CHAPTER VI

VALIDITY OF DIFFUSION THEORY IN RADIO FREQUENCY BREAKDOWN IN MOLECULAR GAS IN LONGITUDINAL MAGNETIC FIELD.

INTRODUCTION

The study of the breakdown of a gas excited by high frequency electromagnetic field has shown that the breakdown voltage depends upon the pressure of the gas, the dimension of the discharge tube and the frequency of excitation. The dominant factors by which electrons are lost are diffusion and mobility and if the gas is an electron attaching one then by electron attachment also. It has been observed that when the pressure of the gas is of the order of a few milli torr and the length of the discharge tube is large compared with the mean free path of the electrons in the gas, both the mobility and diffusion are the dominant factors by which electrons are removed. On the other hand when the gas pressure is high and the exciting frequency of the applied voltage lies in the microwave region the electrons are lost mainly by diffusion. The method of calculating theoretically the breakdown voltage of a gas excited by high frequency voltages at high pressure has been developed by Harlinm and Brown (1948) where the dominant factor for electron removal process has been assumed to be diffusion. Starting from a molecular model, Kihara (1952) developed a method to calculate theoretically the breakdown voltage of a gas under high frequency excitation taking the loss due to both mobility and diffusion into consideration and in a series of papers from this laboratory Sen and Ghosh (1963), Sen and Bhattacharjee (1965, 1966, 1967) the experimental results have indicated that when the pressure is of the order of a few millitorr and the frequency of excitation is of the order of a few MHz, both the diffusion and mobility are the major electron removal processes.

To test the limitations of the diffusion theory it is proposed here to undertake some experiments on the breakdown voltages of gases where the frequency of the exciting voltage is of the order of a few MHz and the pressure of the gas is of the order of a few torr. To study the effect of attachment, breakdown measurements in some electron attaching gases such as air and oxygen have also been undertaken. The object of the present investigation is to find whether the loss mechanism remains the same when the frequency of the exciting voltage is scaled down from microwave to radio frequency keeping the pressure in the range of a few torr.

The breakdown of a gas excited by a xâka radio frequency field in presence of a magnetic field has been studied previously by Lax et al (1950) who performed experiments on the breakdown voltage of helium containing a small admixture of mercury vapour and obtained breakdown curves for different values of the pressure. Ferritti and Veronesi (1955) performed experiments for frequencies ranging from 10 to 30 MHz in air, the magnetic field varying from zero to 600 G and observed a lowering of breakdown voltage in presence of magnetic field, Sen and Bhattacharjee (1969) performed experiments in case of air, hydrogen, oxygen and carbondioxide in presence of a magnetic field from 300 to 1800 G.

Borwn (1959) has explained the change of breakdown voltage observed in presence of magnetic field by assuming that the diffusion length in presence of magnetic field is altered according to the equation

$$\Lambda_H^2 = \Lambda^2 \left[1 + \omega_B^2 / \nu_c^2\right]$$

where Λ = diffusion lengths in absence of magnetic field,

Λ_H = diffusion lengths in presence of magnetic field.

ω_B = electron cyclotron frequency.

ν_c = collision frequency.

To make a further test of diffusion theory in presence of magnetic field, it is also proposed to verify the above eqn. of Brown from the experimental results obtained in the present set of experiments. The results are expected to prove the validity of the diffusion theory in presence and in absence of the applied magnetic field.

2. EXPERIMENTAL ARRANGEMENT

The method of measurement of breakdown voltage was the same as was used in the previous paper Sen and Ghosh (1963). The discharge tube was cylindrical of length 7.2 cm. fitted with two internal electrodes with seperation distance of 2.5 cm. and the diameter of the discharge tube was 2.9 cm. The radio frequency voltage was supplied from a tuned grid tuned plate oscillator, the frequency of the oscillator being variable f from 3.5 MHz to 11 MHz and the out put of the oscillator could be continuously varied from 0 to 550 volts. The r.m.s. out put voltage was measured with a vacuum tube voltmeter. The pressure of the gas was measured with a calibrated Mcleod gauge. The magnetic field was provided by an electromagnet, the lines of force were parallel to the length of the discharge tube and the discharge tube was placed entirely within the pole pieces of the electromagnet. The magnetic field was measured with a calibrated fluxmeter. Keeping the magnetic field at a constant value the pressure was varied and the breakdown voltage was measured for various values of gas pressure. The experiments were repeated and the results were found to be reproducible within $\pm$ 1%.

Pure and dry air was used which was passed through phosphorøus pentoxide to remove traces of water vapour. Hydrogen was prepared by the electrolysis of a warm concentrated solution of barium hydroxide in a hard glass U-tube fitted with nickel electrodes in which hydrogen gas was liberated at the cathode. The gas was dried by passing it over broken pieces of potassium hydroxide and then over purified phosphorus pentoxide. Pu-re oxygen was evolved at the anode in the electrolysis of barium hydroxide solution and was passed through pu re concentrated sulphuric acid before collection in the discharge tube.

3. RESULTS AND DISCUSSION

The breakdown voltages for hydrogen, oxygen and air have been plotted for different values of pressure (0.1 to 2.4 torr) with and without magnetic field (110 G to 795 G) in figures 6.1, 6.2 and 6.3 respectively. It is observed that the breakdown voltage is always smaller in presence of magnetic field than in its absence for all values of pressure and the pressure at which the breakdown voltage becomes minimum always shifts to lower pressure with the increase of the magnetic field. To provide a meaningful interpretation it is proposed to examine the results in the light of the prevalent theories (Brown,1948, Kihara,1952).

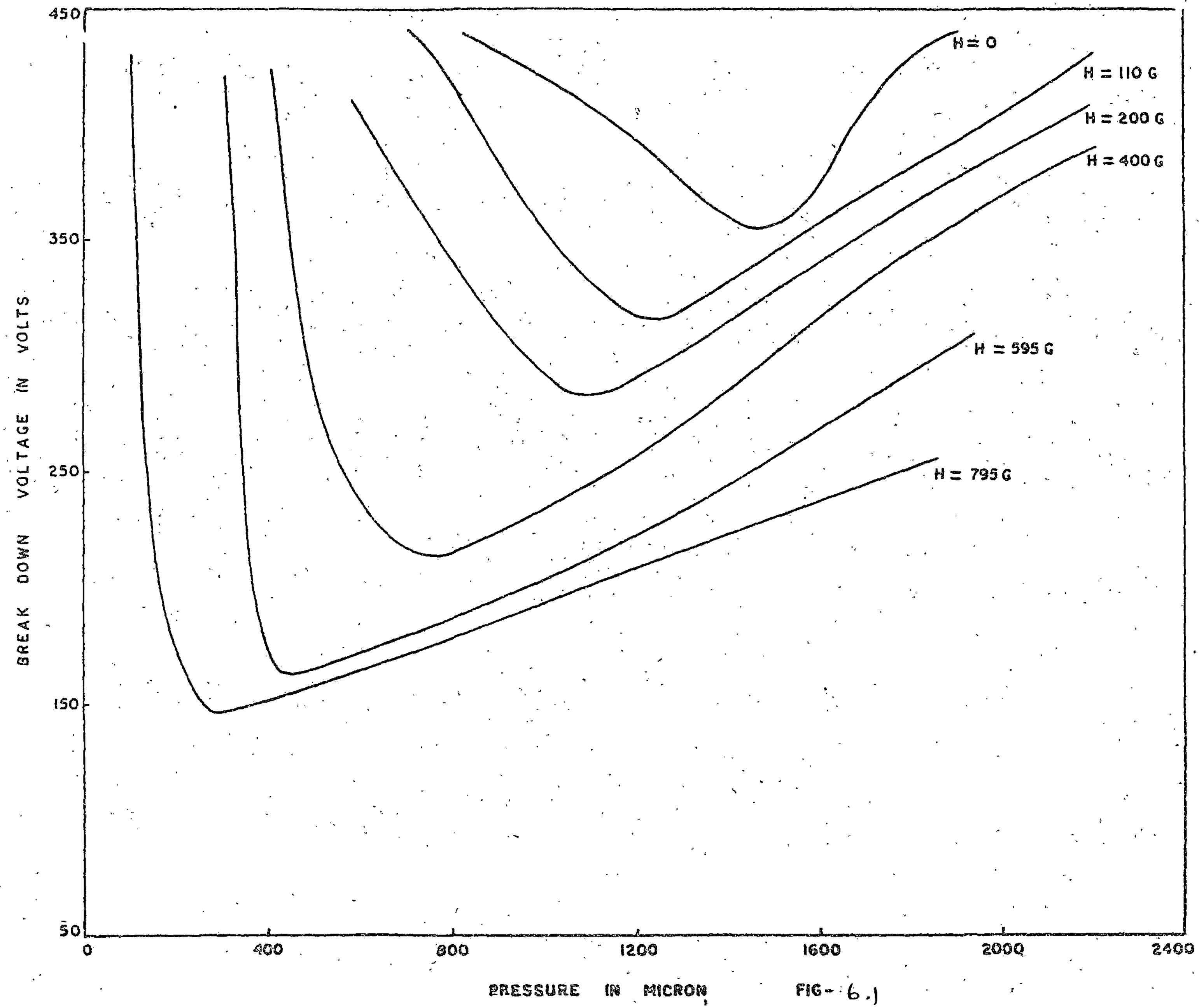

BREAK DOWN VOLTAGE IN VOLTS
450
350
250
150
50
0
400
800
1200
1600
2000
2400
H = 0
H = 110 G
H = 200 G
H = 400 G
H = 595 G
H = 795 G
PRESSURE IN MICRON

FIG- 6.)

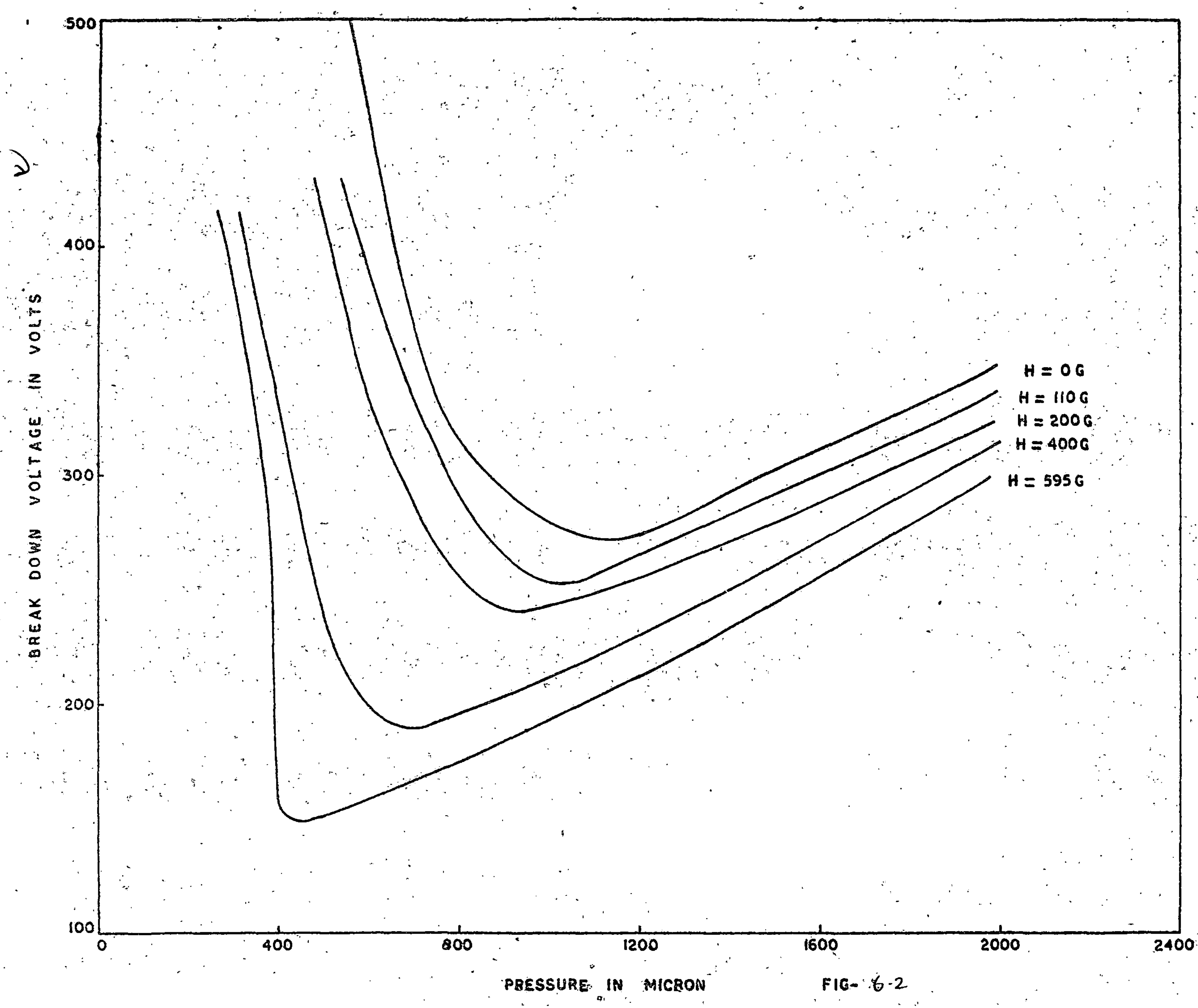

BREAK DOWN VOLTAGE IN VOLTS
500
400
300
200
100
0
400
800
1200
1600
2000
2400
PRESSURE IN MICRON
H = 0G
H = 110G
H = 200G
H = 400G
H = 595G

FIG- 6-2

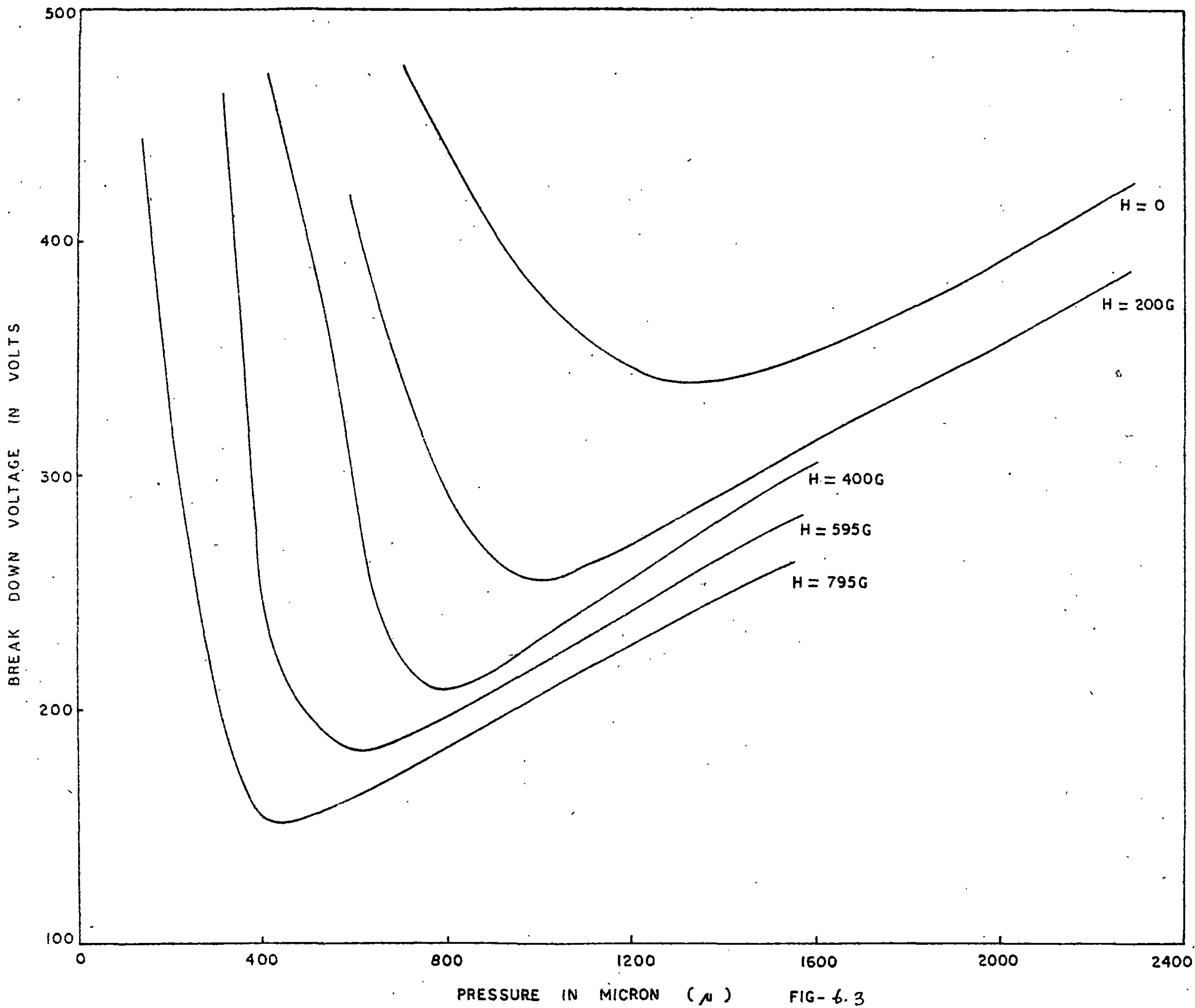

BREAK DOWN VOLTAGE IN VOLTS
500
400
300
200
100
0
400
800
1200
1600
2000
2400
PRESSURE IN MICRON (μ)
H = 0
H = 200G
H = 400G
H = 595G
H = 795G

FIG- 6.3

In order to determine which process is predominant in the process of electron removal under the present experimental set up the following points have been considered.

(i) According to Brown for the diffusion theory to be valid the dimensions of the discharge tube must be small compared to wavelength of the exciting power. As the wavelength is of the order of 51.2 cm. and the length of the discharge tube is 7.2 cm. and diameter 2.6 cm. this condition is satisfied.

(ii) The maximum mean free path of the gases used here is 0.6 cm. at a pressure of 0.1 torr (Townsend, 1947) which is much smaller than either the length or the radius of the tube.

(iii) The amplitude of electron oscillation when calculated from the equation

$$x = \frac{e E_0}{m\omega[\omega^2 + \nu^2]^{1/2}}$$

where E_0 is the field intensity, is 0.02 cm. at a pressure of 1 torr and will be smaller at higher pressures.

(iv) The collision frequency is

$$\nu_r / \lambda_e$$

where ν_r = random velocity

λ_e = mean free path and is of the order of 10^9 collisions/sec. and is much greater than the exciting frequency even at a pressure at 1 torr.

Under the above conditions it is thus appearent that the electrons make many oscillations of small amplitude, because the motion is restricted by collisions and the cloud of electrons appear stationary (there being no drift motion), spreading out wards only by diffusion. Hence loss due to drift can be neglected. New charged particles are formed due to ionizing collisions and loss due to diffusion predominates. In case of electron attaching gases the loss due to attachment should also be taken into consideration.

As stated above, under the present experimental set up and range of pressure investigated the electron suffers many collisions per oscillation of the field. Brown pointed out that as pressure increases, mean free path decreased and the energy gain per mean free path is proportional to mean free path at constant E. Hence to cause breakdown the field must increase in inverse proportion with the mean free path or in direct proportion with the pressure. Thus at high pressure where the electrons make many collisions per oscillation their behaviour is much the same as in the case of d.c. field. The value of (α/p) where α is the ionization coefficient can then be calculated from the experimental values of E/P from the Twonsend's relation

$$\alpha/p = A_0 \exp\left\{-B_0/(E/P)\right\} \qquad (6.1)$$

where A_0 and B_0 are constants for a particular gas.

Kihara (1952) has treated the phenomena of electrical discharge by adopting a proper molecular model for collision processes. Assuming a model for the cross section of the molecule for elastic, exciting and ionisation collisions with a Maxwellian distribution of electron velocities which is nearly valid for the case of molecular gases which have been studied here he has deduced that

$$\alpha/p = \left(\frac{N}{P}\right)\frac{\sigma}{C_i}\left(\frac{3\lambda}{\rho}\right)^{1/2} \exp\left[\frac{-mC_i^2(N/p)(3\lambda\rho)^{1/2}}{2.e(E/p)}\right] \qquad (6.2)$$

where σ = molecular constant equivalent to collision cross section.

λ = another constant having the dimension of $cm^{-3}S^{-1}$,

N = the number density of the gas atom,

K = Boltzmann constant.

ρ = another molecular constant having the dimension of cms.

The values of these molecular constants have been provided by Kihara (1952).

The values of (α/p) have been calculated from equation 6.1 using the experimental values of (E/P) obtained in the present investigation afor hydrogen. The values of (α/p) have also been calculated from equation 6.2 for corresponding values of (E/P) using the numerical values of the constants given by Kihara. The results for hydrogen have been plotted in figures 6.4 and for comparison published experimental values of (α/p) from literature are also plotted in the figure 6.4. In case of electron attaching gases such as air and oxygen the loss due to attachment is also taken into consideration and the ionization coefficient (α/p) have been calculated from the expression

$$\alpha/p = \frac{\alpha_a}{p} + A_o \exp\left(-B_o/_{E/p}\right) \qquad (6.3)$$

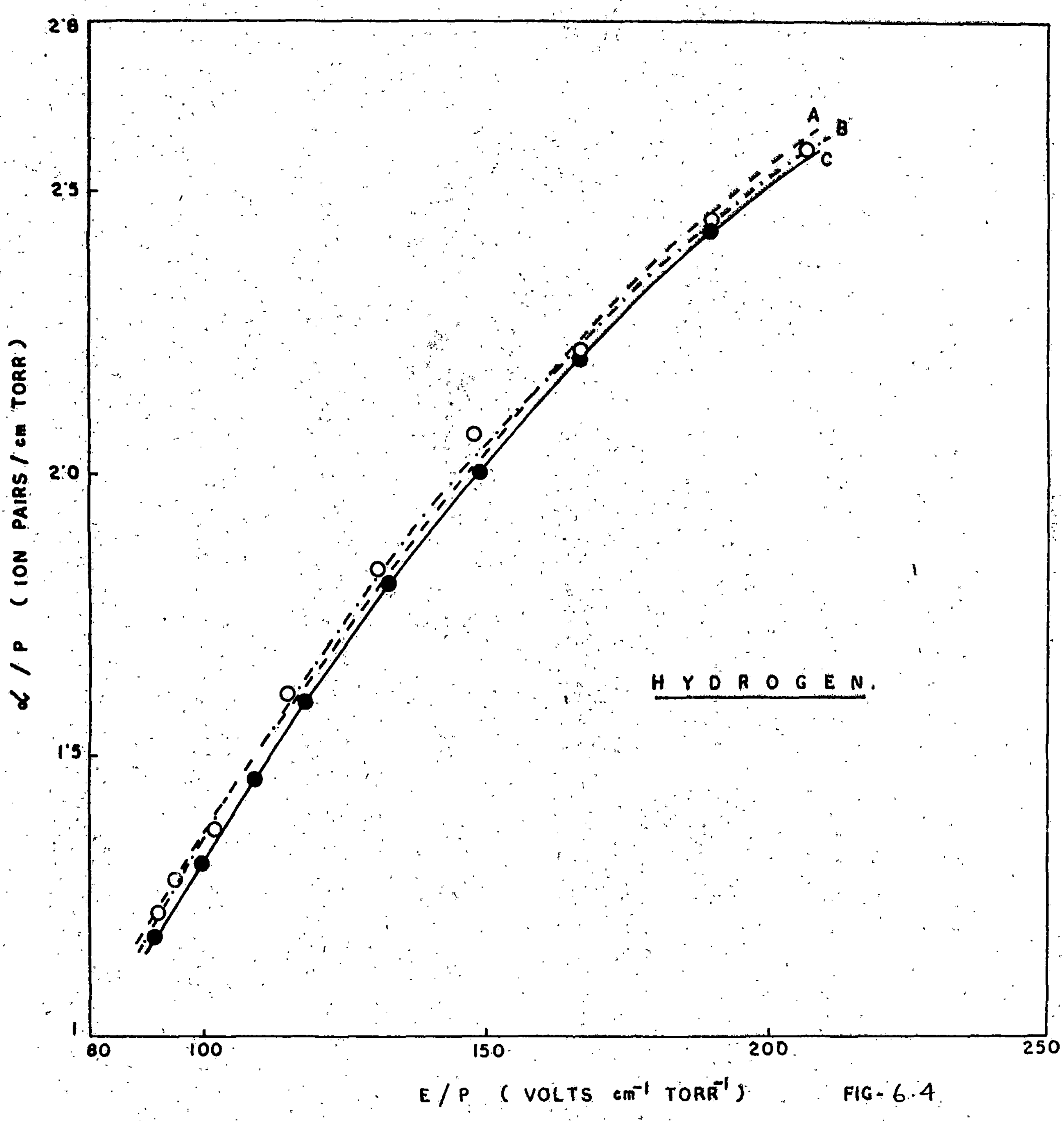
Similarly from Kihara's theory it can be shown that when attachment is taken into consideration

$$\nu - \nu_a = N \frac{3\sigma}{C_i} \frac{kT_e}{m} . \exp\left(-\frac{mC_i^2}{2kT_e}\right)$$

and hence

$$\alpha/p = \frac{\alpha_a}{p} + \frac{N}{p}\frac{\sigma}{C_i}\left(\frac{3\lambda}{p}\right)^{1/2} \exp\left[\frac{-mC_i^2 (N/p)(3\lambda p)^{1/2}}{2e\,(E/p)}\right] \qquad (6.4)$$

k

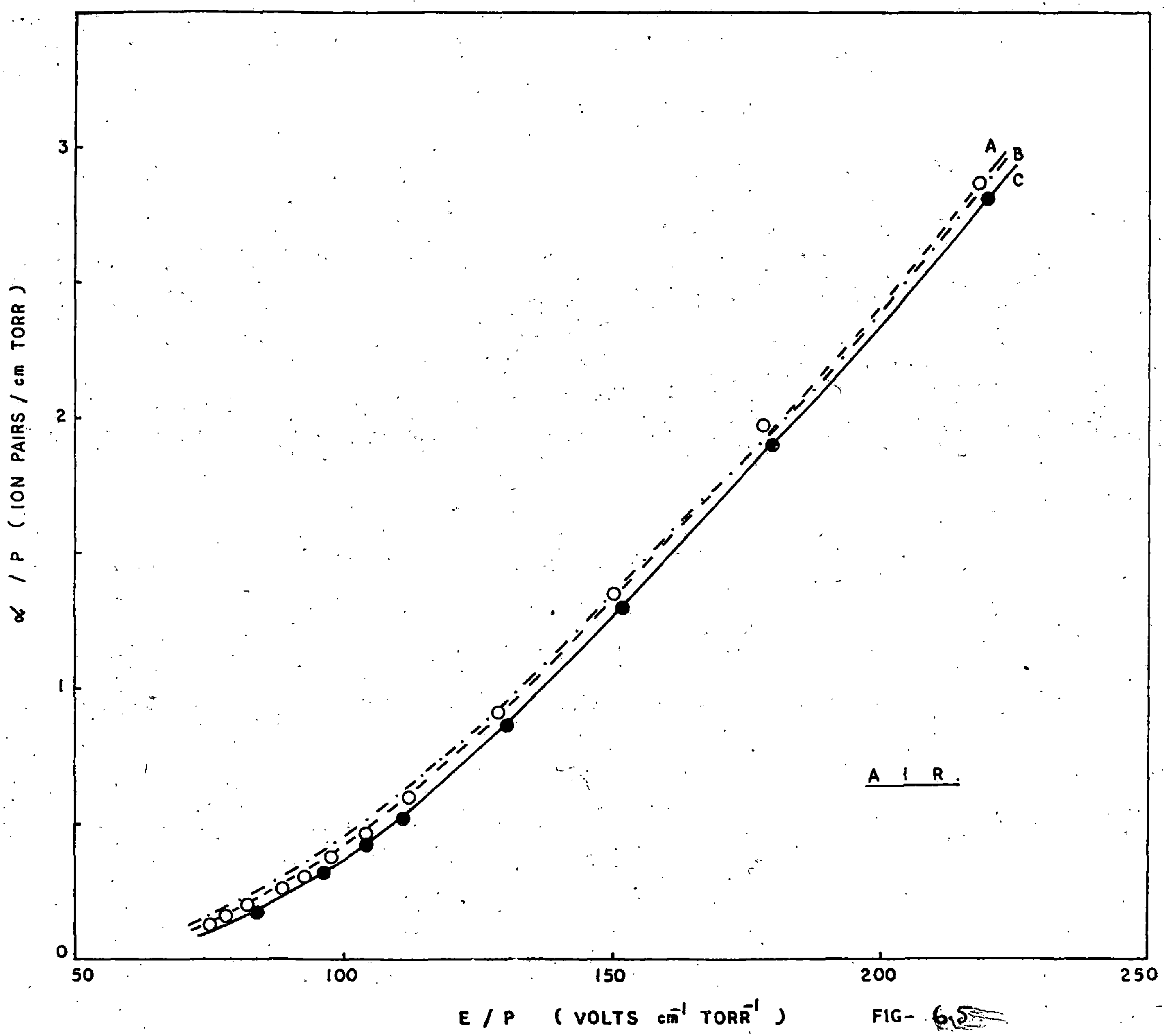


2·8
2·5
2·0
1·5
1
80
100
150
200
250
α / P (ION PAIRS / cm TORR)
E / P (VOLTS cm⁻¹ TORR⁻¹)
A
B
C
HYDROGEN.

FIG- 6.4

The values of (α_a/P) for air and oxygen for different (E/P) values have been obtained from (Brown, 1959) and (α/P) values have been calculated from equation 6.3, using experimental values of (E/P) obtained and also from equation (6.4) and then plotted in figures 6.5 and 6.6, for air and oxygen respectively together with values of obtained from literature.

It is thus evident that in case of all the gases studied here the values of (α/P) calculated from breakdown voltage are in fairly good agreement with the values of (α/P) obtained from literature for (E/P) values studied here. Further the results calculated from Borwn's expression are in better agreement than those calculated from Kihara's theory. This may be due to uncertainties in the values of molecular constants introduced by Kihara. We can further conclude that under the present experimental conditions and where the electwons are making a large number of collisions per oscillation, diffusion is the dominating cause for loss of electrons and the breakdown process is identical with the d.c. breakdown mechanism.



A
B
C
A I R.
3
2
1
0
50
100
150
200
250
α / P (ION PAIRS / cm TORR)
E / P (VOLTS cm⁻¹ TORR⁻¹)

FIG- 6.5

EFFECT OF MAGNETIC FIELD

Since in the above discussion we have concluded that under the present experimental set up and for the values of pressure and the frequency of the applied radio frequency field u sed, diffusion is the main electron removal process, the effect of an external magnetic field is to modify the breakdown mechanism to the same extent as it will modify the process of diffusion. As the diffusion perpendicular to the magnetic field is reduced, the breakdown field will show a reduction in value. The mean square displacement travelled by an electron is proportional to diffusion constant and Brown has shown that the effective diffusion length Λ_H appropriate to infinite parallel plate is given by

$$\Lambda_H = \Lambda \left[1 + \omega_B^2 / \nu_c^2 \right]^{1/2} \qquad (6.5)$$

where

$\omega_B = \left(\frac{eH}{m}\right)$ = cyclotron frequency.

ν_c = collision frequency at the pressure considered.

In the recent communication (Sen and Jana, 1976) we have measured the collision frequency of electrons in hydrogen, oxygen and air by the radio frequency conductivity method and the values at a pressure of 1 torr.

for hydrogen is 1.74×10^9

for oxygen is 3.58×10^9

for air is 3.222×10^9

In order to verify whether Brown's expression for the modified diffusion length is valid the values of Λ_H/Λ have been calculated for each gas separately for different values of H/P from 50 to 500 G torr^{-1}. To see whether these are consistent with the experimental values, Λ_H/Λ has also been calculated from values of E and E_H obtained experimentally. As has been shown that the discharge is diffusion controlled the breakdown criteria is given by

$$\nu/D = 1/\Lambda^2.$$

and

$$\frac{\alpha \mu E}{D} = 1/\Lambda^2.$$

where μ is the mobility

as $\mu/D = \frac{e}{KT_e}$, where T_e = electron temperature.

$$(\alpha/p)\,\frac{eEP}{kT_e} = 1/\Lambda^2$$

From Townsend's equation

$$\alpha/p = A_0 \exp\left\{-\frac{B_0}{(E/P)}\right\}.$$

and $$\frac{kT_e}{e} = \frac{L}{\sqrt{k}}\frac{E}{P}$$

$$= \gamma (E/p).$$ Von Engel (1955)

where $$\gamma = \frac{L}{\sqrt{k}}.$$

L = mean free path of the electron in the gas at a pressure of 1 torr

$$k = \frac{2m}{M}.$$

where m = mass of the electron

M = mass of the ion.

Hence $$A_o \exp\left(-\frac{B_o P}{E}\right)\frac{P^2}{\gamma} = 1/\Lambda^2.$$

or

$$E/p = \frac{B_o}{\operatorname{Log}[A_o P^2(\Lambda^2/\gamma)]}. \qquad (6.6)$$

where magnetic field is present if E_H = breakdown field for the same value of P.

$$E_H/p = \frac{B_o}{\operatorname{Log}[A_o P^2(\frac{\Lambda_H^2}{\gamma})]}. \qquad (6.7)$$

Hence

$$\frac{\Lambda_H}{\Lambda} = \left[\exp \frac{B_o P (E - E_H)}{E . E_H} \right]^{1/2} . \qquad (6.8)$$

From the experimental values of E and E_H the values of Λ_H / Λ for all the three gases have been obtained from equation (6.8) and entered in table 6.1, for H/P varying between 50 and 500 gauss torr^{-1}.

TABLE 6.1

THEORETICAL AND EXPERIMENTAL VALUES OF

FOR DIFFERENT (H/P) VALUES.

GAS	H/P gauss torr^{-1}	Λ_H / Λ (Theo.)	Λ_H / Λ (Expt.)
	78.57	1.008	1.038
	89.80	1.010	1.140
	181.8	1.042	1.232
HYDROGEN	250.0	1.077	1.293
	350.0	1.186	1.301
	533.3	1.317	1.342

TABLE 6.1 (CONTD.)

GAS	H/P gauss torr^{-1}	Λ_H / Λ (Theo.)	Λ_H / Λ (Expt.)
OXYGEN	61.1	1.002	1.031
	111	1.006	1.053
	160.6	1.008	1.060
	222	1.014	1.108
	285.7	1.024	1.079
	333.3	1.034	1.134
AIR	90.90	1.116	1.260
	111.1	1.169	1.167
	200	1.481	1.382
	250	1.682	1.793
	333.3	2.097	1.892
	371.8	2.263	1.982

From a comparison of the theoretical and experimental values it is evident that the values are more or less consistent with one another and lends additional support to the assumption that the loss of electrons under the present experimental set up is governed mainly by diffusion.

We further note that maximising equation (6.6) with respect to pressure, the pressure at which the breakdown voltage becomes a minimum is given by

$$P_{min} = \frac{2\,E_{min}}{B_o} \qquad (6.9)$$

and in presence of magnetic field

$$\frac{2(E_H)_{min.}}{(P_H)_{min}\left[1 + \frac{\omega_B^2}{C^2 (P_H)^2_{min}}\right]} = B_o \qquad (6.10)$$

where $(P_H)_{min.}$ = pressure at which the breakdown voltage becomes $(E_H)_{min.}$

and C = collision frequency at a pressure of 1 torr. From equations (6.9) and (6.10)

$$(P_H)_{min.} = \frac{P_{min}\frac{(E_H)_{min}}{E_{min.}} \pm \sqrt{P^2_{min}\frac{(E^2_H)_{min}}{E^2_{min}} - 4\omega^2_B/C^2}}{2} \qquad (6.11)$$

The values of $(P_H)_{min}$ thus calculated for the three gases for different values of the magnetic field are entered in table 6.2.

TABLE 6.2

THEORETICAL AND EXPERIMENTAL VALUES OF $(P_H)_{min.}$ FROM EQUATION (6.11)

Magnetic field in gauss	HYDROGEN		OXYGEN		AIR	
	$(P_H)_{min}$ torr (Theo.)	$(P_H)_{min}$ torr Expt.	$(P_H)_{min}$ torr theo.	$(P_H)_{min}$ torr Expt.	$(P_H)_{min}$ torr theo.	$(P_H)_{min.}$ torr Expt.
110	1.268	1.25	1.062	1.05	-	-
200	1.0792	1.09	0.9899	0.95	0.9661	0.99
400	Indeterminate	0.75	0.6534	0.66	0.6972	0.73
595			Indeterminate	0.45	Indeterminate	0.60

4. CONCLUSION

It is thus concluded that when the frequency of excitation is much smaller than the collision frequency, the major factor responsible for electron removal is the process of diffusion and this is also the dominating factor when the magnetic field is applied. The mechanism of breakdown becomes almost identical with d.c. breakdown of gases and the experimental results are in agreement with theoretical values calculated on the basis of these assumptions. It is further noted that equation (6.11) becomes invalid for values of magnetic field greater than 400 gauss which shows that deductions are valid for low values of magnetic fieldw which is also corroborated byx the values of Λ_H / Λ as shown in table 6.1.

5. REFERENCES.

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