CONVECTIVE PHENOMENA NEAR A HEATED SURFACE

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1. Introduction

A critical study of the phenomena near a heated surface is of fundamental interest to the physicist as well as the atmospheric physicist or the meteorologist. The convection pattern above a hot plate tells us much about the nature and origin of the instability of the air layers above the insolated ground in relation to the vertical gradients of air temperature, density, vapour pressure, etc. On the other hand, below the hot plate, conditions are obviously stable and, with suitable experimental techniques, it is possible to investigate the phenomenon of thermal repulsion which is molecular in origin.

The bibliography (Nos. 1 to 36) appended to this paper gives a list of papers on these topics published by the present writer and his collaborators during more than two decades after 1930. Some of these investigations deal with the meteorology of the air layers near the ground or micrometeorology corresponding to what may be called phenomena " *above* the hot plate ". We have also carried out numerous studies on the phenomena which may be grouped under the " below the hot plate " type.

Professor K. R. Ramanathan, while he was working at the Meteorological Office, Poona, was much attracted by these investigations of ours. The present writer, therefore, takes this opportunity to dedicate this brief review to him on the occasion of his 60th Birthday.

In what follows we shall present a very condensed review of the results achieved so far and then describe further investigations now in progress.

2. Phenomena Very Close to a Hot Surface

If a small heated[1, 2] plate, say about 2 inches square, is suspended horizontally at the centre of a box with glass windows the air inside which is rendered smoky and the space above and below the surface examined under suitable illumination, one observes that immediately near the hot surface there is a thin film of dust-free air which looks dark. The thickness of the dark layer is uniform and comparatively small, of the order of 1/10 mm. or so, below the plate. Above the hot plate the thickness of the dark layer increases near the centre where it ascends as a pillar or tongue or rising column with rapidly decreasing cross-section. The general appearance of the dark layer and the movement of the smoke particles is as shown in Fig. 1 (*a*).

This pattern remains fairly steady both above and below the hot plate. If the hot plate is made quite extensive, say one foot or more square, the appearance *below the plate* remains steady as before, but conditions *above the plate* become very much more lively and fascinating. The dark layer, which really represents the hottest air close to the plate, now ascends, not in one steady dark pillar as in Fig. 1 (*a*), but at a large number of places as ascending tongues of hot air rushing up into the colder air above, extending several centimetres upwards. While the base of the ascending tongues near the hot plate is 1½ to 2½ cm. broad, their width diminishes rapidly upwards. These ascending columns develop and move about in a random manner, sloping with the wind, if any, across the plate. The appearance at any instant is shown in vertical section in Fig. 1 (*b*) where H, H,.... represent the rising hot air filaments and C, C, C, etc., the compensating downward movements of the colder air from above.

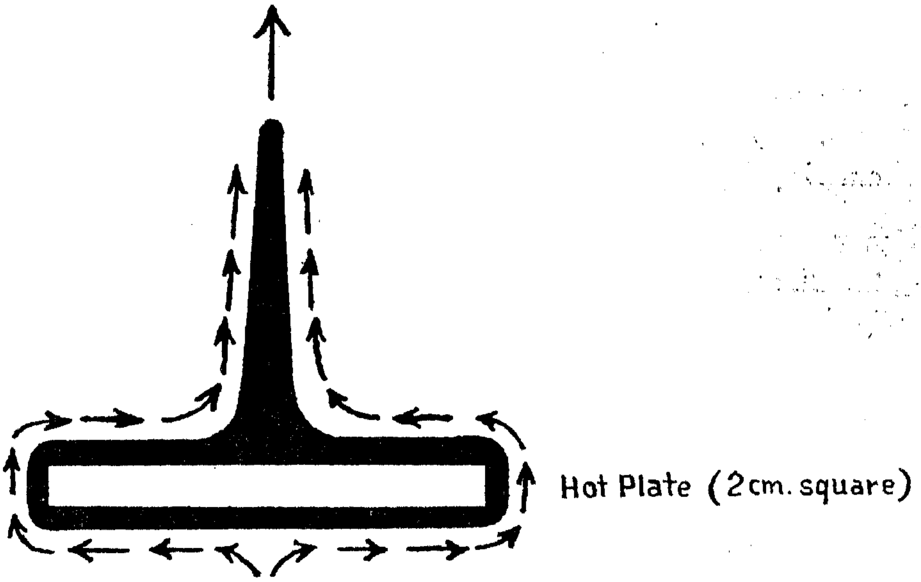

FIG. 1 (*a*)

Fig. 1 (*b*) shows how the dark layer is in unstable equilibrium with the colder layers above it so that it breaks through the cold air, producing also the compensating downward currents of cold air.

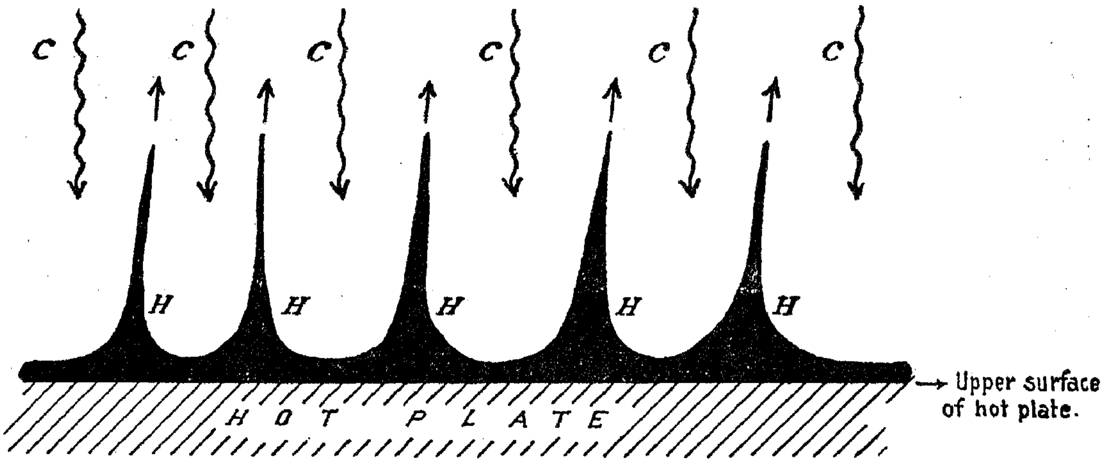

FIG. 1 (*b*)

Even when there is wind (horizontal), this pattern is not wiped off, but is only inclined in the direction of the general air movement.

It will be obvious that the picture shown in Fig. 1 (*b*) really represents what happens above the heated ground during the day-time. This special type of convection is responsible for the well-known " shimmering " of distant objects when they are viewed through the air layers near the ground during a clear day with strong insolation. Indeed, we may call this layer the " shimmering layer ".

We may now continue the examination of the " shimmering layer ", reserving the discussion of the phenomena " below the hot-plate " for a later section of this paper.

3. THE SHIMMERING LAYER AND SOME OF ITS SPECIAL FEATURES

(*a*) *Enormous Temperature Lapse Rates.*—From the hot surface the temperature falls very rapidly with height at first and less and less rapidly as one moves away further and further.[3] Using an interferometric technique it has been shown[11, 14] that within the layer of a millimetre or two nearest to the surface, the variation of temperature is most rapid, but sensibly linear. This is the layer too which develops inferior mirages.[2, 3]

As an example of the variation of temperature and lapse-rate with height above bare ground we have Table I which gives the mean daily values recorded during April 1950 at the maximum temperature epoch at the Central Agricultural Meteorological Observatory at Poona.

TABLE I

Variation of Temperature °C. and Lapse-Rate in Degrees per Kilometre at the Maximum Temperature Epoch at the Central Agricultural Meteorological Observatory at Poona, April 1950

Height above-ground in centimetres	Temperature ° C.	Lapse-rate in °C. per kilometre
0	63·8	$2\cdot02\times10^6$
1	43·6	$7\cdot33\times10^4$
2·5	42·5	$2\cdot60\times10^4$
7·5	41·2	$1\cdot33\times10^4$
15	40·2	$5\cdot33\times10^3$
30	39·4	$2\cdot00\times10^3$
60	38·8	$1\cdot67\times10^3$
90	38·3	$1\cdot33\times10^3$
120	37·9	$5\cdot00\times10^2$
180	37·6	$5\cdot00\times10^2$
240	37·3	$1\cdot67\times10^2$
300	37·2	$1\cdot67\times10^2$
360	37·1	$1\cdot11\times10^2$
450	37·0	$2\cdot00\times10^2$
600	36·7	$1\cdot33\times10^2$
750	36·5	$6\cdot06\times10^1$
900	36·4	

Note that the lapse-rate can be about 2,00,000 times the adiabatic lapse-rate just above the ground and that it decreases very rapidly with height attaining a value of the order of only 6 times the adiabatic lapse-rate about 8 metres above ground.

(*b*) *Fluctuation of Temperature in the Shimmering Layer.*—A sufficiently sensitive temperature recording element will record a fluctuating temperature if placed in the shimmering layer. Using extremely small thermocouples of copper and constantan (45 S.W.G.), one of them kept in a bath at a standard temperature and the other inserted in the position of the thermometer in the smaller-sized Assmann Psychometer, connected to a sensitive Mill-Galvanometer with a period of $\frac{1}{6}$ second, it has been possible to record practically instantaneous values of air temperature at intervals of a few seconds. After aspirating the psychrometer, a series of 50 readings was taken at 10 second intervals at various levels above ground up to 35 feet, at the Central Agricultural Meteorological Observatory at Poona. After smoothing, so as to eliminate long-period or slow changes, values of (i) the mean temperature, (ii) the standard deviations of short-period fluctuations and (iii) the highest and lowest temperatures recorded at each of the levels were calculated. The values obtained at the maximum temperature epoch on the 6th January 1942, a typical clear day, are plotted in Fig. 1 (*c*) the height scale being logarithmic. XX and NN are the highest and lowest temperatures, while MM shows the mean temperature. AA and BB show

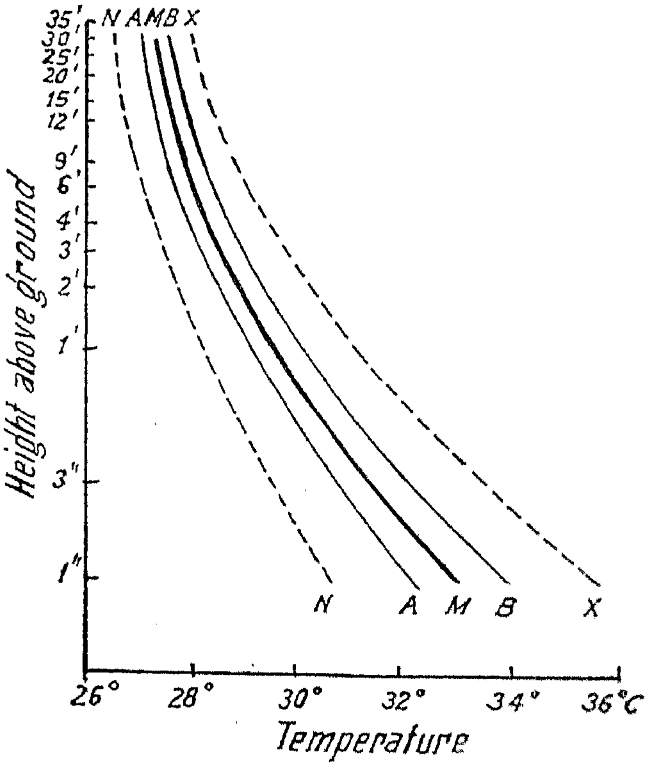

FIG. 1 (*c*). Fluctuation of air temperature at different levels above ground during the interval 1430 to 1530 hrs. I.S.T. on 6th January 1942. Heights above ground in inches″ d feet′.

the mean temperature "minus" and "plus" the standard deviation respectively. The rapid variation with height in the amplitude of the temperature fluctuations within the "shimmering layer" is shown clearly in Fig. 1 (*c*). On plotting the standard deviation against the logarithm of the height it is found that the points all practically lie on a straight line which cuts the height axis at a point corresponding to about 170 feet above the ground. This shows that at the maximum temperature epoch the shimmering layer extends up to 150 or 200 feet above ground. The above method provides an easy method of estimating this height from observations near the ground.[18, 19]

Krishna Rao, at present working in our laboratories, has succeeded in photographically recording the fluctuations with the aid of a quick-run Moll Recorder. The temperature is recorded with a 40 S.W.G. Copper-Constantan thermocouple coated with magnesium oxide and exposed at various levels above ground (Central Agricultural Meteorological Observatory) and connected to the same sensitive Moll Galvanometer referred to above. Using this technique, Rao is studying the characteristics of these fluctuations and their variations with height above ground as well as with time of the day. These results will be discussed in detail in a later paper.

Fig. 2 shows some typical two-minute records at various heights above ground and at 0630 hrs. (minimum temperature epoch), 1000 hrs., 1400 hrs. (maximum temperature epoch) and 1700 hrs. on the 16th of November 1952. Near each record the mean temperature in degrees centigrade is recorded. The fluctuations of temperature are very slight or feeble at all levels at the minimum temperature epoch (0630 hrs.), but there is a slight increase with height up to 4 or 5 mm. above ground and a rapid decrease thereafter; the fluctuations being negligible above 5 cm. level.

Some time after sunrise the temperature is rising rapidly and the records obtained at 1,000 hrs. clearly show that the shimmering pattern is developing rapidly and has already grown to a level beyond 9 metres. The next series of records relate to the maximum temperature epoch (1400 hrs.). Here the amplitude of the fluctuations is relatively greater than before at all levels. The variation with height both at 1000 hrs. and at 1400 hrs., however, bring out some very interesting features. The amplitude of the fluctuations is least at the ground surface and increases rapidly with height up to a few mm. (say 3 mm. at 1000 hrs. and 1 cm. at 1400 hrs.), attaining a maximum value. The amplitude of the fluctuations decrease thereafter with height as indicated in Fig. 1 (*c*).

A reference to Fig. 1 (*b*) will show that up to a few millimetres above ground the temperature measuring element will be more often than not within the dark layer and will begin to be influenced by both the uprising hot and the down-coming cold currents of air only at some distance above the ground. The amplitude of the fluctuations will, of course, depend also on the contrasts of temperature in these air currents.

From the last set of records at 1700 hrs., the rapidity with which the upper limit of the shimmering layer sinks downwards towards the ground, and the decrease in the amplitude of the thermal fluctuations will be quite clear.

A fuller discussion of these results will be presented elsewhere.

Y. D. Altekar[10] working in our laboratory is engaged in building an electronic variance-meter designed by him for recording the sums of squares of fluctuations of air temperature, humidity or wind velocity. When completed this equipment will provide another useful tool for these investigations.

(*c*) *The Shimmering Layer in Relation to the Growth and Decay of Thermal Inversion during Clear Nights.*—The upper limit of the shimmering layer extends upwards beyond 200 feet (about 60 metres) at the maximum temperature epoch and thereafter comes down rapidly towards sunset. In tropical and sub-tropical and lower temperate regions, during clear nights with light or no air movement, the shimmering layer about a foot or less in thickness is found to persist throughout the evening and night. The coldest air is therefore at some distance above ground at the top of the shimmering layer which, of course, is a layer of " lapse " (or temperature decreasing with height).[4-8]

The investigations at Poona show that in an open space with bare ground the nocturnal inversion layer begins forming some time before actual sunset. Its lower boundary merges into the upper boundary of the shimmering layer which also begins to contract. The upper boundary of the shimmering layer indeed approaches the ground rapidly about sunset and within a short time after sunset attains its minimum height, about a foot or so above the ground; thereafter, it remains at this level, more or less, during the rest of the night and until insolation sets in next morning when it grows rapidly again. The transition between the developing inversion and the upper boundary of the shimmering layer is a region of zero temperature gradient and may be called the " lower isothermal layer ". This layer moves *downwards* in the evening about sunset and *upwards* in the morning after sunrise.

It may be observed that while the base of the " inversion " layer is associated with the top of the " shimmering layer " in the manner described above, the inversion layer itself builds up during the night, growing in thickness. Its upper boundary merges into the " upper isothermal layer " above which again there exists a layer with a lapse or decrease of temperature with height. Thus the inversion layer near the ground is cushioned, as it were, between two layers of lapse, one of which, the lower one, is the remnant of the shimmering layer and the other is the free atmosphere above in which also temperature decreases with height. The rise of temperature with height within the inversion layer is quite pronounced.

The growth of the inversion layer during the night and its destruction after sunrise have been investigated at Poona in some detail. While the psychrometric readings of air temperature up to 35 feet (with the aid of the observatory tower) taken at short intervals of time provide adequate information about the base of the inversion, the behaviour of its upper boundary has been investigated recently with tethered radiosonde instruments of the F. Type constructed by the Instruments Division at the Meteorological Office, Poona.[37, 38, 39] The actual instrument used in our experiments had a more open temperature scale than the standard instruments used for upper air investigations. From these observations recorded at the Central Agricultural Meteorological Observatory on the 25–26th November and 28–29th December 1949, it is observed that by 2200 hrs. the thickness of the inversion layer is of the order of 100 metres, increasing to 200 metres by 0300 hrs. and to 250 metres just before sunrise, on the next day. These results will be discussed elsewhere, but it is clear that at Poona the layer can grow up to 250 or 300 metres above ground.

Figs. 3 (*a*) and (*b*) are idealised diagrams constructed to show the development and destruction respectively of the inversion layer. In both these figures the ordinates represent the height above ground (logarithmic scale) and the abcissæ temperature. The temperature height curves are intended to show the nature of the variations which set in before, during and after sunset [Fig. 3 (*a*)] and just before, during and after sunrise [Fig. 3 (*b*)].

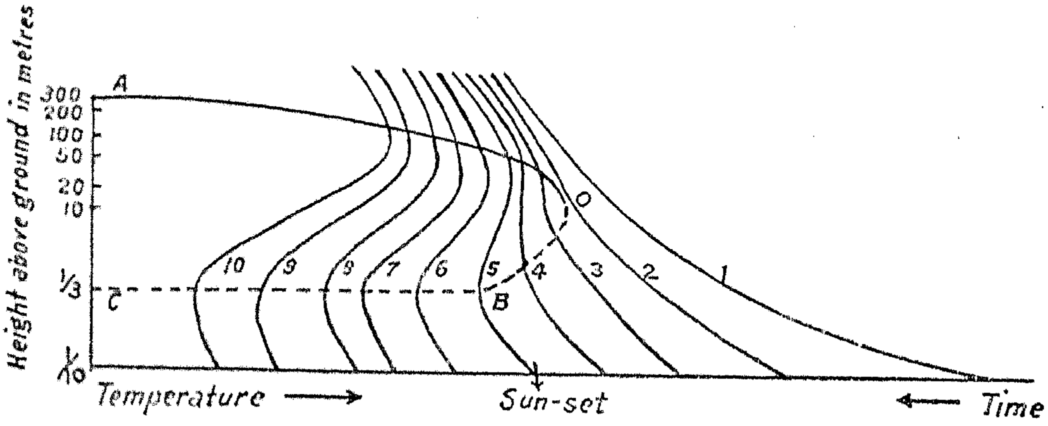

FIG. 3 (*a*). Development of Nocturnal Inversion. The above is an idealised diagram in which the curves 1 to 10 would correspond roughly to the following hours for a clear winter day at Poona.

Curve No.	Approximate time in hr. New I.S.T.
1	1700
2	1800
3	1900
4	1930
5	2000
6	2030
7	2100
8	2300
9	0300
10	0700

N.B.—The temperature range from *B* to *C* is of the order of 10° C. The height scale is logarithmic, ground surface to level of *BC* is of the order of ⅓ metre and O is about 6 to 7 metres above grouud.

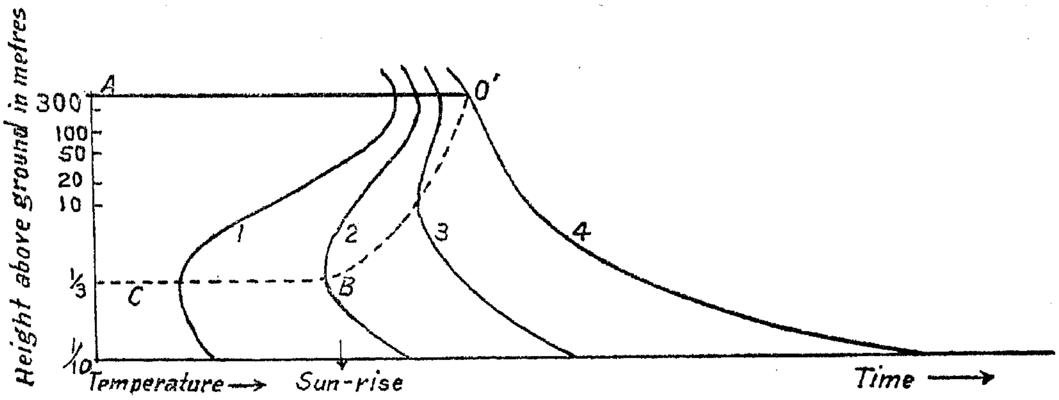

FIG. 3 (*b*). Destruction of Inversion after Sunrise. The above is an idealised diagram in which the curves 1 to 4 would correspond roughly to the following hours for a clear winter day at Poona.

Curve No.	Approximate time in hr. New I.S.T.
1	0700
2	0800
3	0900
4	1000

N.B.—The temperature scale is as in Fig. (3) *a*. *BC* is about $\frac{1}{3}$ metre above ground and *AO′* about 300 metres above ground.

Curves 1, 2, 3....10 of Fig. 3 (*a*) represent the vertical thermal structure at different times. As the temperature decreases with time at all levels, the time sequence is from right to left. Curves 1 and 2 show the thermal structure before the formation of the inversion layer. Sometime before sunset, when the inversion is about to commence, the upper limit of the shimmering layer is at the point O. As soon as nocturnal cooling starts, the inversion starts developing. Its lower boundary, *i.e.*, the "lower isothermal layer" approaches the ground rapidly from O to B within a short while after sunset and thereafter remains more or less steady at about a foot or so above the ground as BC. The upper boundary of the inversion layer, starting at O, begins to rise rapidly at first and more gradually thereafter as OA in the figure. AOBC is the inversion region in the diagram. OA and OBC are in the upper and lower isothermal layers respectively. Below OBC we have the lapse of the shimmering layer[1] and above OA the lapse of the free atmosphere.

Curves 1, 2, 3 and 4 of Fig. 3 (*b*) represent the thermal structure at different times before and after sunrise. As the temperature increases with time, the time sequence is now from left to right. The inversion region is AO′BC. AO′ is the upper boundary of the inversion layer in the morning which remains more or less steadily at the same level during the process of destruction of the layer. CB represents the base of the inversion layer early in the morning. As soon as insolation begins at the point indicated by the vertical arrow (sunrise), the shimmering layer thickens very rapidly from B to C. As soon as it reaches O′ the inversion is completely obliterated.

(*d*) *Other Phenomena.*—We have also carried out numerous investigations on the invisible condensation of water vapour during the night on the soil,[9, 22–30] on the microclimates of plant communities,[7, 8, 32] on the fate of solar radiation,[33–36] on the correlation between the vertical gradients of wind velocity and air temperature,[30] etc.

4 THERMAL REPULSION

Below the heated plate, owing to the stable arrangement of the air layers, the convective phenomena are not violent as in the previous case but very much simpler. In fact, when matters are so arranged that an air cell (filled with smoke and illuminated suitably) is formed with a hot surface above and a cold surface below and the sides are suitably enclosed, the dark layer is found to be restricted in its scope by a pair of vortices. As the cold lower surface is brought nearer and nearer to the hot surface it is found that the vortices separate towards the two sides leaving a calm layer at the centre where the dark layer attains a maximum thickness; ultimately, when the cold surface approaches the hot one within 2 mm. or less the vortices die away completely, all convective phenomena cease, and thermal repulsion has full play. When this " convection-free " state is reached, dust particles are repelled with a uniform velocity as defined by Stokes' Law and are deposited on the cold plate. The velocity is found to be proportional to the thermal gradient. These results have been discussed fully by Ramdas,[12] and Paranjpe.[13] Later, Ramdas and Joglekar[15] studied the movements of oil droplets in a vertical convection-free cell (between a vertical hot surface and a vertical cold surface) and found that the falling particles being acted upon by gravity vertically and by the thermal repulsive force horizontally, move in straight lines inclined to the vertical from the hot to the cold surface.

In the same paper they have described experiments on the steady deflection of a mica vane suspended parallel to the two surfaces by means of quartz fibre. The mica vane is repelled from the hot towards the cold surface, the deflections being proportional to the temperature gradient. The apparatus used in the above experiment is shown in Fig. 4. Here the mica vane M is suspended by a quartz fibre between the two surfaces G H (hot) and K L (cold). These surfaces are maintained at the desired temperatures by circulating hot and cold water respectively through the pipes C_1–C_2 and

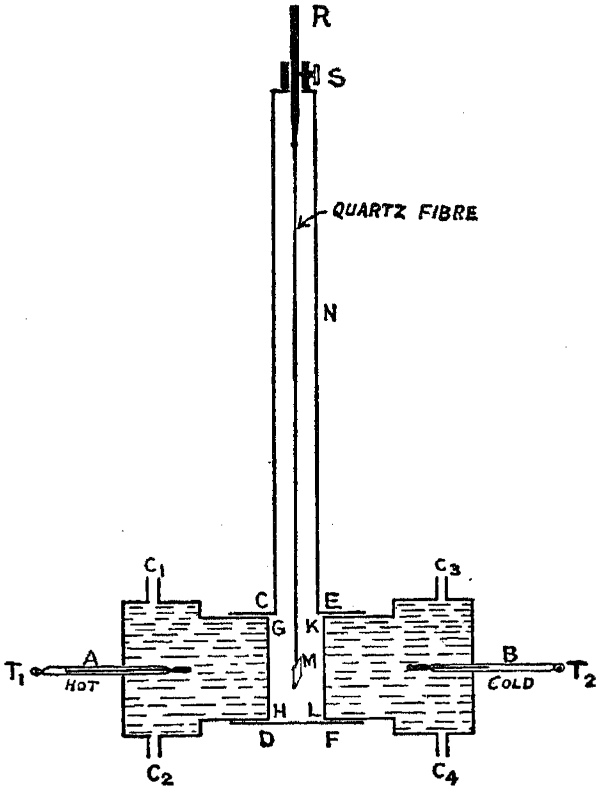

FIG. 4. The Thermal Repulsion Apparatus

C_3–C_4. The distance between GH and KL is adjustable. The joints C, D, E and F are made air-tight and the interspace can be evacuated to any desired pressure. When there is a difference of temperature between G H and KL the mica vane is deflected to the right by an amount proportional to the temperature gradient.

Fig. 5 represents a typical curve showing the dependence of thermal repulsion on the gas pressure. Here the distance between the hot and cold surfaces was 5 mm. δ is the deflection in divisions of the microscope eyepiece scale and ΔT the difference of temperature. One division on the microscope scale equals 1/20 mm. and a unit value of $\delta/\Delta T$ corresponds to a thermal pressure of $5\cdot659 \times 10^{-3}$ dyne per cm.^{2}

It will be seen that the deflection is very small at high pressures but increases to a maximum value as the air pressure is reduced to $6\cdot3\times10^{-3}$ cm. of Hg. The deflection decreases thereafter with further decrease and air pressure. Obviously the left-hand portion of curve where the deflection is proportional to the gas pressure, enables us to design a simple gauge for recording low pressures. Paranjape[16, 17] working under the present writer has discussed in great detail the results he obtained for various gases, kinds

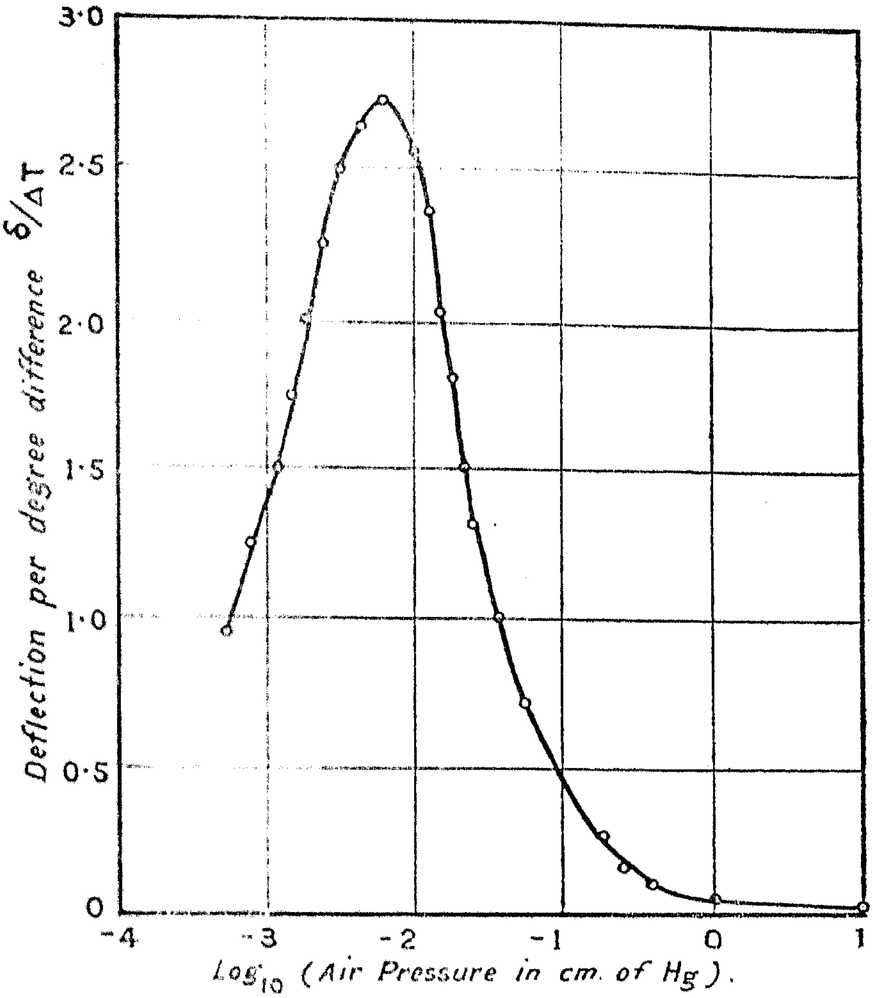

FIG. 5

of vanes suspended, and with the vane parallel and perpendicular respectively to the surfaces GH and KL. He has also shown how the accommodation coefficient can be deduced from the last mentioned experiment. It may also be mentioned in conclusion, that in our experiments, thermal repulsion is shown in all its simplicity as a molecular phenomenon without the complications introduced in the classical Crooke's Radiometer experiments.

The adaptation of the apparatus shown in Fig. 4 for use in radiation measurements is also under investigation.

5. CONCLUSION

In the present paper a brief survey of some of the important experimental results obtained *above* and *below* a hot plate has been made. The subject is still full of new problems.

The present writer wishes to take this opportunity to thank all his collaborators who have helped to make progress in these studies.

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