It is now well known that a thin layer of a fluid with unstable density distribution breaks up into a number of polygonal cells called Bénard cells. The most interesting example of this phenomenon in nature is the formation of certain types of strato-cumulus, alto-cumulus and cirrocumulus clouds, a fact first pointed out by Bénard himself and studied in considerable detail by Sir Gilbert Walker, Prof. Brunt and their students. Much experimental work has been done both on liquids and gases by many investigators including Bénard, Idrac, Terada, Avsec, Philips, Mal, K. Chandra and others. The problem has been mathematically treated by Lord Rayleigh, H. Jeffreys and Low. They have deduced criteria of stability and derived relations between the cell-dimensions and the depth of the layer.

The usual method of making the movements visible is to mix with the liquids shining particles of substances like aluminium, 'gold' paint or lycopodium powder and tobacco or similar smoke for gases. Simple optical methods enable the phenomenon to be studied in much greater detail, as was pointed out some years ago by K. R. Ramanathan. Although optical methods were used by Bénard himself, they do not seem to have been used by later workers. In this paper, some observations on different liquids using optical methods are described.

A horizontal layer of liquid is obtained by floating it on clean mercury. The surface of a volatile liquid like ether or carbon-disulphide cools rapidly by evaporation resulting in an unstable distribution of density. With less volatile liquids like cocoanut oil, instability can be produced by placing the tray of mercury on a flat heater. A divergent beam of light from a point source is reflected at the mercury surface at nearly normal incidence, and the reflected light is received on a screen. A pattern is formed on the screen which is in a way an image of the local deviations of the optical thickness of the layer. Bright points and lines correspond to optically denser liquid and dark points and lines to optically lighter liquid. The liquid layer behaves roughly as a composite lens backed by a plane reflector. The pattern usually remains in good focus over a considerable distance from the layer.
Pictures were obtained by placing a photographic plate in the path of the reflected beam and giving a suitable short exposure. The thickness of the layer was measured with a micrometer screw provided with a long sharp pointer. A thermocouple in series with a galvanometer gave the temperature at the bottom of the layer. Once instability sets in, there were both vertical and horizontal temperature gradients and with such small thicknesses as were used, it was difficult to measure these.

Moderately viscous liquids such as water and some vegetable oils when heated uniformly at the bottom give the simplest patterns. With such liquids, only bright bordered cells were obtained showing ascending movement at the centre and descending movement at the boundary. The descending movement organises itself approximately along uniform continuous lines. The origin of instability being at the bottom, the upward movement is stronger than the downward and the latter is therefore distributed over a greater area. Viscosity slows up the movements and the patterns are stable.

For making quantitative measurements stable liquids are convenient; it is easy to keep the depth of the layer constant and vary the temperature or to keep the temperature constant and vary the depth. (i) to (iii), Plate II, show the variation of cell-size with depth in a layer of coconut oil, the temperature of the bottom of the layer being constant at 100°C. The temperature of the top surface of the layer was not measured. Fig. 1 shows the area of cell plotted against the depth of the layer. The size of the cell is seen to increase rapidly with increasing depth. (iv) to (vi), Plate II, show the variation of the area of the cell with the temperature at the bottom of the layer the thickness of the layer of coconut oil being constant at 1.43 mm. The dark centres of rising columns are more concentrated with greater temperature gradients. With decreasing temperatures, the dark centres become less and less conspicuous and below about 40°C the pattern disappears. Fig. 2 shows that the area of the cell at constant depth increases approximately linearly with temperature at the bottom of the layer.

Viscous liquids show a tendency to form long rolls as a result of movement. (vii), Plate II, shows the pattern obtained with an undisturbed layer of water. The dark spots are due to air bubbles which collect on the surface of mercury when the water is heated. (viii) shows the effect of movement when the air bubbles were swept out with a sheet of glass. The cells become elongated in the direction of movement and form rolls or columns which persist even on further heating. (ix) shows similar elongated cells with coconut oil.

Volatile liquids such as ether, benzene, alcohol, carbon disulphide and carbon tetrachloride give patterns easily, due to the cooling of the top
surface by evaporation, without any special heating at the bottom. (x) to (xii), Plate II, show the typical successive stages in the appearance of the pattern on the screen as a layer of ether floating on mercury gradually gets thinner. When the layer is thick, prominent dark canals and rapidly moving thin bright filaments make their appearance. The dark lines are regions at which the liquid ascends. As the thickness as well as the temperature diminish, the bright filaments converge to a series of points or lines surrounded by dark canals. As the film gets thinner the movements become less brisk, the dark canals get narrower and the bright spots in the middle of the cell get more concentrated and become connected together by bright lines. After a certain stage, the dark lines become invisible and we get bright bordered polygonal cells showing an ascending movement at the centre and descending movement at the boundaries. This stage persists

![Graph](image-url)

**Fig. 1.** Variation of cell area with depth of the layer. Coconut oil—Temperature at the 100° C.
as the layer gets thinner and breaks into a large number of cells of diminishing size—ultimately tending to become a network of more or less regular hexagonal cells of uniform size. Finally when the film thickness is about 0.1 mm. or less, the pattern disappears.

With ether, even with thin layers we do not get cells with uniformly bright boundaries. The bright lines tend to knot up and the knots become more prominent when the thickness increases. At one stage, (xi), Plate II, the dark and bright lines form an orthogonal system of intersecting cells. Even then, the knotting up at the descending bright points is rather more prominent. It appears that at small thicknesses the descending movement
due to sinking of cooled liquid is more vigorous while at larger thicknesses, the ascending movement becomes more vigorous. With increase in thickness of cell the effect of viscosity decreases and movements become more vigorous; any asymmetry in vertical movements gives rise to horizontal movements. The dark spots elongate and tend to join up. The advancing ends of the dark lines are seen to end abruptly. The pattern in ether is different from the pattern in cocoanut oil in that even in the thinnest stages, the bright lines in ether are not uniform in intensity but appear knotted. Descent is most vigorous at the knots. At a thickness of 0.85 mm., the dark spots have organised themselves into smooth lines. In fact in this picture both descents and ascents appear equally conspicuously. At greater thicknesses, at 1.85 mm. for example, the dark lines become much more conspicuous. With still greater thickness they become more and more sinuous and turbulent. When seen on the screen they present a most lively spectacle.

All volatile liquids show the same succession of changes, the briskness of movement increasing with diminishing viscosity and increasing coefficient of expansion. Any particular liquid also shows the same succession of patterns whatever the original thickness of the layer, provided it is larger than about 1 mm. The nature of the pattern seems to depend upon the thickness of the layer as well as the temperature gradient. It is possible to transform a particular pattern into the previous one by artificially heating from below.

With groundnut oil which is more viscous than cocoanut oil there is a tendency to form isolated perfectly circular cells, which later join up on further heating, (xiv) and (xv), Plate III. A careful examination of the plate shows that between neighbouring cells that have not joined up, there is a streaming movement of fluid. Within the bright bordered circular cell is seen a concentrated bright spot surrounded by a diffuse white ring. This effect is apparently due to diffraction of light from the edges of the cell and can be imitated by floating a small oil lens on water (xiii), Plate III. When drops of oil or mercury floating on water are examined by the same method, sharp bright spots are observed at the centre of the dark circle which represents the image of the drop, similar to the spot in "Poisson's disc experiment".

(xvi) and (xvii) show photographs of patterns obtained by the Schlieren method for ether and (xviii) for cocoanut oil. The similarity of the Bénard cells with cloud forms is more obvious from these pictures.

It was easy to observe the nature of the vertical circulation in an individual cell by watching the movement of fine particles of dust. In the case
of a cell with an ascending movement at the centre, a tiny dust particle is seen to shoot rapidly upwards at the centre and outwards towards the boundary where it sinks with diminished speed and almost creeps inwards towards the centre near the bottom of the layer.

Fig. 3 shows the vertical circulation in a cell, the number of arrows indicating the different speeds of the particle along its trajectory. The nature of the movement is well brought out in (xix) and (xx) of Plate III which show (1) a point source photograph of a thin layer of unstable carbon tetrachloride and (2) a photograph of a similar layer in which lycopodium dust had been put in. The lycopodium settles down in places of descent and is cleared out in places of ascent.

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EXPLANATION OF PLATES

PLATE II

(i) Cocoanut Oil, 2 mm. thick.
(ii) Do. 1 mm. thick.
(iii) Do. 0.5 mm. thick.
(iv) Do. temperature of lower surface 95° C.
(v) Do. do. 74° C.
(vi) Do. do. 55° C.
(vii) Water, 1.23 mm. temp. 72° C.
(viii) Do. 1.73 mm. temp. 71° C with movement.
(ix) Cocoanut Oil, 1.5 mm. temp. 60° C.
(x) Ether, 1.2 mm.
(xi) Do. 0.85 mm.
(xii) Do. 0.65 mm.

PLATE III

(xiii) Oil Lens on water.
(xiv) Groundnut Oil, 1.1 mm. 120° C.
(xv) Do. 1.1 mm. 148° C.
(xvi) Schlieren-photograph of ether, 1 mm. thick.
(xvii) Do. of ether, 0.5 mm. thick.
(xviii) Do. of Cocoanut Oil, 0.7 mm. thick.
(xix) Carbon tetrachloride; point-source photograph.
(xx) Do. with lycopodium powder deposited in middle of cells.