STUDIES ON THERMAL REPULSION

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1. *Introduction*

IN a series of papers[1, 2, 3, 4, 5] published during the last few years the subject of the dust-free or dark layer of air surrounding a hot body in relation to the convective movements in its neighbourhood was discussed in the light of experimental work carried out at Poona. It was shown by Ramdas and Paranjpe[3, 4] that the dark space may undergo variations in its extent under the influence of convection but that when care was taken to eliminate all convective movements in the interspace between a hot and a cold surface by bringing them sufficiently close to each other, the whole interspace is filled by the dark or dust-free layer. The above result was very significant because the phenomenon of thermal repulsion could be observed in its *true simplicity* for the first time without the element of confusion introduced by the convective movements which were always present in the experiments made by earlier workers.[6, 7, 8, 9, 10] *In all our subsequent investigations on this problem, we have worked with convection-free air cells.*

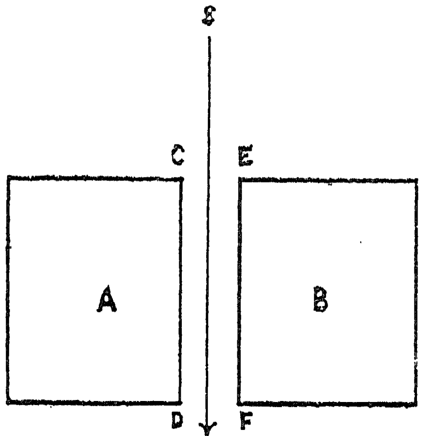
For example, in the work referred to above,[3, 4] when a *horizontal* cold surface was brought to within 3 mm. of a *horizontal* hot surface, the convective movements present at larger separations, all stopped. Under these conditions if some smoke or dust particles entered the interspace, the particles were seen to be repelled *vertically downwards towards the cold surface.* The movement of the particles was *normal* to the hot surface and without any trace of a horizontal component. The velocity was also shown to be proportional to the temperature gradient. By an interferometric method[5] it was found that the temperature gradient between the hot and the cold surface was *uniform* as soon as the thickness of the horizontal air cell was made less than 4 mm.

In the earlier experiments at Poona the observations of the velocity of the particles in the interspace were made by introducing a layer of smoke very gently and noting the time taken by the upper edge of the smoke to move to the cold surface. The particles here moved downwards under the joint influence of gravity and of the force of thermal repulsion. Knowing the average size of particles and applying Stokes's law, an estimate of the force of thermal repulsion was made. Since then a considerable amount of work has been done on individual particles moving under the joint influence of gravity (*vertical*) and a horizontal thermal gradient between vertical hot and cold surfaces placed parallel to each other. The thermal repulsion could also be observed when the free particle was replaced by a thin flake of mica suspended in the space between the hot and cold surfaces by means of a fine quartz fibre. Some instruments have also been designed for making air or water free from dust by passing the fluid through the interspace between hot and cold surfaces kept sufficiently close to each other to prevent convection.

In the present paper the authors intend to give a brief outline of some of the main results to indicate the scope of these investigations. A detailed account of the different experiments including those with the suspended mica piece using (1) various thicknesses of mica piece, (2) different gases, (3) mica pieces coated with silver and lamp black, and (4) different air pressures ranging from a few millimetres of mercury to one atmosphere is being given in a thesis under preparation by the junior author of this paper. An explanation of the phenomenon of thermal repulsion on the basis of the kinetic theory of gases will be discussed in a later paper.

2. *Measurements of the Velocity of Individual Particles in a Thermal Field and the Estimation of the Force of Thermal Repulsion*

(*a*) *Description of experimental arrangements.*—Fig. 1 shows the horizontal section of the experimental arrangement. A and B are two rectangular



vessels, the sides CD and EF of which enclose a thin film of air through which oil drops sprayed from above fall vertically (perpendicular to the plane of the paper). To eliminate stray air currents the ends CE and DF are covered by glass plates. Hot water of the required temperature is circulated in A and cold water in B. Oil drops sprayed above and entering the space CEFD are illuminated at a slight angle by the pencil of light ST. The illuminated drops are viewed through a low power microscope M into which the direct beam ST does not enter, but light scattered or reflected by the falling drops can enter. Under the influence of gravity alone an oil drop falls vertically; the thermal gradient repels it from A to B. The distance from CD to EF is decreased sufficiently to eliminate convection in the air cell. Careful observations of the movements of particles let into the vertical air cell showed that when the distance between the hot and cold surfaces is 1 mm. or less, convection is absent. Under these circumstances the oil drops are observed to travel in straight lines inclined downwards from the hot towards the cold surface in a plane perpendicular to the direction of observation. The eye-piece of the microscope M is provided with a square graticule with the help of which the number of divisions through which a droplet moves vertically and horizontally in a given time interval can be measured. In the arrangement used 1 mm. was equal to 3·5 divisions of the graticule and the time intervals were measured with a stop-watch reading correct to 1/20th of a second. The advantage of this experiment is obvious. The vertical component of the velocity of a droplet can be used to calculate its radius r by using Stokes's law

$$6\pi r \eta v = \tfrac{4}{3}\pi r^3 (\rho - \rho') g$$

where η is the viscosity of air [η at temperature $t°$ C.

$$= 1715{\cdot}5 \times 10^{-7}(1 + {\cdot}00275\, t - {\cdot}00000034\, t^2)],$$

v is the vertical velocity of the droplet,

ρ is the density of the droplet (0·92 gr. per c.c.)

ρ' is the density of air, and

g is the acceleration due to gravity.

Neglecting ρ' which is small compared to ρ, we have

$$r = \sqrt{\frac{9}{2} \cdot \frac{\eta v}{\rho g}}.$$

The size of droplet and the horizontal component of its velocity are thus obtained simultaneously by observation on the same droplet in a single measurement.

Table I gives the values of r and v_h the horizontal velocity for a set of nine droplets observed one after the other in a single experiment when the hot surface was at 51 ·5° C. and the cold one at 23 ·4° C., the separation between them being 0 ·0572 cm. The temperature gradient was 409° C. per cm.

TABLE I

Droplet No.	Horizontal distance travelled by droplet in cm.	Vertical distance travelled by droplet in cm.	Time taken in seconds	Vertical velocity in cm./sec.	Radius in cm. × 10^4	Horizontal velocity in cm./sec.
1	·0143	·0629	0·55	·1143	3·293	·0260
2	·0357	·1510	1·25	·1208	3·385	·0286
3	·0143	·0692	0·45	·1537	3·818	·0318
4	·0215	·1258	0·75	·1677	3·987	·0287
5	·0143	·1133	0·55	·2060	4·420	·0260
6	·0215	·2831	1·15	·2461	4·831	·0187
7	·0257	·2831	1·20	·2359	4·731	·0214
8	·0172	·0787	0·55	·1431	3·684	·0313
9	·0143	·0787	0·65	·1211	3·388	·0220

More than a thousand measurements with individual drops like those given in Table I were made with different temperature gradients. It may be remarked that with the arrangement described in Fig. 1 it was quite easy to make measurements on droplets varying in radius from 2×10^{-4} to 5×10^{-4} cm. Droplets smaller than 2×10^{-4} cm. moved too early from the hot to the cold surface for observations to be made on them while those larger than 5×10^{-4} cm. moved vertically too fast for their velocities to be measured. We are thus left with only a small range of size. A wider range of size can be brought under observation only if a more elaborate time-measuring device and photographic methods of recording the tracks of the droplets are used.

(*b*) *Discussion of measurements made with oil drops.*—In this section we shall focus our attention on the variation of the horizontal component of the velocity of a droplet with the horizontal thermal gradient. Any possibls influence of drop-size is restricted by picking out observations on drops within the small range $2 \cdot 8 \times 10^{-4}$ to $3 \cdot 2 \times 10^{-4}$ cm. out of the very large number of available observations. These observations were then grouped under small intervals of temperature gradient, *viz.*, 50–69° C. per cm., 70–89° C. per cm., and so on up to 450° C. per cm. The mean values of v_h the horizontal velocity are plotted against the mean values of temperature gradient (*viz.*, 60, 80, 100 · · · 420° C. per cm.) in Fig. 2. The dots in the diagram cluster about a straight line drawn through the origin indicating that the velocity of a particle under the influence of a force acting in the direction of the thermal gradient is proportional to the thermal gradient. From the slope of the straight line in Fig. 2 it is found that the horizontal velocity due to unit temperature gradient (1° C. per cm.) is of the order of $8 \cdot 17 \times 10^{-5}$ cm. per second.

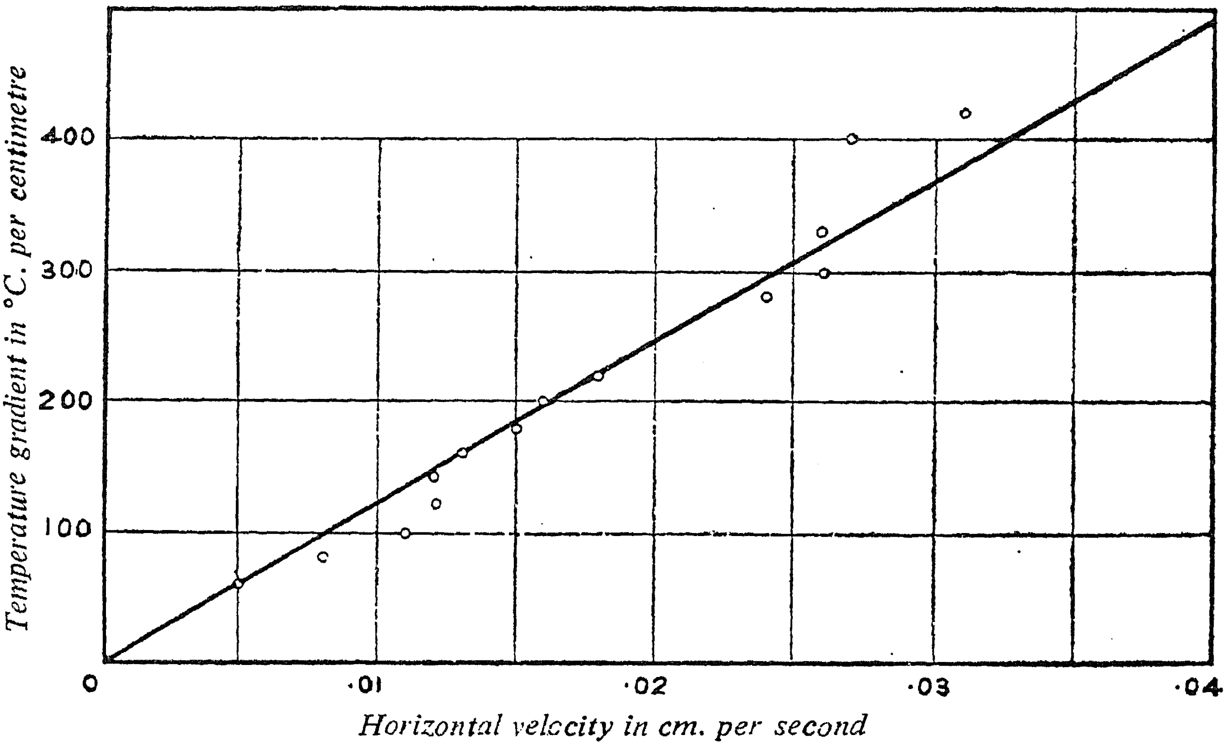


FIG. 2

Variation of horizontal velocity of particles ($2 \cdot 8$ to $3 \cdot 2 \times 10^{-4}$ cm.) with temperature gradient (between two vertical surfaces ·6 to ·7 mm. apart)

Velocity due to a temperature gradient of 1° C. per cm. $= 8 \cdot 17 \times 10^{-5}$ cm./sec.

As discussed in previous papers[3,4] the uniform velocity of the droplet should be looked upon as being due to an extra pressure or force acting on a droplet moving through a viscous medium, *viz.*, air, under the influence of the temperature gradient. We may apply Stokes's law to this case also. Neglecting the density of air as compared to that of the droplet we have,

$$6 \pi \eta r v_h = \tfrac{4}{3} \pi r^3 \rho \alpha$$

where v_h is the horizontal component of the velocity of the droplet and α is the acceleration due to the thermal gradient. Then,

$$\alpha = \frac{6 \pi \eta r v_h}{\tfrac{4}{3} \pi r^3 \rho} = \frac{9}{2} \frac{\eta v_h}{r^2 \rho}.$$

Substituting the value $\eta = 1 \cdot 9 \times 10^{-4}$,

$v_h = 8 \cdot 17 \times 10^{-5}$ cm. per second for a unit temperature gradient (1° C. per cm.), $r = 3 \times 10^{-4}$ and $\rho = \cdot 92$, we have $\alpha = \cdot 8437$ per unit temperature gradient.

The value of α for a temperature gradient of 400° C. per cm. is equal to 337. This is slightly more than 1/3 the value of g, the acceleration due to gravity.

The force per unit area or the extra pressure P exerted on the droplet, when expressed per unit area of the cross-section of the droplet through its centre and normal to the direction of its movement, under the influence of temperature gradient of 400° C. per cm. is given by

$$\mathrm{P} = \frac{\mathrm{F}}{\pi r^2} = \frac{m \alpha}{\pi r^2} = \frac{\frac{4}{3} \pi r^3 \rho \alpha}{\pi r^2} = \tfrac{4}{3} r \rho \alpha = \cdot 124 \text{ dyne/cm.}^2$$

Again $\mathrm{P} = 3 \cdot 1 \times 10^{-4}$ dyne/cm.^{2} per unit temperature gradient.

3. *Measurements with Thin Pieces of Mica Suspended in the Space between Vertical Hot and Cold Surfaces*

In the previous pages we have attempted to estimate the force acting on a free drop or particle when it is in a thermal field from the uniform velocity with which it moves against the viscous resistance of air. This led us to investigate whether this force can be measured directly by suspending a light object like a piece of thin mica in a horizontal thermal field by means of a long and very fine quartz fibre and observing the steady displacement from the vertical experienced by it as soon as the thermal field is put on. Preliminary observations showed that the mica piece does undergo a visible displacement in a thermal field.

A suitable apparatus was constructed immediately for carrying out the measurements with precision. Fig. 3 shows a vertical cross-section of the apparatus. The temperature gradient is maintained between the faces GH and KL of the vessels A and B which are maintained at the desired temperatures by circulating hot and cold water respectively through the tubes C_1, C_2 and C_3, C_4. Thermometers T_1 and T_2 for measuring the temperatures of the water in A and B are inserted through apertures provided for the purpose. The vessels A and B slide in the outer piece CEFD so that the distance between GH and KL may be adjusted as desired. The joints at C, D, E and F can be made air-tight by means of modeller's clay or a mixture of bees-wax and rosin. The mica piece M is suspended by means of a quartz fibre, the upper end of which is attached to the end of the moveable rod R. The rod R can be fixed in position as desired by

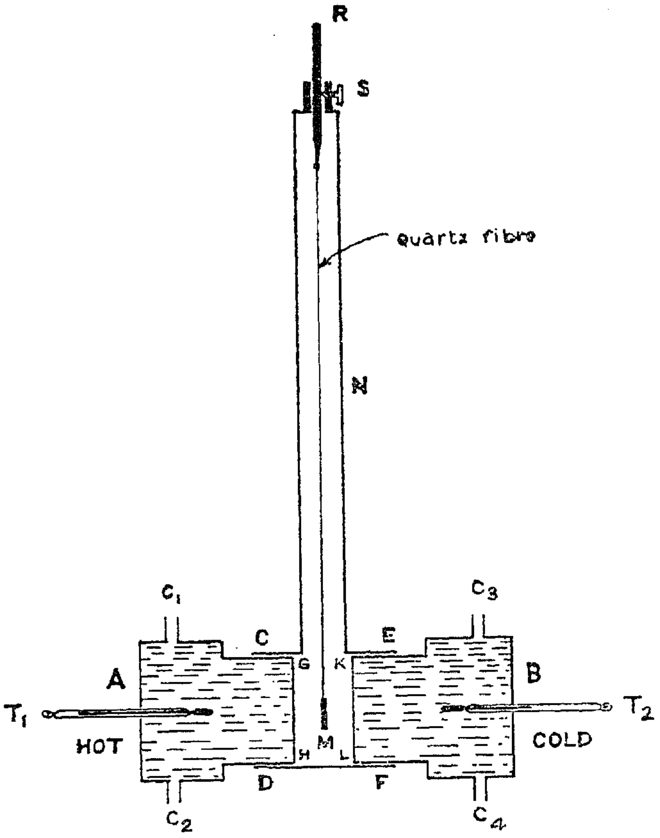


FIG. 3

means of the screw S. The tube N is screwed on to an aperture in the upper surface CE. The joints at both ends of the tube N can also be made air-tight. The mica piece kept parallel to the surfaces GH and KL is seen edge-wise in Fig. 3, its thickness being shown exaggerated. The pieces used in the experiments were square or rectangular (dimensions 2 or 3 mm. by 4 or 5 mm.) weighing 20 mg. or less. A low power microscope with a graticule is used to view the edge of the mica piece which is visible through a circular glass window on the front side of the apparatus. The mica piece is illuminated by sending a beam of light through another glass window at the back. The position of the quartz fibre where it meets the edge of the mica piece can be read off from the vertical lines in the graticule. The magnification was 6 divisions in the graticule equal to 1 mm. When the temperatures in A and B are the same, the quartz fibre hangs vertically. When hot water is circulated through A, the mica is displaced towards the cold surface KL. If cold water at the same temperature as in B is again circulated through A, the mica piece comes back to its original position.

From the displacement of the lower end of the quartz fibre where it meets the mica piece and knowing the length of the quartz fibre we know

θ the angle by which the suspended system is displaced from the vertical. If M is the mass of the mica, A its area, then the total horizontal force on the mica piece due to the temperature gradient is given by $F = Mg\,\theta$, for small values of θ. The pressure P on the mica or the force per unit area is given by

$$P = \frac{F}{A} = \frac{Mg\,\theta}{A} = mg\,\theta,$$

where m is the mass per unit area of mica.

To give one example, in one of the experiments the mass of the mica piece was ·00198 gr., its area being 0·09 sq. cm. The length of the quartz fibre was 20 cm. The deflection corresponding to a difference of temperature of 44·8° C. between the faces GH and KL (Fig. 4) when separated by 0·108 cm. was 0·8 of a scale division in the graticule, *i.e.*, $\frac{0\cdot 8}{60}$ cm. The value of θ is equal to $\frac{0\cdot 8}{60\times 20}$ radian and the temperature gradient is equal to $\frac{44\cdot 8}{0\cdot 108}$ or 414·1° C. per cm.

The force F on an area ·09 sq. cm. $= Mg\,\theta$

$$= \cdot 00198 \times 981 \times \frac{0\cdot 8}{60\times 20}$$

$$= 1\cdot 295 \times 10^{-3} \text{ dyne.}$$

The pressure P per sq. cm. for a temperature gradient of 414·1° C. per cm. .. $= 1\cdot 439 \times 10^{-2}$ dyne per cm.^{2}

Using the same piece of mica, quartz fibre, etc., the pressure per unit area has been measured for different temperature gradients. Some typical values are given in Table II.

TABLE II

Temperature gradient in ° C. per cm.	P, pressure in dynes per sq. cm. × 10^2
89	·36
144	·54
170	·72
243	1·08
331	1·25
385	1·43

From the above values it is estimated that the mean pressure per unit area for unit temperature gradient is of the order of $3 \cdot 8 \times 10^{-5}$ dyne per cm.^{2}

A number of experiments were performed using mica sheets of the same thickness but different shapes and areas. They show that the pressure per unit area due to a given thermal gradient is constant, the actual force on the mica being proportional to the area.

Thermal pressure and radiation pressure.—Before concluding this section we may compare the pressure due to the thermal gradient with the radiation pressure exerted by the temperature radiation from the two surfaces on either side of the mica piece in the above experiments.

It can be shown that the pressure of radiation on a small surface facing another plane surface parallel to it but infinite in extent is given by $\frac{4R}{5V}$, where R is the black body radiation falling on the small element (equal to σT^4, where σ is the Stefan-Boltzmann's constant and T is the absolute temperature of the infinite plane) and V is the velocity of radiation. The difference of pressure due to radiation from two infinite plane surfaces on a surface of unit area suspended between them will be

$$4 \sigma \frac{(T_1^4 - T_2^4)}{5V},$$

where T_1 and T_2 are the temperatures of the hot and the cold surfaces. Putting $T_1 = 70°$ C. and $T_2 = 30°$ C. we have a difference in the pressure of radiation of the order of $8 \cdot 3 \times 10^{-6}$ which is roughly $\frac{1}{1000}$ of the thermal pressure when the two surfaces are separated by a distance of 1 mm. *We thus see that we are dealing with a phenomenon which is very much more conspicuous than radiation pressure.*

4. *An Apparatus for the Filtration of Dusty Air or Water*

It is obvious that the *greater efficiency* with which a particle is repelled in the presence of a temperature gradient *when convection is eliminated* than when convection is present can be utilised for the rapid removal of dust in ordinary air. A thermal filter based on the above principle has been designed. A vertical cross-section of the apparatus is shown in Fig. 4, where EFGH is maintained at ordinary temperature by circulating cold water through the tubes T_3 and T_4 in the outer chamber ABCD, and KLMN is maintained at a high temperature by heating water contained in the inner vessel. The separation between the surfaces EF and KL is of the order of 1/5 mm. A large temperature gradient is thus maintained between KLMN and EFGH.

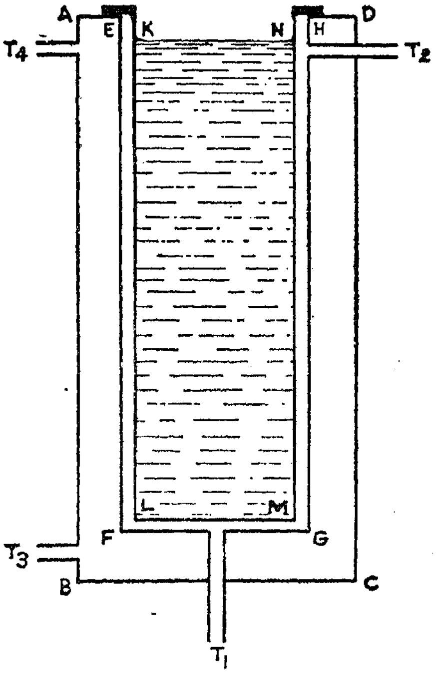


FIG. 4

Thermal filter for dusty air or water

Dusty air can be admitted through the tube T_1 into the interspace between the hot and cold surfaces, and when it comes out through the tube T_2 it is quite free from dust as all the particles are repelled towards the cold surface before the air stream leaves the apparatus. The efficiency of this filter has been tested by passing air heavily laden with smoke into the apparatus and verifying that when the air, after passing through the thermal filter, is allowed to enter another chamber illuminated by a condensed beam of light, not a single particle can be seen in the track of the beam of light. An attempt was made to see whether particles suspended in water can be removed by passing water through the above apparatus. The movement of the particles through water which is a very much more viscous medium, must be correspondingly slower, so that for the complete elimination of the suspended particles, the apparatus will have to be correspondingly longer.* With the present apparatus, therefore, one can only expect a partial elimination of the dust particles in water. Our experiments made with a number of soil suspensions, fully justify the above expectation. A comparison between the number of particles present before and after filtration can be made by examining corresponding samples of water kept in rectangular glass vessels in a condensed beam of light. In Fig. 5 photographs of the tracks of the

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* Such an apparatus is being made.

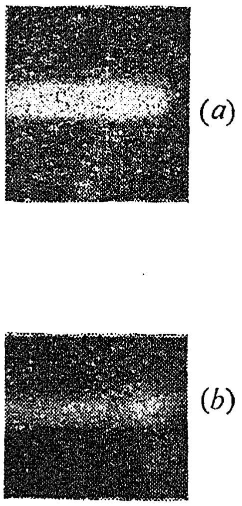

Fig. 5

Photographs of the track of a beam of light in water containing clay particles in suspension (*a*) before and (*b*) after passing through the thermal filter

beam of light in (*a*) unfiltered water and (*b*) water after filtration through the apparatus are shown. The intensity of the Tyndall cone is seen to be very much weaker in the case of filtered water. It may be remarked that the current of water through the apparatus has to be passed sufficiently slowly to attain maximum efficiency with the given size of the apparatus.

5. *A Simple Dust Counter*

The same principle was used for the design of a simple dust counter. A vertical section of this apparatus is shown in Fig. 6. The hot surface is

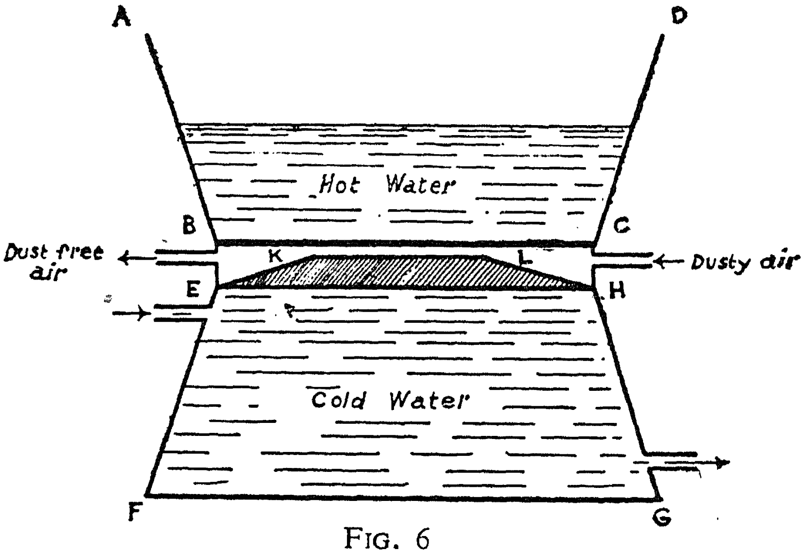

Fig. 6
Dust counter.

the bottom of the vessel ABCD in which water is maintained at a higher temperature. The cold surface below is formed by the upper surface of the lower vessel EFGH through which cold water is circulated. The inter-space between the two surfaces is covered at the two ends by means of metal plates of suitable shape, to which the tubes for the admission of the dusty air and for its exit are attached. The interspace is wide at the beginning and end so that dust particles will not be affected in these regions. As soon, however, as the air enters the narrow region KL which is about 1/5 mm. in thickness the particles are repelled and they stick to a microscope slide kept above the cold surface. In fact, the size of the cold surface is exactly that of the standard microscope slide. Preliminary observations with air heavily laden with smoke show that all the particles are deposited on the microscope slide if the air is aspirated through the apparatus at a rate of 1 c.c. per second or less.

Precise measurements using the instrument described in Sections 4 and 5 above are in progress and the results obtained will be discussed in due course.

6. *Conclusion*

In the present paper work done on the phenomenon of thermal repulsion of particles or objects placed in a thermal field (where convection has been eliminated by bringing the hot and cold surfaces sufficiently close to each other) has been described. Observations have been made with (*a*) drops falling freely under the joint influence of gravity and a horizontal thermal gradient and (*b*) objects like thin mica pieces suspended in the thermal field by means of a fine quartz fibre. The pressure due to the thermal field is verified in both cases and estimates have been given. The pressure is about 1000 times as large as radiation pressure. A thermal filter and a dust counter utilising the above phenomenon have been designed by the authors. These are described.

In conclusion, the authors have great pleasure in thanking the Director-General of Observatories for the facilities given at the Meteorological Office for these investigations.

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