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Surface Convection and Variation of Temperature near a Hot Surface

BY

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(Plates I, II and III.)

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ABSTRACT.

The paper is in continuation of the previous communication entitled "Theory of extremely high lapse-rates of temperature very near the ground." In Part I the nature of the turbulence near a hot surface is experimentally shown to consist of the upward incursions of very hot (dust-free) air near the plate and the downward movement of the colder air above. These movements are also suitably illustrated.

In Part II laboratory measurements of temperature above and below a hot plate are discussed. The variation of temperature with height both in the skin layer and in the surface layer agrees more or less with the theoretical expression derived in our previous paper.

The value of α in the surface layer is about 0·29 ; this is found to be 15 times that in the skin layer in the same experiments.

There also appears to be a "boundary layer" of the order of.1 mm. or so in thickness in which extremely low heat conductivity probably prevails. It is hoped to extend the temperature measurements into this layer to verify this point.

Introduction.

In a recent paper it has been shown that the temperature distribution very near the ground on a clear day under the steady conditions prevailing at the time of the diurnal maximum temperature can be represented by

$$\phi = \phi_0 \frac{\sinh \alpha(h-z)}{\sinh \alpha h}$$

where ϕ is the variable part of temperature, ϕ_0 is a constant, and h is the thickness of the "surface layer"; α is a constant equal to $\sqrt{\frac{16a\sigma\theta_0{}^3}{k}}$ involving the effective absorption co-efficient a of water vapour per centimetre and σ the Stefan Boltzman's constant; θ_0 is the absolute temperature, and k is the conductivity term due to convection processes.

In the present paper we confine ourselves to a discussion of results obtained from laboratory experiments. In Part I the nature of the convection process prevailing very near a hot surface will be discussed. In Part II it will be shown that the observed distribution of temperature near a hot surface is in fair agreement with the theory proposed by us in the earlier paper.

Further applications of the theory to actual meteorological conditions will be considered in a later paper.

PART I.

The mechanism of the conduction of heat upwards from a hot surface by means of surface turbulence.

The mechanism responsible for conveying heat upwards from a horizontal hot surface exposed to the atmosphere is not well understood at present. From observations on "shimmering" on a hot day one may conclude that there must be an interchange of hot air tending to ascend and cold air tending to descend. In a previous note this state of affairs was represented roughly by arrows pointing upwards to show hot ascending air and arrows pointing downwards to show the cold descending air.

FIG. 1.

A number of experiments were made in the laboratory to discover the actual phenomena involved in such a process. A plane sheet of iron B (see Figure 1), 1½ ft. by 4½ ft. was heated from below. As soon as the plate began to get hot shimmering was visible. A long glass tube A the lower surface of which provided a bright linear source of light when exposed to the sky-light near a window at a distance of 15 feet from the hot plate, was kept horizontal and adjusted so as to be very slightly above the upper surface of the hot plate. On viewing the illuminated lower surface of the glass tube from C in a direction almost parallel to the hot surface its mirage image could be seen distinctly. On carefully watching the reflected image it was found that the image A was wavy in form, the number of crests being more or less the same from time to time. Ordinarily, whenever there was the slightest movement of air across the space above the hot plate, a train of waves passed along the mirage image in the direction of the draught, but the cessation of any general drift of air did not cause the image to become straight. This shows that the waviness of the image is independent of any outside agency and that as long as the plate is hot the surface convection responsible for it will continue. The appearance of the straight object and its wavy mirage image is shown by the figures in Plate I which are photographs taken with a camera provided with telephoto attachment with exposures of the order of $\frac{1}{10}$ second. It may be noted that the undulations of the image correspond to simultaneous undulations of an equivalent plane which may be considered to be responsible for the mirage reflection. The size of an undulation above the plate is about 2 cms. It is clear that the deformation of the equivalent reflecting plane (which is a millimetre or so above the actual heated surface) must be due to some type of convection in which the heated air tries to break through colder layers above and the latter tries to take its place so as to complete the local circulation. In this connection it will be interesting to see the figures in Plate II which represent the steam figures obtained by spreading a thin layer of water on the hot plate. These discontinuous isolated columns in which the steam rises are indeed very suggestive.

An interesting observation was made while watching the steam figures. It was noticed that below the steam, and in contact with the hot surface was a dark space about 1 or 2 mms. thick which was free from steam and which persisted under all circumstances ; the upper boundary of this layer underwent fluctuations similar to those indicated by the mirage image (see Plate I). This observation together with the extraordinarily rapid fall of temperature noticed in the first few mms. above a hot surface suggested that one has to deal with fluctuations in the dark space observed in the steam experiment.

Our attention was drawn at this stage to the work of Tyndall,[1] Rayleigh,[2] Aitken,[3] Lodge[4] and Clark done between 1870 and 1885 on the region of warm dust-free air around hot bodies. Aitken performed numerous interesting experiments bringing out the essential features of this phenomenon. The

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[1] Tyndall, Proc. Roy. Inst., London, 6, 1 (1870).

[2] Rayleigh, Proc. Roy. Soc., Dec. (1882).

[3] Aitken, "On the formation of small clear spaces in dusty air," Trans. Roy. Soc., Edinburgh, 32, 239-272 (1884).

[4] O. J. Lodge and J. W. Clark, "On the phenomena exhibited by dusty air in the neighbourhood of strongly illuminated bodies, Proc. Phy. Soc., London, 6, 1-29 (1884). Also Phil. Mag., 17, 214-239 (1884). See also a recent note by W. J. Hooper on "the deposition of dust on walls," Physics, Vol. 1, No. 1, 1931 (July).

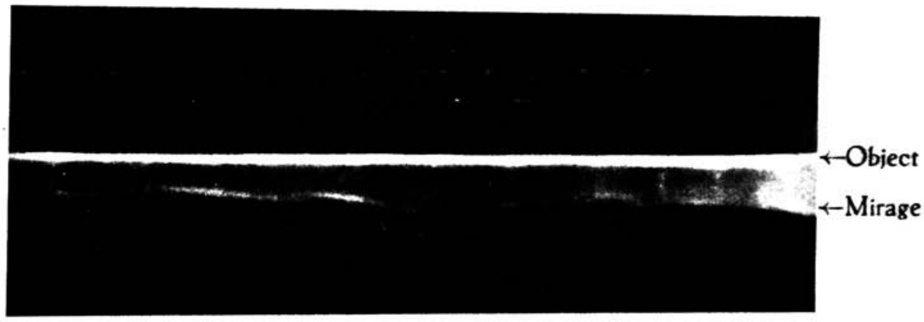

Fig. 1.

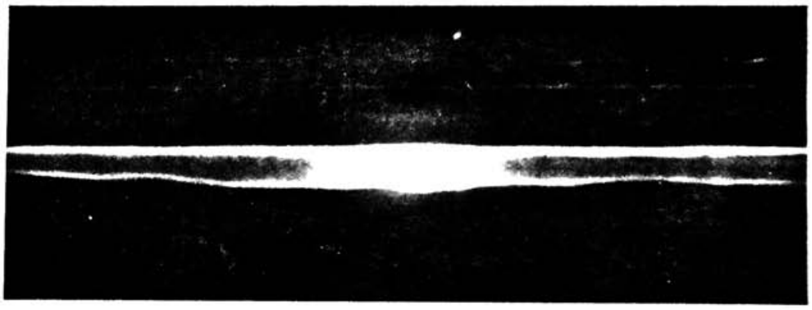

Fig. 2.

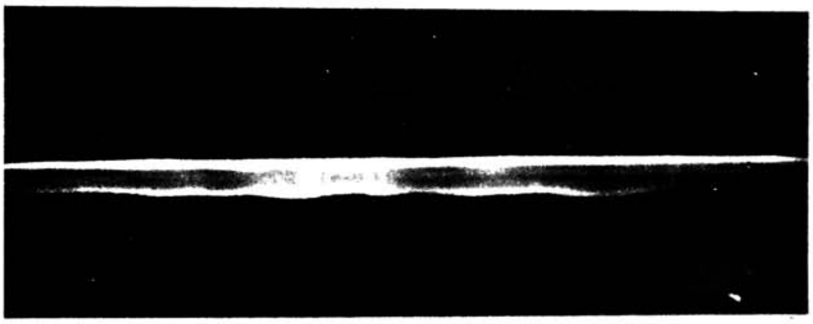

Fig. 3.

Fluctuations of the mirage reflecting plane over a hot plate.

general explanation of the phenomenon was given by Lodge. Briefly, the explanation is that owing to the very large temperature gradient near a hot body a dust particle receives less momentum by molecular bombardment on the side away from a horizontal hot surface than on the side facing it. This differential bombardment by molecules connotes a slight difference of pressure which ought to vanish in the steady state (*i.e.*, steady from a molecular standpoint where only molecular diffusion prevails). In all these experiments, however, a steady state is never reached as there is a continuous convection set up near the hot surface where fresh air is being continuously brought by the convection process and made warmer.

The explanation given by Lodge is qualitative. The whole phenomenon is being critically examined both experimentally and theoretically in order to see (1) whether it is molecular in origin and (2) whether there are any points of similarity to the "boundary layer" which is known to exist when a current of air is flowing past a solid surface.

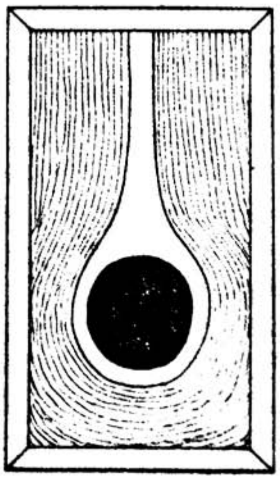

FIG. 2(a).

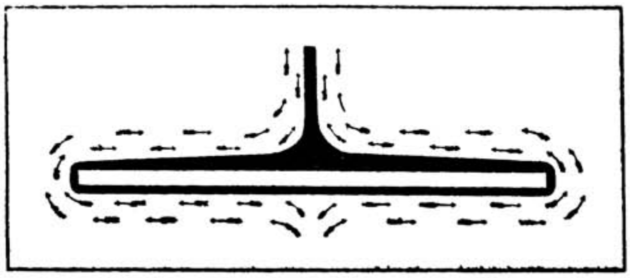

FIG. 2(*b*).

Fig. 2 (*a*) shows the appearance of the thin dust-free layer surrounding a hot sphere immersed in a dusty atmosphere. Fig. 2(*b*) shows what happens when a small heated plate is similarly exposed. These are reproduced here from the original figures given by Aitken. It may be noticed that in both cases the dust-free air ascends above the centre of the heated object like a wedge. Most of the previous workers seem to have used hot objects which had areas of the order of 2 or 3 centimetres square enclosed in observation chambers of small dimensions, as their object was to see the dark space in a steady or undisturbed state and to explain its origin. But very interesting results are obtained when the dimensions of the hot plate and its enclosure are of sufficiently large magnitude. Smoke from burning sulphur and ammonium chloride fumes are found suitable for making these phenomena visible. When the hot plate rests over an extensive surface to cut off the influence of the under side, the situation is no longer that suggested by Fig. 2(*b*). On illuminating the cloud of ammonium chloride or sulphur smoke by means of a condensed beam of sunlight, one begins to see that the dust-free hot air near the plate actually shoots up into not one, but several tongues of ascending air; these dark columns of hot air rushing up into the cold air above, extend several centimetres upwards, but while their base near the hot surface is 1½ to 2½ cms. broad, their width rapidly diminishes towards the apex.

PLATE II

Fig. 1.

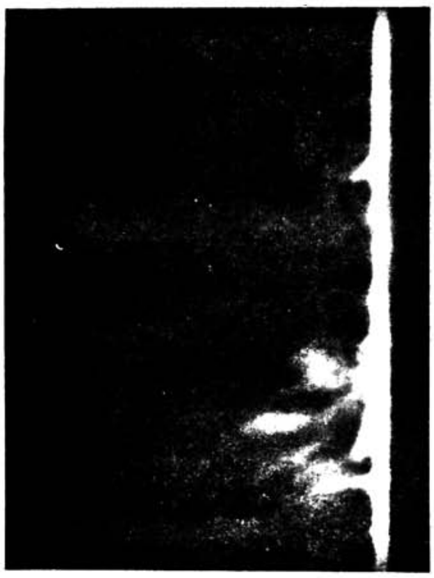

Fig. 2.

Fig. 3.

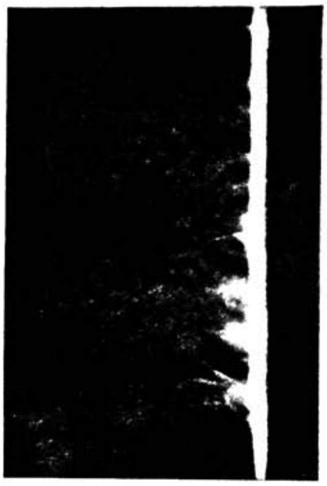

Fig. 4.

Stream figures over heated plate.

These dark columns are by no means stationary as in the experiments of Aitken or Lodge ; they develop and move about in a random manner with a tendency to drift with a general wind, if any, across the plate. The corresponding downward movements by the side of these hot ascending columns are not very distinct if the plate is large and there are numerous ascending columns ; if the experiment is repeated on a smaller scale it can be seen that, while the hot wedge thrusts itself upwards, two vortices also appear one on either side ; the direction of motion of these vortices is roughly as shown in Figure 3. It may be seen that while the motion in the smoky vortex is in the same direction as the ascending dust-free column of hot air adjacent to it, away from it the motion is downward. The detailed structure of the ascending and descending columns under controlled conditions is under investigation, but for our present purpose it is sufficient to note that the process responsible for the supply of heat from the hot surface to the upper layers is the ascent of the dust-free columns which are at any instant distributed above the plate in a more or less irregular pattern ; every ascent inducing or being accompanied by a descent of the colder air. The figures in plate III show a side view of this phenomenon. The photographs were taken with Gavart plates (speed 700) using sunlight for illumination with exposures of $\frac{1}{10}$ of a second.

FIG. 3.

The upward velocity in the ascending columns is found to be small near the surface, but rapidly increases a few centimetres above the plate. This was also observed in the steam figure experiments. On occasions when the up-streaming was sufficiently vigorous, one could even observe a series of vortices one above the other generated by the column on either side of it during its vigorous ascent.

One can easily visualise now what caused the undulations in the mirage reflection referred to previously and the shimmering round hot bodies. The fundamental nature of the skin layer cannot be over-emphasized in all these cases where instability between a heated layer below and a colder layer above is the cause of the observed phenomena.

It may be mentioned here that, when a vessel containing hot water is placed in the observation chamber, the skin layer and ascending columns of warm moist air are easily seen. There seems to be no essential difference from the phenomenon above a hot solid plate except that the ascending tongues convey not only heat but also moisture upwards. The variation of temperature and humidity over a surface of water is of great meteorological interest. The problem is therefore now under detailed investigation.

Phenomena below the heated plate.

We have so far confined our attention to the phenomena taking place *above* the hot surface. One cannot close this discussion without referring to what takes place *below* the heated plate, when the latter rests over suitable supports so as to expose the bottom surface to the air below. Here also the superheated dust-free layer of air is developed but, as there is no colder air mass above it, all that happens is a slow drifting of the hot air clinging to the underside of the plate as observed by Aitken (see Figure 2 *b*). There is practically no turbulence and the mirage image has no apparent

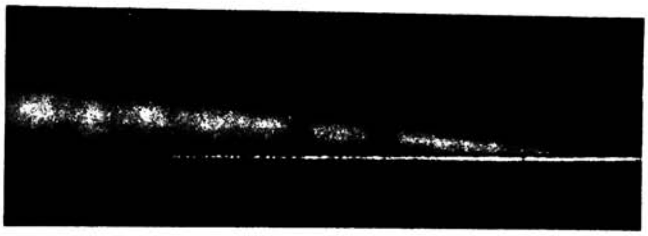

Fig. 1.

Fig. 2.

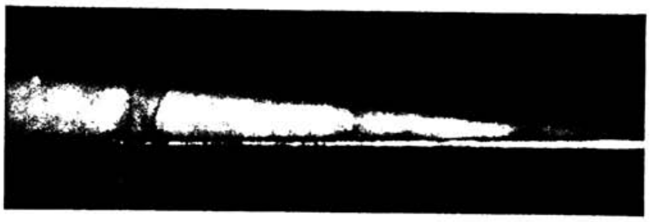

Fig. 3.

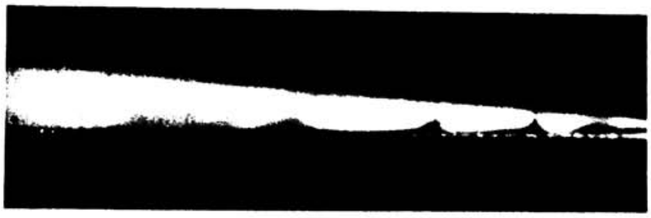

Fig. 4.

Dark space over hot plate and its incursions into the air above.

undulations as in Plate I. The dust-free air turns round the edges and later augments the supply of the superheated air above the upper side of the hot plate ; but, as shown by Aitken and others, the dust-free layer is itself not all manufactured at the bottom of the plate.

That the turbulent convection below a hot plate is very small or negligible is in a way well known ; for this is kept in view in all experiments on molecular heat conductivity of gases.

Questions relating to the discontinuous changes of conductivity while passing from the skin layer just above the hot surface to the "surface layer" which extends higher up to 20 or 30 cms. will be considered in the next part.

PART II.

Temperature distribution near a heated surface.

In this section we shall discuss the distribution of temperature in (1) the surface layer extending from about 1 cm. to 20 or 30 cms. above a hot surface, (2) the skin layer extending up to about 10 mms. above a hot surface and (3) the distribution of temperature in the stable and comparatively turbulence free layer below a hot surface.

Experimental arrangements.

These experiments were made above and below a steam-heated chamber 2 ft. square and 1″ thick made of galvanised iron and provided with suitable inlet and outlet tubes. The source of the steam with its heating arrangements was kept at a sufficient distance so as not to influence the temperature of the air near the experimental chamber; all radiation from the fire above which the source of steam was kept, was cut off by suitable screens. Two series of measurements were made; in the first series thermometers (Assmann spare thermometers) with the bulbs covered with a highly reflecting metal-foil so as to avoid heating by direct radiation from the hot chamber were used. In the latter series radiation-proof (*i.e.*, silver coated) copper constantine thermal junctions of very small size (about 1 mm. in size) were used, with one of the junctions kept at 60°C. and the other junction at various heights above or below the experimental chamber. To give the temperature readings a calibrated unipivot galvanometer was kept in the circuit. It was found that the results obtained by the two methods gave more or less concordant results. In the first series, owing to the larger size of the thermometer bulbs the skin layer could not be investigated.

Observations in the surface layer.

Fig. 4 shows the distribution of temperature in the surface layer. The crosses are the observed values and circles the theoretical values calculated from the expression

$$\theta = \theta_0 + \phi_0 \frac{Sinh\ a\ (h-z)}{Sinh\ ah}.$$

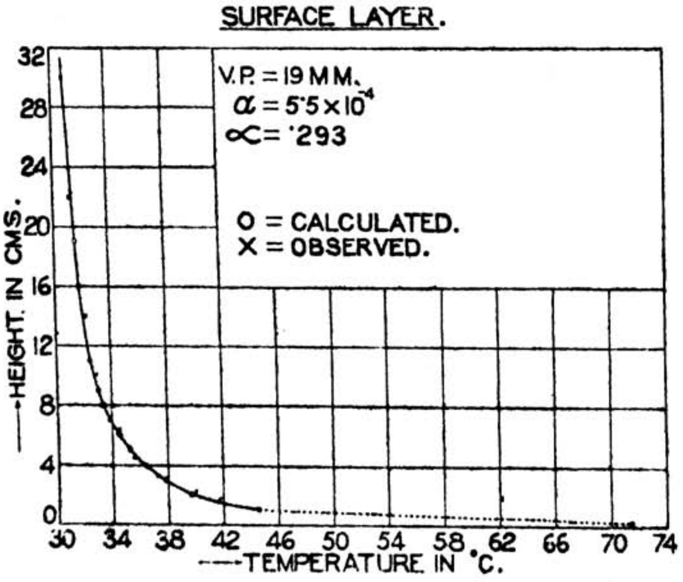

FIG. 4.

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It may be noted that the value of a is found to be ·29. Several series of observations confirm these values.

It is interesting to compare these results with those obtained above the road. In this case a was ·26.

It was thought that variations in the temperature distribution arising from variations in the water vapour content from day to day could be determined from the laboratory experiments. Unfortunately the observed variation of the water vapour content as well as of the temperature distribution were too small to be detected. For example the largest variation of the water vapour pressure was from 10 mm. up to 30 mm. From

$$\beta = \sqrt{\frac{16\ a\sigma\theta_o{}^3}{k}}$$

it will be seen that we are dealing with the square root of the effective absorption co-efficient of water vapour for long waves. It is hoped to study the influence of a by further experiments inside chambers where the humidity can be altered at will by larger amounts than is possible in the open.

Observations in the skin layer.

Fig. 5 shows the distribution of temperature in the skin layer. Here the heights are given in cms. It will be noticed from the more microscopic standpoint adopted in this figure, that the height-temperature curve has an appearance somewhat similar to the corresponding curve for the surface layer.

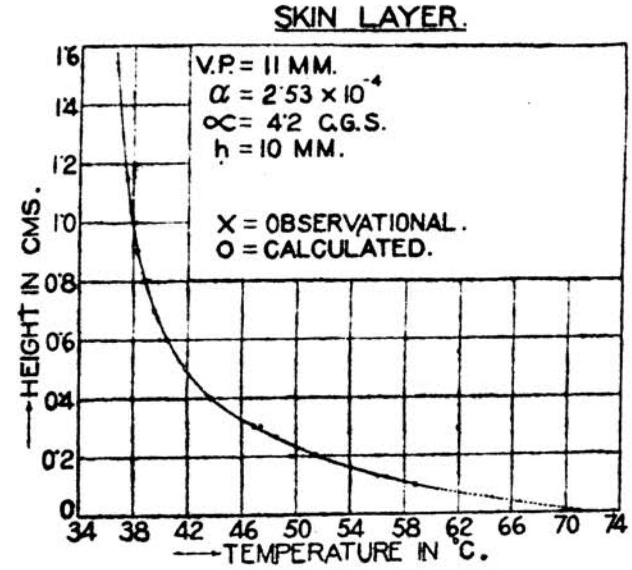

FIG. 5.

The actual observations on the skin layer show that the surface turbulence is least intense in this layer. It is found that on applying the theory for the surface layer to the skin layer, it is possible to explain the observed temperature distribution in the layer extending from 1mm. to about 10 mms. above the hot surface with the value of $\propto = 4{\cdot}2$. In the figure the crosses represent the observed values and the circles represent the theoretical values. It will be noticed from figures 4 and 5 that there is an abrupt transition from the low value of a in the surface layer to a much larger value in the skin layer; this is quite consistent with visual observations of the turbulence near the surface. We hope to show by temperature measurements in the 1st mm. that the skin layer falls off to a quiet " boundary layer " in which extremely low heat conductivity probably prevails.

Observations below the hot plate.

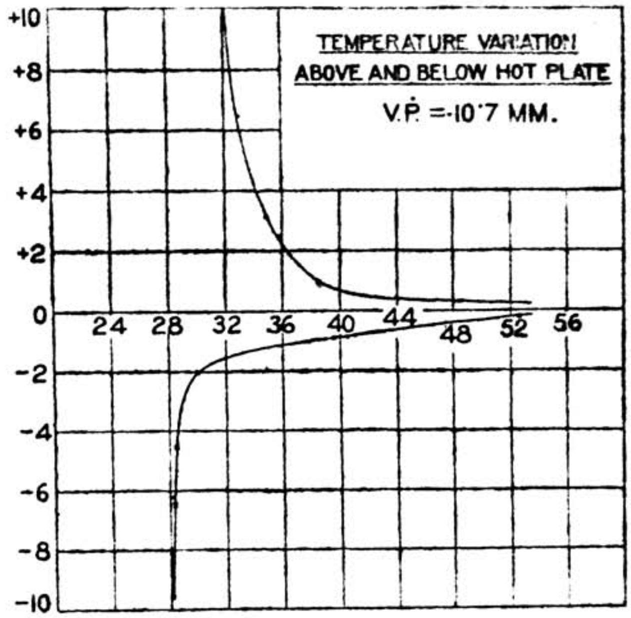

FIG. 6.

Fig. 6 shows the distribution of temperature above and below the hot plate. While the curve above is showing the usual gradual change above the hot plate, the curve below shows the large fall of temperature in the skin layer later changing rapidly to a fairly constant value.

In conclusion we wish to express our thanks to Dr. C. W. B. Normand, Director General of Observatories for giving us necessary facilities for the experimental work.