SOME RECENT WORK ON DIFFUSION.[1]

II.

WE have seen that when steady diffusion is going on down a cylindrical column which is absorbent at the bottom there is a uniform diminution in the density of the diffusing substance from one end of the column to the other, evidenced in the case of a coloured substance by a gradual and uniform thinning out of the colour in the direction of the axis of the column. But in any horizontal cross-section of the column the colour is of the same intensity in all parts of the section, which means, of course, that the diffusing substance is of equal density along these planes.

In a diagrammatic section of such a column we should therefore represent the surfaces of equal density by straight lines drawn at right angles to the axis of the cylinder, and the stream lines of the diffusing substance by straight lines drawn parallel to the axis.

I am able to show you the horizontal lines of equal density in a cylinder, produced by a process of intermittent diffusion presently to be described.

When diffusion goes on into a flat absorbent disc, or aperture, instead of into a cylinder, it is clear that the stream lines of the diffusing substance must strongly converge towards the disc instead of moving vertically downwards as they do in the cylinder, and it is also clear that the lines or surfaces of equal density in the diffusing substance must form curved surfaces of some kind over the disc. We must now consider the exact form which these lines and surfaces will take.

It so happens that there is a problem in electrostatics which is analogous to the one before us, and it is one which has been fully worked out by mathematical physicists.

When an insulated conductor receives an electric charge the form taken by the surfaces of equi-potential around the conductor

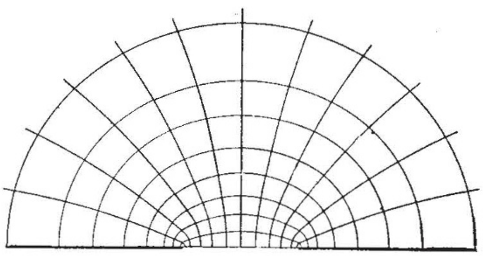

FIG. 1.

depends on its shape, and on the nature and distribution of other charges in its neighbourhood.

If we suppose the absorbing disc or perforation used in our diffusion experiments to be replaced by an electrified disc of similar dimensions, embedded flush in a wide non-conducting rim, then the surfaces of equal electric potential in the air above the disc will take the form represented in Fig. 1. The surfaces will form a series of hemi-spheroids which in any vertical section passing through the centre of the disc will give a series of ellipses, having their common foci in the edges of the disc. Faraday's lines or tubes of force, on the other hand, will in this case be represented by a series of hyperbolas, also having their foci in the edges of the disc.

Now we have every reason to believe that in a diffusion experiment with an absorbent disc the surfaces of equal density of the diffusing substance over that disc are the exact analogues of the surfaces of equi-potential over the similar electrified disc, and that the stream lines of the diffusing substance are the analogues of the lines or tubes of force. If this is so the diagram will equally well represent an experiment in which, for instance, the carbonic acid of perfectly still air is being absorbed by a disc of soda solution, surrounded by a wide rim.

Fig. 2 represents what we might expect to be the state of things when diffusion takes place through a circular aperture in a diaphragm. Here the stream lines of the substance, which are convergent as they approach the aperture, diverge again when the opening is past, and we should expect to get a double system of the ellipsoidal zones of equal density on either side of the aperture.

Did time permit I could show you that this hypothesis is not only capable of giving reasonable and consistent explanations of all the phenomena of diffusion into and through apertures, but completely explains the "diameter law," and also enables us to predict the amount of gas, vapour, or solute which will pass under given conditions, and the results can be verified by experiment.

I have only time to glance at one or two readily verifiable deductions from this hypothesis. In the first place, it fully accounts for what I have called the "diameter law," that is to say, that diffusion through circular apertures in a diaphragm is proportional to their diameters, not to their areas.

In two diagrams on the wall we have represented the arrangement of the equi-density curves and stream lines over two absorbent discs, one double the diameter of the other. We may take these discs to represent an alkaline solution absorbing carbonic acid from the air.

The two systems are on the same relative scale, but one is magnified by two diameters.

It will be seen that a curved line corresponding to any given actual density of the diffusing substance must be twice as far from the surface of the larger disc as it is from the surface of the smaller; that is to say, the *gradient of density* on which the flow depends is twice as steep over the small disc as it is over the large one. From this it follows that for equal areas the flow into the smaller disc is twice that into the larger and that the *total* flow must be proportional to the diameters, which is just what is found to be the case.

Wherever we get conditions favourable for the formation of a

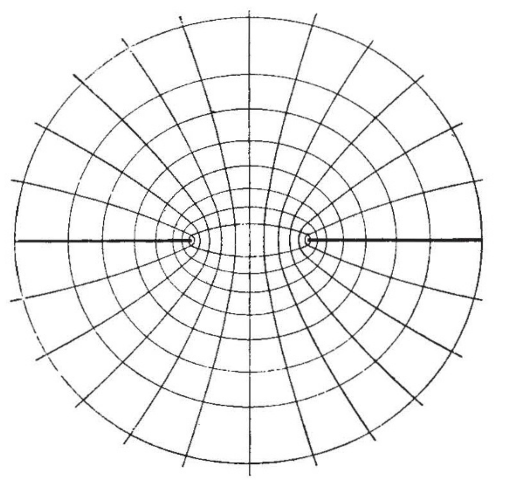

FIG. 2.

system of equi-density zones on one or both sides of a perforated diaphragm, diffusion will go on in accordance with this "diameter law." But one system of zones is quite sufficient for the purpose, so that in a case like that of Fig. 2, which represents the course of diffusion of atmospheric CO_2 in perfectly still air into an absorbent chamber, we might allow the outer system of equi-density shells over the aperture to be completely swept away by air currents, and still the "diameter law" would hold good on account of the inner series of zones, which, from their position, are protected from the air currents. This explains in a very satisfactory manner why it is much more easy to demonstrate the diameter law with apertures in a diaphragm than simply with absorbing discs, where only one external system of equi-density shells can exist, which is, of course, extremely liable to be influenced by disturbing currents.

Satisfactory, however, as this hypothesis is in explaining everything connected with these curious facts of diffusion, it must be borne in mind that the reasoning on which it is based is in part deductive and in part dependent on an analogy.

Nearly 300 years ago it was said by Sir Thomas Roe that "many things hold well in discourse, and in the theorique, satisfie curious imaginations, but in practice and execution are found difficult and ayrie."

Fortunately this does not apply to the present case, and I am able to bring before you this evening for the first time an experimental demonstration of the existence of zones of equal density in the neighbourhood of an aperture through which diffusion is

[1] Discourse delivered at the Royal Institution, Friday, March 22, by Dr. Horace T. Brown, F.R.S. (Continued from p. 174.)

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going on, and to show you that they have the exact shape which the theory requires.

I have here a rectangular glass cell divided horizontally by a thin plate of celluloid having a circular hole punched through it. The lower half of the cell is filled with a solution of gelatine containing a little barium chloride, and the upper half with a solution of sodium sulphate.

The relative strengths of the solutions are so adjusted that the two salts, diffusing in opposite directions, shall meet somewhere in the gelatine where a precipitate of barium sulphate is thrown down at the surfaces of contact of the two opposing streams of diffusion. The result is that we get a slowly growing, spheroidal mass of precipitate, starting from the aperture and resembling in shape the head of an inverted mushroom.

If we arrange for the diffusion of the sodium sulphate to be intermittent, or, better still, if we alternate the diffusion of a sulphate with that of a chromate, we get well-marked *zonings* in the precipitate forming the spheroid, zonings which correspond to the successive forms which the spheroid has assumed during growth, and which, therefore, must have been zones of equal density of the diffusing substances. We can study the forms which these assume in relation to the aperture by subsequently cutting sections through the gelatine, but by a little arrangement we can make the apparatus cut its own sections as the diffusion goes on.

This is done by making the aperture in the diaphragm *semi-*

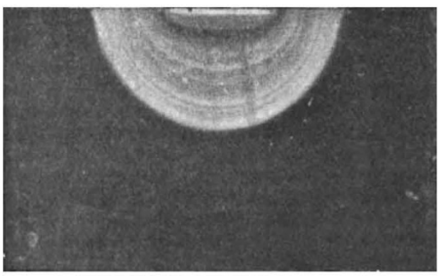

FIG. 3.

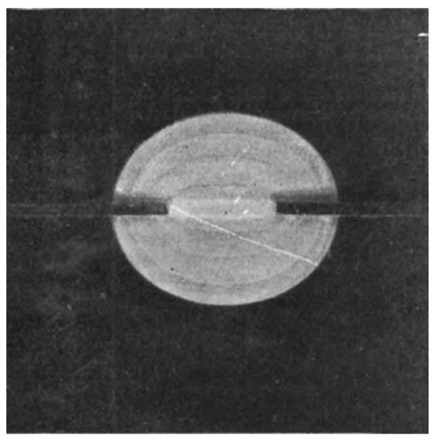

FIG. 4.

circular instead of circular, and bringing its straight edge close up to the side of the glass vessel.

I will now throw on the screen some photographs of vertical sections of spheroids of diffusion of this kind. (See Fig. 3 and Fig. 4).

On comparing the lines of equal density around the aperture with the diagrams on the wall you will at once see that their shape is exactly that required by theory—they describe a series of ellipses having their common foci in the edges of the aperture through which the diffusion is taking place.

The actual stream lines of the diffusing substance are not visible, but as these must necessarily be normal to the curves of equal density they can only be represented by a series of hyperbolas, also having their foci in the edges of the aperture.

The electrostatic analogy which has served us so well in determining the form of the zones of equal density around *single* apertures may also be used for predicting their distribution around a series of apertures in a diaphragm.

If we regard the individual holes in a multiperforate diaphragm as so many minute discs, all electrified to a common potential, the lines of equi-potential and the lines of force should take a form something like that represented in the diagram, Fig. 5, the lines of equi-potential forming complete ellipses in the immediate neighbourhood of the electrified discs, but gradually intersecting and forming a series of wavy lines, which become more and more horizontal as the distance gets more remote.

Could they be rendered visible these are also the forms which we should expect the lines of equal density of a substance to take when it is diffusing through a series of small apertures. I am

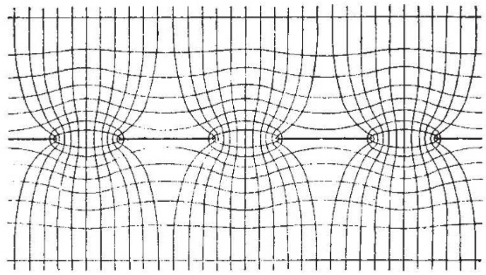

FIG. 5.

able to give you a verification of this by throwing on the screen photographs showing the result of intermittent diffusion through a series of such apertures (Figs. 6 and 7). The lines of equal density are marked out by the alternate bands of sulphate and chromate of barium as they were in the last experiment.

From the shape of these lines of equal density it is possible to determine the form of the stream lines of the diffusing substance and to show that the tendency of a multi-perforate septum of this kind is to locally increase the gradient of density in its neighbourhood and so to accelerate the flow through the small apertures. We get, in fact, a complete and satisfactory explanation of the small amount of obstruction which such a diaphragm produces when put in the way of a diffusive flow of gas or liquid.

Intermittent diffusion such as I have described may be used to illustrate in a variety of ways the distribution of electric potential around electrified bodies which are within the sphere of each other's action.

It is generally a difficult and laborious task to work out the distribution of the surfaces of equi-potential around electrified bodies which are near enough to influence each other. By this system of intermittent diffusion we may sometimes make Nature

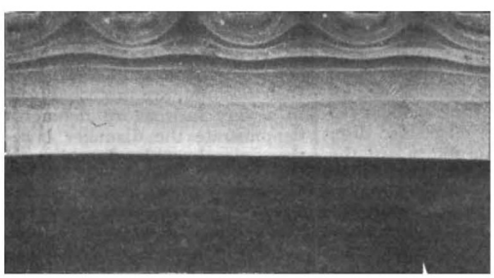

FIG. 6.

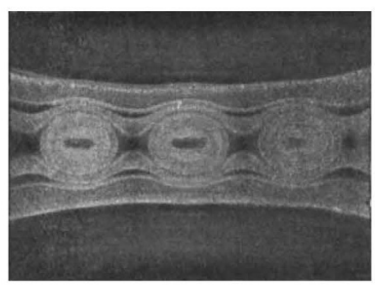

FIG. 7.

work out the problem for us. Here, for instance (see Fig. 8), is a figure copied from Clark Maxwell's "Electricity and Magnetism," representing the form which is assumed by equi-potential surfaces around two points charged with quantities of electricity of the same kind in the ratio of 4 to 1. If the analogy is

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correct diffusion, through apertures having their diameters in the ratio of 2 to 1 ought to give the same series of figures. You see from the photograph of an actual experiment given in Fig. 9 that this supposition is correct.

In Fig. 10 are given the calculated lines of force at the edges of two parallel plates, one of which is insulated and electrified, the other connected with the earth. These ought to correspond in shape to the equi-density lines of a substance undergoing steady diffusion from between two parallel plates, as, in fact, you see they do. (See Fig. 11).

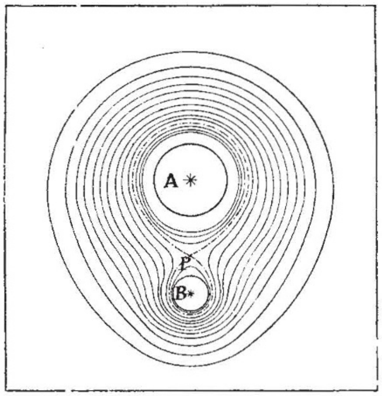

FIG. 8.

But considerations of this kind, although of interest in showing the striking analogies between certain phenomena of electrostatics and static diffusion, would carry me too far from my main subject, and I must again bring you back to the green leaf which was the starting point of my lecture.

If we regard the structure of the leaf from the new point of view which now suggests itself we can readily understand how it is that the stomates, notwithstanding the relatively small area of the leaf surface which they occupy, can drink in the atmospheric carbonic acid with such rapidity.

The finely perforated epidermis of the leaf, tightly stretched over the interior air-spaces, whose walls can absorb carbonic acid, constitutes a multiperforate septum which is under the most favourable conditions to produce an acceleration of the diffusive flow of the gas into the leaf.

The laws of gaseous diffusion through small apertures are now so well understood that we can predict with certainty the particular quantitative effect produced on a given diffusive flow by any screen with perforations of known size and distribution providing they are not within a certain number of diameters distant from each other. These deductions can then be verified by experimenting with small shallow glass cylinders, made absorbent inside, and closed at the top with very thin discs of celluloid perforated in a known manner. Such a piece of apparatus may be regarded as an artificial leaf, the perforated celluloid representing the epidermis with its stomates, whilst the absorbing solution of caustic soda acts the part of the assimilating centres.

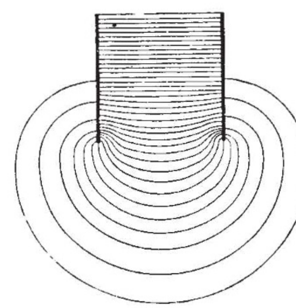

FIG. 10.

Having obtained confidence in the accuracy of the method of calculation we can then apply the same principles to determining the efficiency of the leaf stomates, when the whole system is regarded as a piece of mechanism for promoting diffusion.

In the first place it is found experimentally that the most economical arrangement of very small apertures is to have them set about 8 or 10 diameters apart, for at that distance the interference with each other practically ceases. *This is about the distance at which we generally find the stomates arranged on the underside of most leaves.*

You will remember that the amount of atmospheric carbonic acid which enters an assimilating leaf in an hour is about ·1 c.c. for every square centimetre of leaf. Now it can be shown tha for this amount of gas to enter through the stomates it is only necessary for the CO_2 content of the air just within the leaf to be kept down to 2·8 parts per 10,000, when that of the outer air is 3 parts per 10,000. This very slight difference in the partial pressure within and without is quite sufficient to account for all the entering CO_2, thanks to the special structure of the leaf.

Thus all the apparent difficulties in the way of accepting the

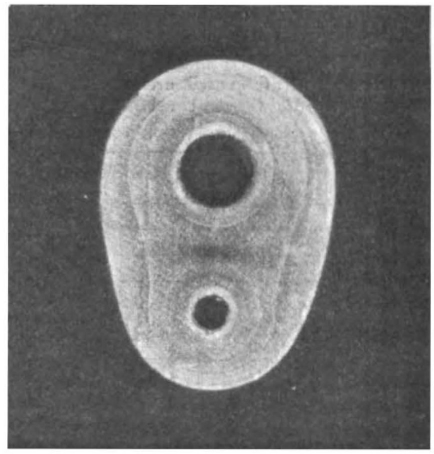

FIG. 9.

minute stomates as the sole pathways of gaseous exchange in the leaf entirely disappear when the leaf is studied in this new light, and it becomes evident that the adjustment of the mechanism of the leaf to the physical properties of its surrounding medium is far more perfect than has been hitherto suspected. The leaves of plants have, in fact, proved to be better physicist

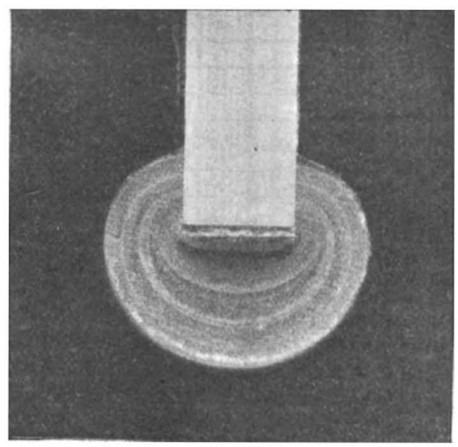

FIG. 11.

than we are, since their structure bears the impress of response to certain properties of gases of which we have hitherto been ignorant.

This is by no means the first occasion on which the plant has given us a lead in physics. The theory of dilute solutions, formulated by van 't Hoff, and indicating that the laws of Boyle and of Avogadro are as applicable to dilute solutions as they are to gases, had its origin in the observations of De Vries and of Pfeffer on the plasmolysis of living cells and the properties of natural semi-permeable membranes.

Nor can we doubt that there are many more such instances which only await detection, and we may reasonably hope that the boundaries of physics and of chemistry will be materially enlarged in unexpected directions if we pay due regard to the whispered hints and slender clues which are on all sides given by the living world of Nature.

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