XIV. *On the Formation of Definite Figures by the Deposition of Dust.*

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OWING to the kindness of Dr. W. J. RUSSELL, F.R.S., I received in June an advance copy of his paper on the above subject.* After reading this paper it appeared to me that all the figures illustrated in it could be explained on well-known principles. I shall therefore do what I can to fulfil the hope expressed by Dr. RUSSELL at the end of his paper that physicists from his descriptions may be enabled to explain their formation.

The formation of these dust figures appears to be due principally to three causes: (1) the convection currents set up by the hot plate; (2) to gravitation; and (3) to the repelling action of the hot surface. It seems trivial to remind the reader that gravitation plays a part in the formation of these figures, but it is to be feared that it is from not keeping the effects of gravitation fully in view that difficulty has been experienced in explaining them. It is principally owing to gravitation, or rather to an after-effect of gravitation, that no dust is deposited on certain parts of the plate. Gravitation acts on the dust under the plate as well as on the dust over it, thus causing the film of air flowing along the under surface of the plate to be dust-free, all the dust having fallen out of it. This dust-free film of air, after flowing along the under surface of the plate, turns round the edges and flows over the top surface, presenting its dustless side to the plate, and the air has to travel some distance over the top surface before the dust falls through the dustless film. That is, it takes some time for the upper current to undo the work of the under current, and the result is no dust falls on the plate till the current has flowed some distance from the edge. As stated, the third influence at work in the formation of these dust figures is the repelling action of the hot surface. It is well known that a hot surface tends to keep itself free from dust while surrounded by dusty air. The hot surface may in a manner be said to repel the dust, the action being probably due to the air next the hot body being warmer than the air at a slight distance from it, and the dust particles, being more strongly bombarded by the hotter air molecules on the one side than by the colder ones on the other, are driven away from the hot surface. The energy of this action will probably be the greater the quicker the temperature gradient in the air in a direction at right angles to the hot surface.

* 'Phil. Trans.,' series A, vol. 201, pp. 185–204.

The above principles seemed to offer the explanation of the dust figures, but as reasoning on physical phenomena should always be put to the test of observation when possible, I prepared apparatus to repeat Dr. RUSSELL'S experiments, and made arrangements for seeing the directions of the air currents and the condition of the air at the under and upper surfaces of the plate. For these experiments it was found most convenient to use small plates on which to deposit the dust figures. Metal plates were used, as they were easily prepared, and they were coated with black varnish to show the figures. To prevent any obstruction that might result from the use of three wire supports to rest the plate on, only one wire was used fixed in the centre of the plate. The plates were about 2·5 centims. square and 2 millims. thick. A thick plate is best, as it keeps its heat longest and gives time for observations to be made under fairly constant conditions.

The object of using small plates was that the observations could be made with a lens of greater magnifying power than was possible with large plates. An ordinary glass shade 12 centims. in diameter, made of thin glass, was used for confining the dusty air. A thin glass receiver has the advantage of being better made, the glass being of more even thickness than the thick glass ones, so enabling a more perfect image to be obtained by the lens. For illumination a narrow strip of incandescent gas mantle was hung over a Bunsen burner, exposing two thicknesses of the mantle to the flame. The Bunsen burner was enclosed in a lantern, the glass condenser of which was removed and its place filled with a globular flask of water. This had to be adopted, as the heat coming from, and through, the glass lens interfered with the formation of the figures. The gas mantle and flask were mounted at the same level as the plate, and a small hand lens was used to further concentrate the light, and by means of it the light could also be directed to any part of the plate where illumination was desired. The air was examined by means of a hand lens of as high a magnifying power as possible.

When making observations on the air currents, it was found in some cases to be an advantage not to use much dust, only as thick as might be called a haze, because when the dust is dense the beam of light illuminates by reflected light the whole interior of the receiver and makes observation difficult, whereas with few dust particles the illumination is confined to the part under investigation. In some cases it was found best to reduce the dust to such an amount that the individual particles of magnesia could be seen in the narrow illuminated area.

Turning now to the results of the observations made with this apparatus, the following points may be noted :—Bringing the light to bear on the under surface of the hot plate it is seen that there is a dust-free space below the plate, the dust in the film of air next the plate having fallen out and been repelled by the hot air above. This dustless film is seen to flow horizontally along the under surface, turn sharply round the edges of the plate, and flow horizontally over the top surface, no dusty air being in contact with the plate at any point when the plate is first put in and fairly warm

Fig. 1 represents the appearance of the plate at this stage. As the temperature of the plate falls, the rate of flow slackens and the repulsive action of the heat grows less, and at last a certain stage is reached when the current has become so slow that the under side of the dusty air comes close to the plate over the area where the

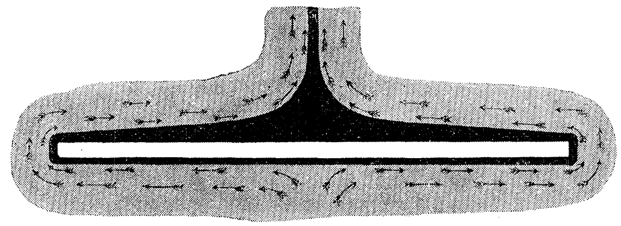

Fig. 1

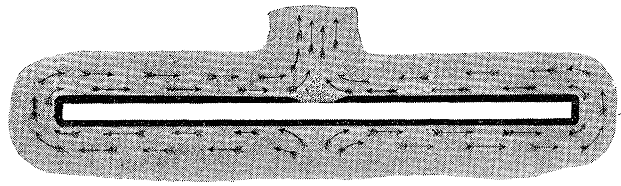

Fig. 2

currents meet, and as these currents here turn sharply upwards, there is a small space under their meeting point where the air is still and into which the dust collects and is seen showering down on the plate, as shown in fig. 2.

As these air currents rising from beneath all flow round the edges of the plate and move horizontally in a direction at right angles to the edges, they thus meet over the diagonals of the square; hence the deposition of the dust in Dr. RUSSELL's figures on the diagonal lines in his fig. 1 and on the lines bisecting the angles of the triangle in fig. 2 and the octagon fig. 3.* In fig. 4, for evident reasons, the currents here meet about the same angle as in fig. 1, and deposits take place on the lines bisecting the angles, but the stronger currents provided by the longer sides of the oblong plate prevent much deposit taking place where they meet in the centre of the plate. Further, in all these four cases, the currents meeting over the diagonals do not turn directly upwards, but flow also towards the centre of the plate, taking more or less of a horizontal movement along the diagonals, so tending to give time for the dust to fall. Further, when the currents have met and their direction has become partly vertical and partly horizontal, the repelling effect of the hot surface nearly ceases, as the temperature gradient perpendicular to the hot surface is in the rising current practically *nil*. The reason for the narrowing of the deposits as they approach the centre of the plate would appear to be due to the greater velocity of the currents where they meet over the centre of the plates caused by the union of all the currents from the different sides.

* Reference must be made to Dr. RUSSELL's paper for these dust figures, as they are not reproduced here.

The importance of the dustless film from the under side of the plate is evidenced by the fact observed by Dr. RUSSELL that no figure is obtained unless the plate be supported above the bottom of the receiver. When we examine by means of the beam of light the surface of a plate laid on the bottom of the receiver, we still find the dust-free film of air over the plate when the plate is pretty hot. This dustless film is very thin at the edges and thickens towards the centre, and a rising current can be seen flowing over it towards the centre, the rising current having a dustless core. This dustless film soon disappears as the temperature of the plate falls, and long before the plate is cold dust falls all over it, but no definite figures are formed.

Turning again to Dr. RUSSELL's figures, the effect of the velocity of the current is well shown in figs. 7 and 8. Fig. 7 was obtained with only a slight heating of the plate, and fig. 8 by a higher temperature. In the former figure the slow currents produced by the slight heating only kept the outside edges free from dust and allowed a large deposit to take place over the centre of the plate; while in the latter the higher temperature gave a current strong enough to prevent almost any deposit at the centre.

The cause of the extension in the breadth of the arms of the cross in Dr. RUSSELL's fig. 9, which was obtained by placing a hot cylinder some distance below the plate, is not so evident, but the probable explanation seems to be the following: When the currents are due to the hot plate alone the circulation is mostly horizontal from centre to edge below and from edge to centre above the plate, and the area where the currents meet is narrow, but when there is a hot body under the plate there will be an upward current all round it of hot air. This upward current will prevent the horizontal movements above described being so markedly horizontal, and will cause them to turn upwards at an easier curve, so broadening the dead dust-depositing area under the up-curving air.

In fig. 10 the extra deposit is probably due to some interference with the under air current produced by the piece of glass held under the plate. This subject will be referred to later.

Turning now to the effect on the figures of flames, &c., placed at a distance from the apparatus, as shown in Dr. RUSSELL's figs. 11, 12, and 13. These alterations in the figures appear to be due not to any direct effect of the flames, &c., on the dust or on the plate, but to the heat radiated by them heating the receiver and so giving rise to convection currents at the side of the plate. These currents entirely change the symmetrical flow of the air over the plate and cause the centre of the current rising over it to move to one side, as shown in figs. 11 and 12. When making observations with the apparatus described in this paper, it was not possible to get any of the figures quite regular; even the slight amount of heat given off by the small incandescent strip of mantle after passing through water interfered with the results, and air currents could be seen rising in the receiver on the side next the light. In support of this convection explanation, it may be further stated that the

same deformations as shown in figs. 11, 12; and 13 can be equally well produced by heating the receiver by means of the hand held on it.

Turning now to the results obtained by Dr. RUSSELL when the plate was rested on a hot cylinder of metal, as shown in fig. 14. Here everything is reversed; black centre and black diagonal arms where in the other figures it was white, and white to the edges of the plate where before it was black. How, it may be asked, stands the explanation now; where is the protecting effect of the dustless film from under the plate? For explanation let us turn to experiment. When the beam of light is turned on to this new condition of matters we find the air circulation is all changed. The dustless film from under the plate no longer turns round the edge and flows horizontally over the upper surface, but the large amount of hot air coming from the hot cylinder below the plate causes the dustless film to rise straight up from the edge, and an induced current of air is seen flowing over the plate from the centre to the edge, depositing its dust as it goes. It is only at the corners of the plate, where the mutual influences of the neighbouring currents and the amount of hot air is less, and where the currents approach and bring the dustless film over the plate, that there is any protection.

Both of Dr. RUSSELL'S figures, shown in figs. 9 and 14, were produced by somewhat similar conditions. In both cases a hot body was placed beneath the plate, but in the case shown in fig. 9 the hot cylinder was placed some distance below the plate and only heated to 55° C.; whereas, in the other case, the hot cylinder was at a temperature of 150° C., and the plate rested on it. Referring to fig. 9, Dr. RUSSELL points out that as the temperature of the body underneath the plate is increased the amount of deposit also increases, and ultimately the figure of the cross disappears; but, as will be seen from fig. 14, it reappears in a reversed form when the temperature is high enough and the plate rests on the hot body, all of which is easily understood by what has been said above.

Figs. 15 and 16 do not call for any special observation. Fig. 17 is interesting as showing the effect when the plate is cold and the currents are produced by an influence above the plate. In this case the currents flow over the cold plate towards the hot cylinder placed at the centre. As these currents do not come from the under side of the plate, they do not have a dustless film. So the plate has dust deposited all over it, but the figure of the cross can still be seen and is produced by the currents from the different sides flowing towards the centre, meeting over the diagonals, and causing the calm depositing areas as in the previous cases, only more feebly. In fig. 18 the white deposit round the cold cylinder is caused by the cold air flowing down the cylinder and forming a calm dust-depositing area round it.

The effect of placing the plate in a sloping position is shown in figs. 19, 20 and 21. These alterations in the forms of the deposited dust are evidently due to the slope of the plate interfering with the flow of the dustless film from underneath the plate and to the change produced by the slope on the currents over the upper surface.

Take, for instance, fig. 20. Here most of the air from beneath the plate flows to the higher edge and but little curves round the lower one, while the side streams keep about the usual strength. The current, however, round the higher edge being warmer and stronger than usual, does not flow to the centre of the plate, which is in a downward direction, but rises in an easy curve, with the result that over a large area of the plate the air is nearly motionless and the dust is free to deposit itself on the plate. In fig. 21 no dustless film seems to have come from the lower edge owing to the high angle of the plate, and all the hot air from the under side has flowed to the higher edge; where the rising current has been so strong it has curved in but little, and as the side currents are weak, as most of the hot air has flowed to the upper edge, the greater part of the plate is therefore exposed to the dusty air flowing over it from the lower edge.

The figure shown in fig. 22 seems to be due to the obstruction placed on the plate interfering with the regular flow and causing eddies and deposition of dust, while the dustless film enters the holes in the obstruction and, as usual, protects the surface in front of them over which they flow.

The curious effect of cutting a re-entering angle out of the plate, as shown in fig. 22A, is very interesting, and shows that the cutting out of that angular piece has in some way introduced new conditions which have interfered with the protecting action of the dustless film. Referring this to experimental observation, it is seen at once how this peculiar deposit is produced. The beam of light shows that the air streaming up through the angular opening does not turn over and flow over the plate but rises straight up, owing to the large quantity of hot air drawn to the one point. This upward-moving current induces another current over the plate moving towards it from the centre, and as this current flows slowly and is composed of dusty air without a dustless film, the particles settle out of it and cause the peculiar marking extending from the centre to the angular opening.

The next series of figures, from fig. 23 to 29A, produced by the action of a piece of glass, a pin, a hair, or other obstruction touching, or even near the edge of, the plate, are most curious and unexpected. On putting these conditions to the test of observation, it was seen that all these obstructions cause deposits to form by the interference they offer to the stream-lines of air moving over the surface of the plate. Where the obstruction cuts the stream the current is slackened, and more or less eddying probably takes place, enabling the dust to settle. What is seen when the air is examined with the lens while illuminated by a narrow beam of light is as follows:—While the beam of light is moved about on either side of the obstruction the air is seen to flow in well-defined stream-lines, the lower surface of the dusty air being distinct and clearly defined, but when the light shines on the air that has passed the obstruction, the upper limit of the dustless air has lost its definition. And further, if the beam of light were moved backwards and forwards, from one side to the other of the obstruction, it was observed that not only the upper limit of the dustless air on each side of the obstruction was well defined, but there was always a

greater thickness of dustless air on each side than opposite the obstruction. As the light travelled backwards and forwards the lower limit of the dust always seemed to dip just when the light was opposite the obstruction. As the plate cools, dust begins to fall behind the obstruction, while as yet there is a space of dustless air on each side of it. While it may be strange that so small an obstruction as a hair should produce these deposits, yet it is known that when stream-lines are interfered with, unexpected results frequently happen.

Figs. 30, 31 and 32 call for no special remarks, as these cases are explained in the previous paragraph, the deposits being due to the rough edges of the plates interfering with the stream-lines.

Fig. 33 is the same as fig. 23, already explained, only in the former the obstruction is placed on one of the diagonals, and not on the side of the square, as in fig. 23.

It seems unnecessary to consider in detail the other figures in Dr. RUSSELL's paper, which show the effects of different kinds of obstructions placed on or above the hot surface. The manner in which these figures are formed can be easily understood with the aid of what has been said. Only a few remarks may be made as to figs. 44 and 44A. When we examine by means of a beam of light the conditions in these two cases, it is seen that the dust-free film from underneath the plate rises and flows upwards past the edge of the top plate. In doing so, it seems to draw away with it some of the air from between the plates, with the result that a very slight negative pressure is established in the space between them. The beam of light shows that the upward current does not move in a straight line but curves inwards, drawn in by the lower pressure between the plates. The amount of this in-curving is least at the middle of the sides of the plate and greatest at the corners, the reason for this being that at the middle of the sides the air currents are stronger, as they contain more hot air than the currents at the corners, with the result that the weak currents at the corners are drawn more out of their course than the stronger currents at the sides. As the temperature falls the currents weaken, and at last the currents at the corners yield and the air is drawn in there and brings its dust with it, but its velocity being small, only the edges get any protection from the dust-free film and the dust settles on the plate before it travels far, giving the patches of dust shown in the corners of the plates in figs. 44 and 44A.

What perhaps surprises one most in the formation of these dust figures is the important part the dustless film from the under side of the plate plays in protecting the upper surface from deposits of dust; and we have seen that whatever tends to destroy this dustless film tends to bring about conditions favourable for the dust settling on the plate.

[*Note by* Dr. RUSSELL, *July* 23, 1903.—The interesting observations made by Mr. AITKEN by means of his exploring beam of light have contributed substantially to the elucidation of the dust-figures. It was, of course, clear from the first that the

agency was the currents of air creeping over the edge of the plate, the dust being deposited where the drift was slowest; but the sharpness of the patterns and the cleanness of the rest of the plate are made more intelligible by the existence of Mr. AITKEN's clear layer of drifting air through which the dust from above has to fall before reaching the plate. It will be observed that the explanation requires that the dust has had time to fall completely out of the layer when it was travelling underneath the plate, but has not had time to fall through it to any extent from above when the layer was above the plate. The thinning out of the clear layer in the wake of a pin or hair, owing to eddies or broken motion, as described by Mr. AITKEN, throws light on the features of the deposit thus produced by revealing that it is denser near the centre of the plate, because the dust has had more time to fall through this thinned-out layer of clean drifting air; yet the persistence of the effect when the obstacle is far removed from the edge of the plate remains very remarkable.]