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OPENING LECTURE
VISUALISATION OF HEAT TRANSFER

U. Grigull
Technische Universität München
Bundesrepublik Deutschland

Ladies and Gentlemen,

In this Opening Session of our Conference it is an honour for me to give a lecture which is meant to tune you in, to the problems of heat transfer and at the same time warming us up for the four days full of work ahead of us.

The topic chosen deals with visualization, the visualization of processes in heat transfer, that means, things are to be made visible which normally are invisible. Three methods are commonly used

the shadowgraph
the Schlieren- and
the interference method.

The following pictures and the movie will mainly show interferograms, in two phase systems, condensation and evaporation, also pictures are shown,taken in direct light, and Schlierenpictures taken for better contrast. In the interferograms the lines (fringes) indicate isotherms.

A few remarks may be appropriate on the question why a University Institute engages in the production of scientific films.

Three reasons can be given right away:

1. The qualitative observation

In many problems of heat transfer it is necessary to observe directly the processes going on, and the region investigated. There might be laminar or turbulent flow, film- or dropwise condensation, nucleate- or film-boiling. Since there are also pseudo-stable transients, a decision "from outside" is not always clearly possible.

It may be recalled that Osborne Reynolds' famous discovery of what is called now the "critical Reynolds-number" was the result of a visualization. In such qualitative observations sometimes details are seen which otherwise would have remained unobserved. Two examples for this:

a) Dropwise condensation of water (fig.1a - c).
   In three subsequent pictues dropwise condensation of water is shown on a non wettable vertical wall.
   The time intervall between consecutive pictures is some hundreth of a second. Between figure 1a and 1b, a droplet rolling down has cleaned the surface. The new drops do not form arbitrarily, statistically distributed on the surface but the old contours of the last and last but one drop generation is clearly preferred.

   The "mean nucleus density" is a very complex term therefore.

b) Film boiling of carbon dioxide near the critical point (fig.2). The horizontal heating wire is a tenth of a millimeter in diameter. Because of the small differences in density and surface tension the vapour rises in columns in rather uniform distances. This distance corresponds to about the "most critical wave length" of a disturbation, just as G.J.Taylor (1950) has calculated it in a similar case. Later on, in the movie you will see how a distance, accidentally too small, is healed out by disposing of one column.

These have been examples for the qualitative consideration.

Another point is:

2. The quantitative evaluation of interferograms

An example is shown in fig.3. This is a rotating cylinder in air at medium Reynolds-numbers. The local temperature gradient is obtained from measuring the distances between the fringes. In this, interferometry is probably superior to almost all other measuring techniques. Because of a thickening of the thermal boundary layer in the upper stagnation point,a Nusselt-number value is obtained with only 91 % of that of a still cylinder.

Since here we have the normal and usual application of interferometry I do not need to present further examples.

But this picture can also serve as an example to the third point, which is

3. The instructional value of visualization

Heat transfer is considered among students -at least in our country- as dry and hard to conceive and therefore difficult; examinations are feared. In this situation it appears reasonable to use in lectures all means of communication, first of all slides and films to show the processes going on. This picture (fig.3) may serve as an example. The student is taught how to predict a thermal boundary layer, but he has never seen one, and he is not sure whether there is such a thing at all. This is no trivial problem.

The picture presents such a boundary layer, so, there it really exists. The student recognizes its characteristics, in a stream-line picture (which we do not show here) he observes that the boundary layer is fed from outside, has a certain thickness and ends on the outside rather abruptly. Approximation methods based on finite boundary layer thicknesses promise therefore to be successful.

Highly instructive also, is a comparison of the rotating cylinder (fig.3) with one in cross flow, shown in fig.4.

Although at an equal Reynolds-number (Re = 590), two very different thermal boundary layers are formed depending whether the characteristic velocity is taken as the wall- or the free-stream-velocity.

The next picture (fig.5) shows a problem which is not of pure boundary layer type. A horizontal container is suddenly heated from outside. At first, there is pure heat conduction, but then the upward flow within the boundary layer induces a downward flow in the center. 75 seconds later (fig.6) the region of undisturbed fluid has become smaller and a little later the first isotherm vanishes. The final state would be the white field when the heating is accomplished. For the prediction of the temperature field the approximations of boundary layer theory are not applicable.

4. Interferometer as an analogue computer.

The interferometer does not have to be considered only an instrument for visualization but also as an analogue computer. The system of fringes in fig.3 to 6 does present differential equations with their boundary conditions, obtained by analogy using the temperature dependance of the refractive index. Thus they present exactly the same as a recorder connected to a digital computer. The interferometer excels the computer in the fact that it does not care about stability problems encountered in numerical computations. Complicated geometric forms as well as variable boundary conditions are easily simulated. These interrelations are demonstrated in an example (fig.7). This is a horizontal gap heated from below, in which, as you know, convection will set in, at a certain Rayleigh-number. In the two dimensional case, rolls will form for which isotherms had been calculated and presented at the third Conference in Chicago 1966 (lower picture) by Professor Churchill, then at Ann Arbor, Michigan.

In the upper picture you see our respective experiment in the interferometer. The agreement is very satisfactory, especially, considering a difference in Prandtl-number, since in the experiment water (Pr = 7) was used while the calculation is based on Pr = 1. For this calculation, Churchill had used the transient, i.e. the computer started out from a homogeneously heated gap and stepwise calculated the progress of the temperature field up to the final stage in fig.7. The question was then (1966), does nature really follow this way? In the movie we shall see the confirmation: in transient heating (in the experiment, for simplicity the cooling is from above) the calculated profiles actually do form. These photographs were hard to obtain since non-steady fields are very sensitive for thermal disturbances.

5. The pathological cases.

In the interferometer also processes can be made visible which normally resist a numerical computation. These are transients from one stable state into another, crossing a stability-limit. In such cases, which we may call "pathological" the change can be slowed down by carefully regulating and thus the unstable interstate is also made visible. This shall be demonstrated by two examples.

In fig.7 a vertical gap is shown, open on top- and bottom-end and heated along the left wall.

Along the left wall, a fan blowing air downwards creates a counterflow to free convection. The right wall serves as a flow guide and provides those velocity distributions which are covered by theoretical solutions by Sparrow and co-workers (1959). In the stable region good agreement exists with theory, but in the movie you will also see the transition from the forced flow downwards into the predominantly upwards directed free convection flow. Fig.8 gives an intermediate stage in the unstable region.

An example of simultaneous heat and mass transfer is shown in fig.9. Here you see a horizontal cylinder wrapped into blotting paper soaked with methanol. By heating the cylinder, methanol vapour is produced having about the same density as the surrounding air.

In this state methanol vapour flows neither up nor down, but causes a distinct thickening of the boundary layer as demonstrated in fig.9. This state is extremely sensitive for disturbances from outside; the system will start into a wobbling motion as will be seen in the movie. You will also see the reversal in flow direction from downwards into upwards, influenced by the heating.

6. Heating and ventilation, meteorology

Now a few models in the field of heating and ventilation and of meteorology shall be presented. In fig.10 we shall see a cold air stream on the right side coming from a big glass window in winter. Below it, a heater directs this cold downward flow to the lower left so that uncomfortable drafts may occur. In the movie you will see later on that the resulting flow can be guided to any direction, depending on the heating.

The air-exchange through a window, now in Summer, is shown in fig.11. Shortly after opening the window the warmer air from outside is flowing to the inside in the upper part of the window, the cold inside air to the outside in the lower part. This exchange soon dies off, as you will see in the movie, but the room left below the window sill does not take part in the exchange. For the Winter situation (outside air colder) this picture only has to be turned upside down.

Finally two meteorological problems shall be presented in models. Fig.12 gives the development of the sea breeze along the coast a couple of hours after sun-rise. The air over the ground (right) gets more heating than over the ocean (left). This creates a heavy breeze from the sea, with the rising warm air, right, beeing forced away. In order to increase the effect we have applied both heating on the right and cooling on the left, which does not basically change the phenomenon.

At last fig.13 demonstrates the effect of an inversion layer in the atmosphere. After a cold, clear night an overstabilized temperature-layer has developed above the ground.

The convection starting in a layer close to the ground befóre noon, often cannot penetrate the overstabilized layer until the afternoon, the exchange with upper layers is thus prevented. The result is an accumulation of exhaust fumes close to the ground and the feared smog formation. The movie will show several states of this process.

Before I start the movie I would like to thank all my co-workers who have shared in the work: First of all Dipl.-Ing. W. H a u f who has taken and cut the film and who has contributed with scenes from his own work. Other scenes are added from Dr.E. Abadzic and Dr.S. Krischer. Dr.E. Hahne provided the English version to this lecture and to the movie.

We shall now see the movie.

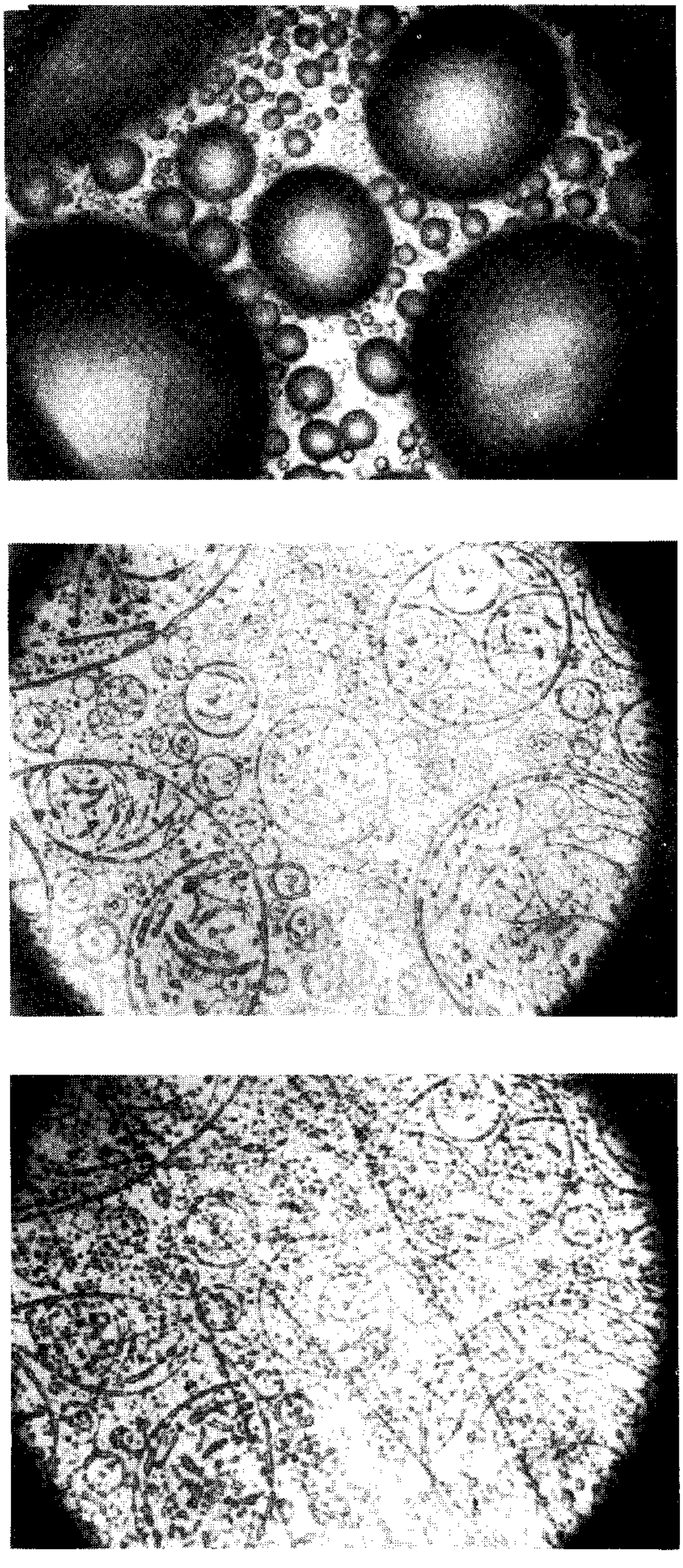

Fig. 1a – c Dropwise condensation of water on a non wettable vertical wall. Fig.1a t = 0 sec, fig.1b t = 0,25 sec, fig.1c t = 0,3 sec.

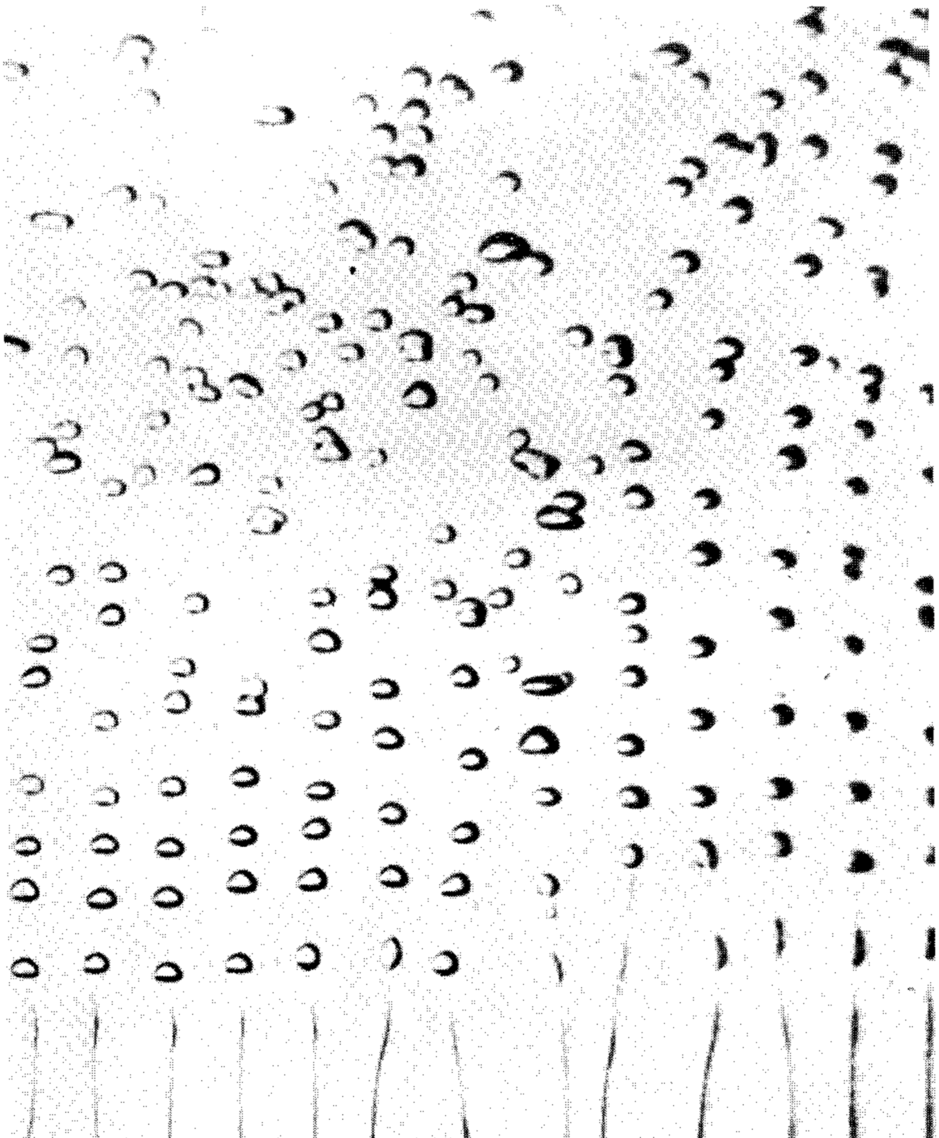

Fig. 2 Vapour columns of carbon dioxide in the critical region in film boiling.

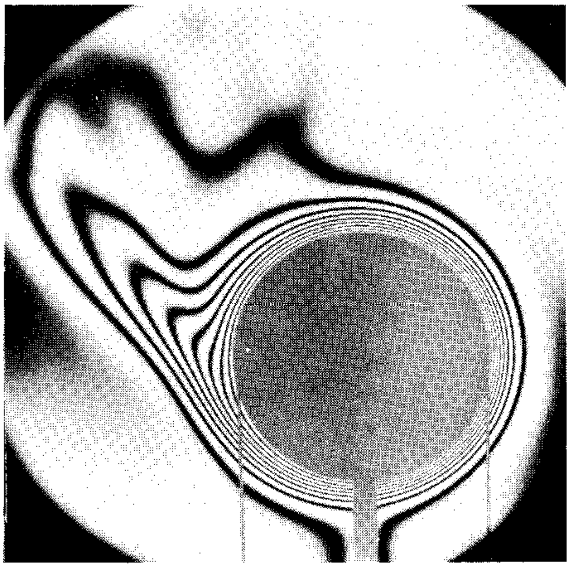

Fig. 3 Rotating heated cylinder in air. Re = 590

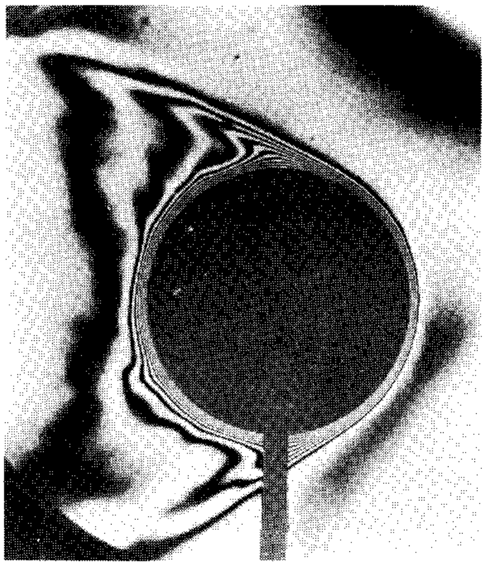

Fig. 4 Heated cylinder in cross flow. Re = 590

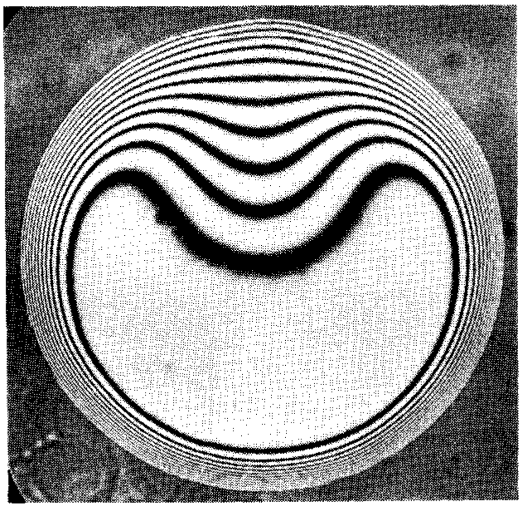

Fig. 5 Horizontal container heated from outside (35 sec after start)

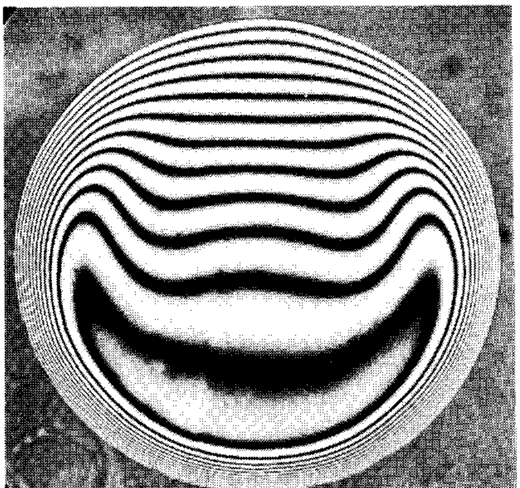

Fig. 6 Horizontal container as in Fig. 5, 75 sec. after start.

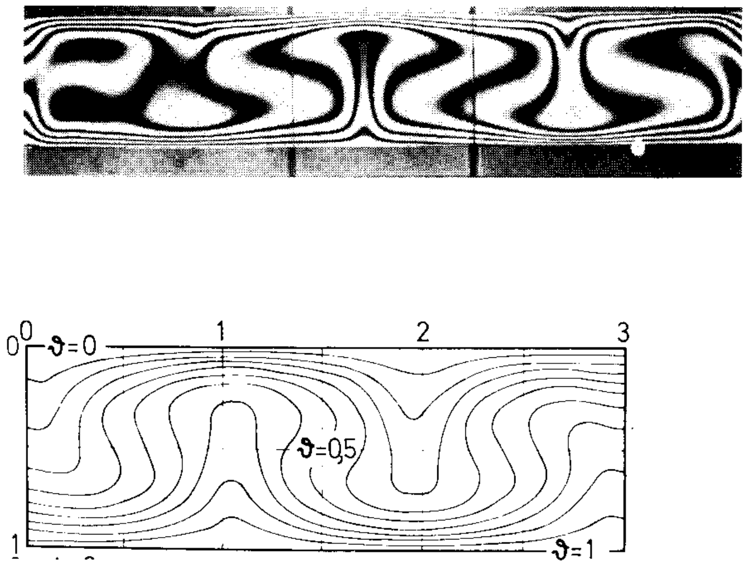

Fig. 7 Horizontal gap, heated from below. Comparison between the interferogram (above) and the theoretical solution by S.W.Churchill (1966) (below).

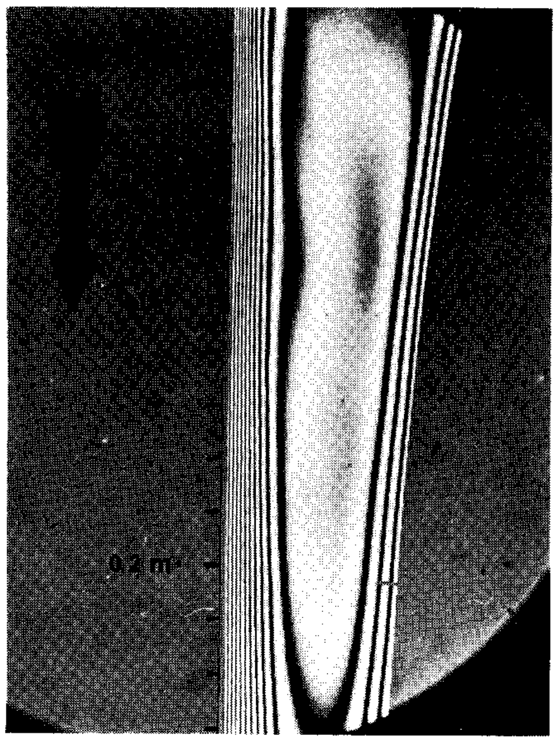

Fig. 8 Vertical gap with counterflow. The left wall is heated, air is blown through the gap from above.

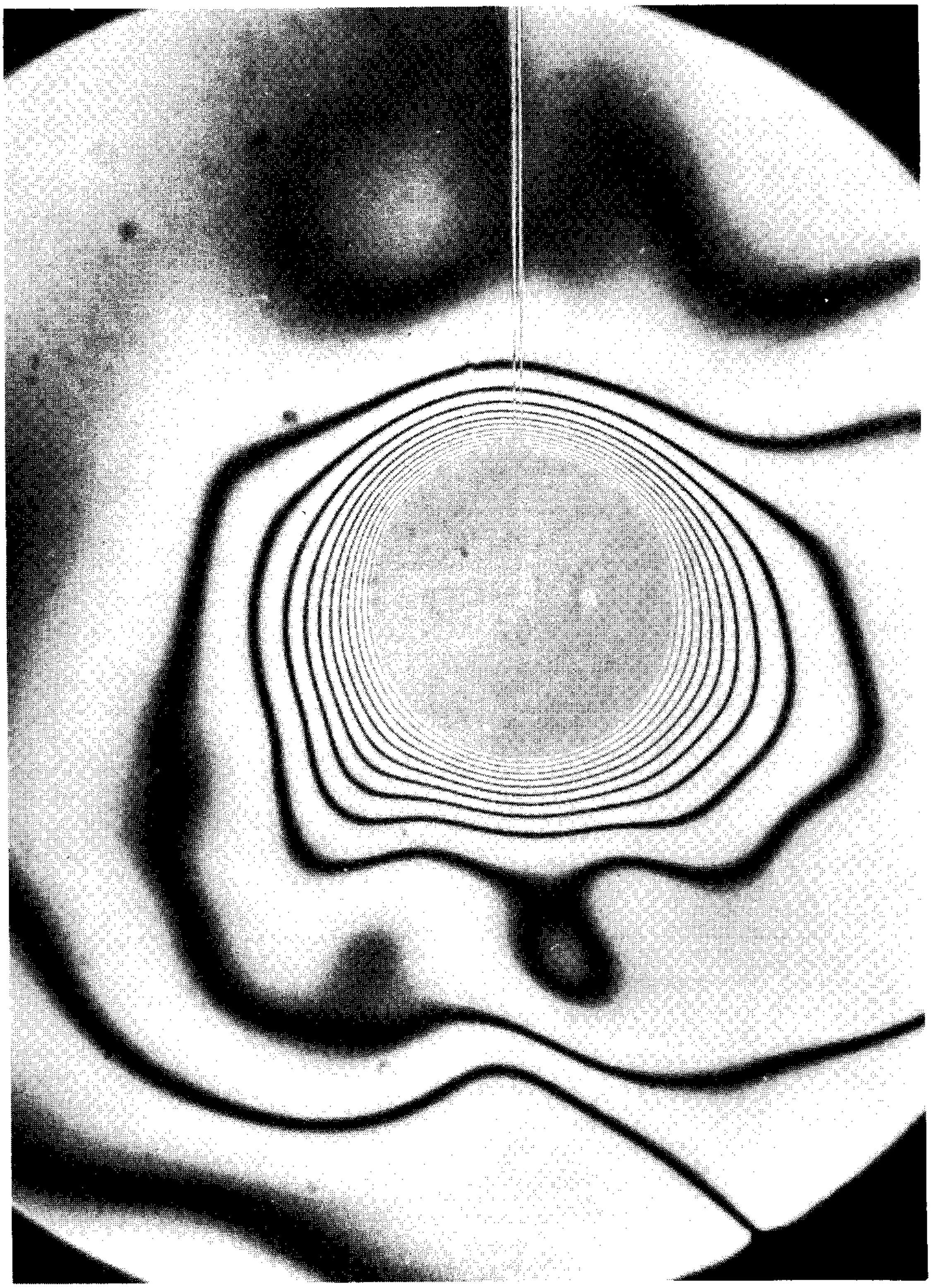

Fig. 9 Simultaneous heat and mass transfer.
Evaporating methanol on a heated cylinder.

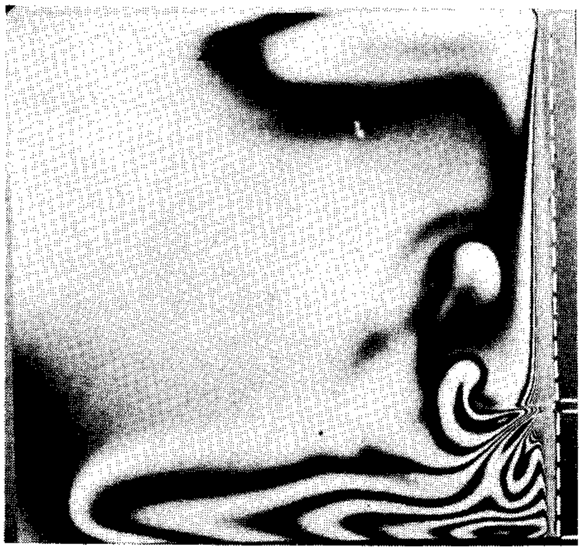

Fig. 10 Interaction between the downward flow on a cold window and the upward flow on a heater.

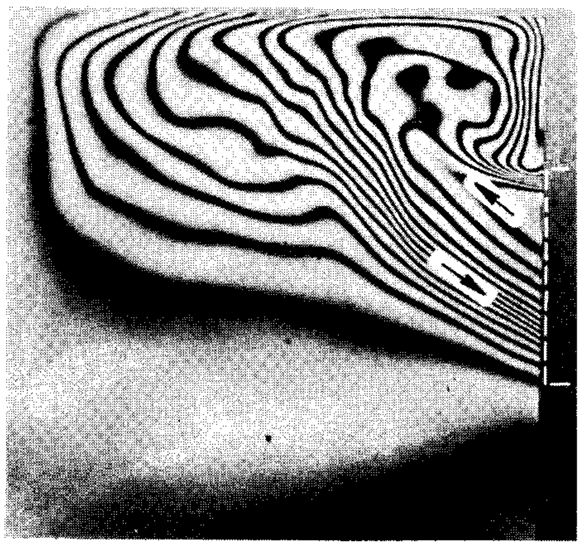

Fig. 11 Air exchange through a window in Summer (outside air warmer)

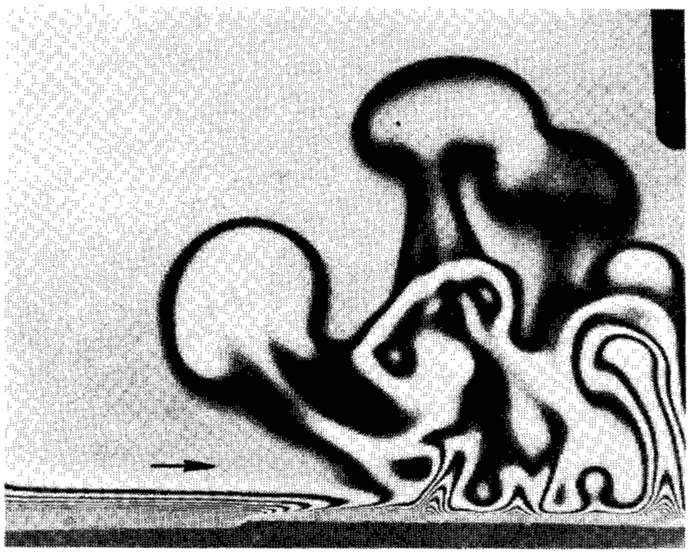

Fig. 12 Development of a sea-breeze. The temperature above the ground (right) is higher than above the sea (left).

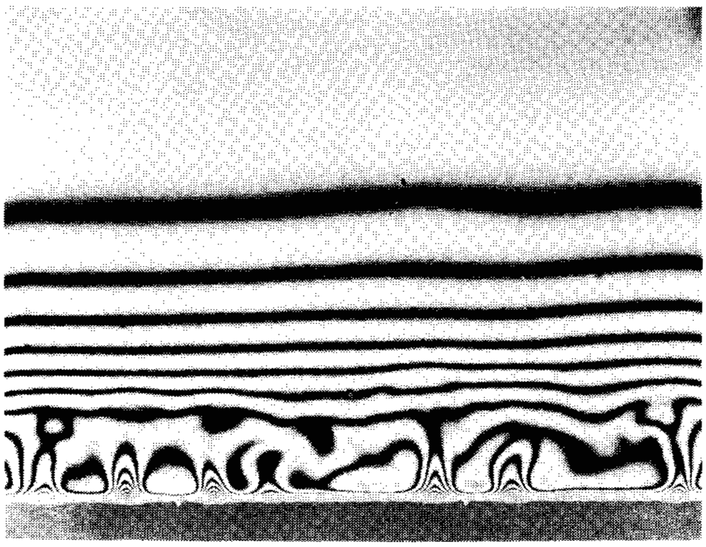

Fig. 13 Inversion layer in the atmosphere. The rising convection plumes are stopped by the overstabilized layer.