^{(1)}$. Moreover for strictly uniform field data the product pd (d=gap spacing) was kept to the value less than about 20 barμm, and the gap spacing to the value less than one fifth of overall diameter of the electrode in order to exclude the possibility of either axial field asymmetry reducing the breakdown voltage or avalanche development outwith the mominally uniform field region of the test gap$^{(5)}$.

The pressure in the vessel was set at about 1 bar and raised in stages to about 4 bar by adjusting the gas inlet value. When the pressure of the vessel was changed, the electrode seperation was reset byan electrical short-circuit measurement after allowing a suitable time for mechanical stabilization.

The applied voltage was initially set at approximately 80% of the anticipated breakdown level and thereafter raised at about 500 volts per second until breakdown occurred. The breakdown voltage Vs was determined rfo several gap spacings. On average 10 breakdowns were recorded for each condition. As tests with different time internals between shots showed no difference in breakdown voltages, the time internal allowed between successive breakdowns was maintained at about one minute. The gas pressures quoted are referred to 20°C.

3. Results and Discussion

3,1 The effect of compressibity on breakdown

Figure 2 presents results obtained with SF_6 in the form of a graph of Es/p against pd (Es=breakdown field strength) up to pressures of 2.63 bar. From this figure it can be seen that breakdowns always occurred at values above the limiting value of E/p except in the special case of edge breakdowns and a small pressure dependence was observed at pressures above about 1 bar.

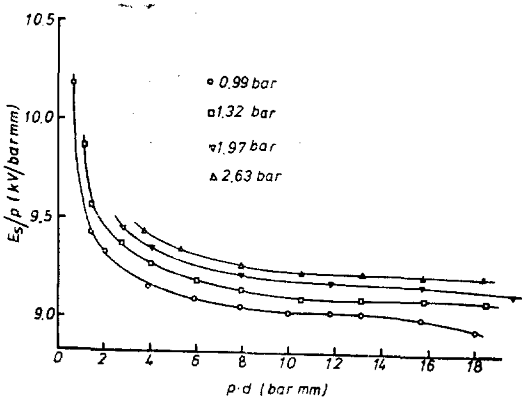

Fig. 2. Measurements of Es/p as a function of p.d in, SF_6

Gas imperfections or deviations from the ideal gas law, may be stated in terms of the compressibility facter Z, which is defined by

$$Z(p,T)=pv/nRT \text{ or } p=Z(p,T)NRT$$

whereep is pressure, v volume of gas sample, n the number of moles of gas in the sample, R the gas constant, T absolute temperature and $N=n/v$. A compressibility factor equal and close to unity means an ideal gas and nearly ideal behaviour respectively and a compressibility factor significantly different from unity shows that the ideal gas law no longer holds.

Consider the effective ionization coefficient for SF_6 in a region of applied field E. Fundamentally α=F(E,N). Experimentally, however, only α=G (E,p) may be determined and the form of the function F calculated employing the relationship between p and N. Experimental determinations of α are normally confined to sub-atmospheric pressures and so the form of F can be readily determined since under these conditions, Zmmay be assumed to be unity. In SF_6 at pressures above about 1 bar, this no longer holds. However, if it is assumed that the basic ionization processes do not alter significantly as pressure is increased above 1 bar then the form of the function F determined at low pressures is still valid. Consequently the experimentally determinable function G must be modified above 1bar to account for the loss of proportionality between p and N. This may be perrormed by replacing the variable p by the quantity $p/Z(p)$ which is proportional to N. The form of $Z(p)$ as a function of pressure at 20°C may be calculated using the Beattie-Bridgeman equation of state and in the range $0 \leq p \leq 10$ bar has the numerical value for SF_6;

$$Z(p)=1-1.15\times10^{-2}\cdot p-1.18\times10^{-4}\cdot p \qquad (1)$$

$Z(p)$, therefore, decreases with increasing p and so leads to a reduction in the value of α/p at constant E/p as pressure is increased, thus leading to higher discharge thresholds under conditions where the effect of electrode surface roughness may be negleated.

From equation (1) the compressility factor $Z(p)$ is within 1% of unity up to pressures of about 1 bar and therefore. in this pressure range, any deviation from ideal gas behaviour would not be marked. However, at 1.5 bar $Z(p)$ decreases to 0.98, at 4 bar to 0.95 and at 10bar to about 0.87. In figure 2, the increase in E_s/p with pressure at constant pd observed for pressures between 1 and 2.63 bar can now be explained in terms of non-ideal-gas behavior of compressed SF_6. This can be seen from figure 3 where E_s/p is plotted against pd up to a pressure of 2.63 bar but with the compressibility factor for SF_6 at each pressure taken into account. As seen in Fig.3 each value of E_s/p now lies closely to a common curve, indicating no anomalous dependence on pressure at constant pd.

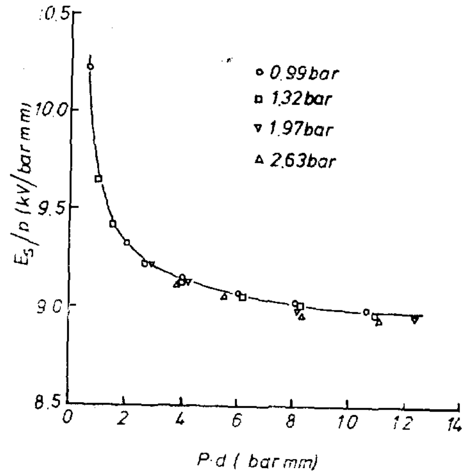

Fig. 3. Measured values of Es/p taking in to account the comressibiliey factor in SF_6

This idea of compressibility in SF_6 may be combined with. the equations describing the low-pressure ionization and static breakdown characteristic of SF_6 presented by Boyd and Crichton [6]. The effective ionization coefficient α is given by

$$\alpha=\beta E-\kappa p/Z(p) \qquad (2)$$

where $\beta=27.8\text{kv}^{-1}$ and $\kappa=246(\text{barmm})^{-1}$ and the extrapolated from of the breakdown voltage becomes

$$V_s=0.38+8.84\ pd/Z(p) \qquad (3)$$

or $$E_s/p=0.38/pd+8.84/Z(p) \qquad (4)$$

whese $8.84\text{kv}(\text{barmm})^{-1}$ is the value of(E/p)lim $(\alpha=0)$ determined at low pressure. Thus using equation (4), theoretical values of E_s/p may be plotted as a function of pressure at constant values of the parameter pd and compared to the measured values of figure 2. These results are shown in figure 4 and it is evident that the increase in E_s/p with pressure at constant pd observed for pressures up to about 2.6 bar may be accounted for by considering the decrease in the compressiblity at these pressures. The horizontal lines shown in figure 4 represent the constant values of E_s/p obtained by simple eztrapolation in which an ideal gas is assumed.

3.2 Modification of the surface roughness factor

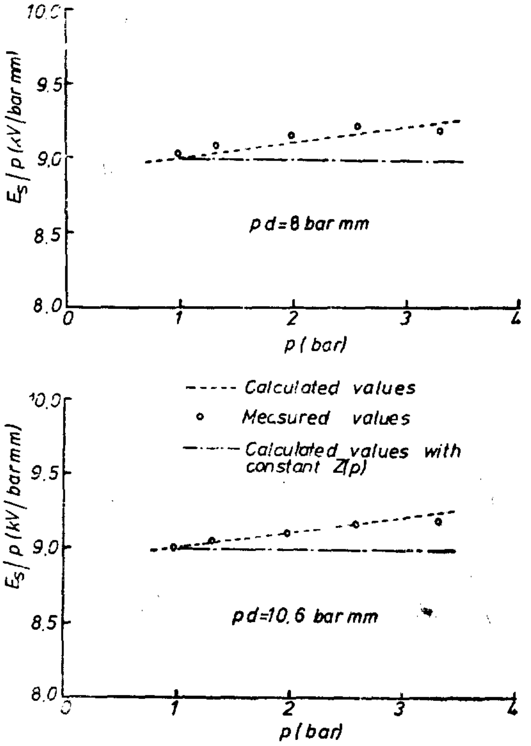

Fig. 4. Values of E_s/p as a function of p at constant pid in SF_6

The equations describing α/p and E_s/p for SF_6 used to derive the form of the surface roughness factor $\xi^{(6)}$ as a function of product pR were those derived from measurements at low pressures. Following the above arguments, it becomes necessary to modify the calculated dependence of ξ upon pR to allow for changes in the value of Z (p) at pressures above~1 bar. Therefore the expression $\xi=\psi(pR)$ becomes $\xi=\psi\left(\frac{1}{Z(p)}\cdot pR\right)$ and this requires

$$\xi=Z(p)\cdot\frac{E_s}{p}\Big/\left(\frac{E}{p}\right)\lim \qquad (5)$$

instead of original form(6) $\xi=\frac{E_s}{p}\Big/\left(\frac{E}{p}\right)\lim$•In equation (5) it should be stressed that the quantity (E/p)lim is the measurable values of 8.84 kV $(barmm)^{-1}$.

4. Conclusions

The good agreement shown between the experimental results and the theosetical calculations suggests that the compressibility factor must be considered in the interpreation of experimental observations of the electrical breakdown of SF_6 and should be taken account when computing discharge thresholds in this gas at pressures about 1 bar. Therefor the equations obtained at low pressure SF_6 may be extended to higher pressures by replacing the variable p by the quantity p/Z which is proportional to N.

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