J. Fluid Mech. (1986), *vol.* 165, *pp.* 73–77
Printed in Great Britain

Flow visualization in parallel-plate ducts with corrugated walls

By W. W. FOCKE AND P. G. KNIBBE
Chemical Engineering Research Group, Council for Scientific and Industrial Research, PO Box 395, Pretoria 0001, Republic of South Africa

(Received 7 January 1985 and in revised form 19 August 1985)

For flow visualization *o*-cresolphthalein was found to be superior to thymol blue as an electrode-activated pH indicator because its slower reverse reaction results in better colour retention; its poor solubility was overcome by using a 50:50 water–ethanol mixture.

The method revealed unknown flow patterns in plate heat-exchanger configurations with the corrugations on opposite walls abutting. The main flow is along the furrows on each wall. The interaction between these criss-crossing flows causes spiralling in the flow along a furrow. At angles between corrugations and the duct axis of at least up to 45°, the furrow flow is reflected only at the sidewalls of the duct, whereas at high angles, e.g. at 80°, there are intermediate 'reflections' at the nodes where the crests of opposite walls meet.

1. Introduction

The flow patterns in ducts with corrugated walls are complex and not well understood. The local flow structure controls any heat- or mass-transfer process in the duct, e.g. in industrial plate heat exchangers. Flow visualization can help to elucidate the heat-transfer mechanism on these ducts by providing information on:

the direction and magnitude of the local velocity field;
the dynamic behaviour of the flow;
the onset of transition to turbulence;
the presence of flow recirculation zones.

Conventional methods of flow visualization, such as dye injection, are not suitable because of the inevitable disturbance they cause to sensitive local flow patterns. One of the most effective (and least disturbing) flow-visualization methods is the electrode-activated pH method (Baker 1966; Merzkirch 1974). With this method a change in the pH of the indicator is induced in the vicinity of an electrode. In the present study a superior variation of this method has been used to identify flow patterns in rectangular ducts with corrugated walls. The influence of the corrugation inclination angle to the mainstream flow direction was studied.

2. Selection of the indicator

The working fluid is an aqueous solution of a pH indicator. Usually an inert salt is added to improve the electrical conductivity of the solution; its pH is adjusted to just below the indicator colour-change interval. By electrolysis hydrogen is formed at the cathode. This results in a local excess of hydroxyl ions and thus an increase in pH, causing the solution to change to a prominent colour in the vicinity of the cathode. It is important that the potential applied should not be too high, so that the hydrogen produced will dissolve and not form hydrogen bubbles.

The ideal pH indicator for flow visualization would meet the following requirements:

it must have a high molar absorptivity in the activated form and must be highly soluble;
it should be inexpensive and readily available;
it should be stable towards light, air, excess reactants, etc.;
the change in the colour of the indicator should have a high contrast (the indicator should preferably be colourless in the inactivated state);
the indicator reaction must be reversible, with the dye-activation reaction very fast, but the reverse reaction relatively slow.

Most pH indicators have low solubility in aqueous solution; Baker (1966) overcame this problem by using thymol blue. However, the main disadvantage of thymol blue and several alternatives considered previously is that the reverse reaction is too fast and consequently the colour fades as the indicator diffuses or disperses in the bulk fluid. This limits its use to low fluid velocities. Another limitation of thymol blue is that it is a two-colour indicator. Although the colour contrast can be increased by employing a sodium lamp as a light source, a one-colour indicator would be more suitable when wall flow patterns are to be visualized with micro-electrodes, i.e. when high indicator concentrations are required.

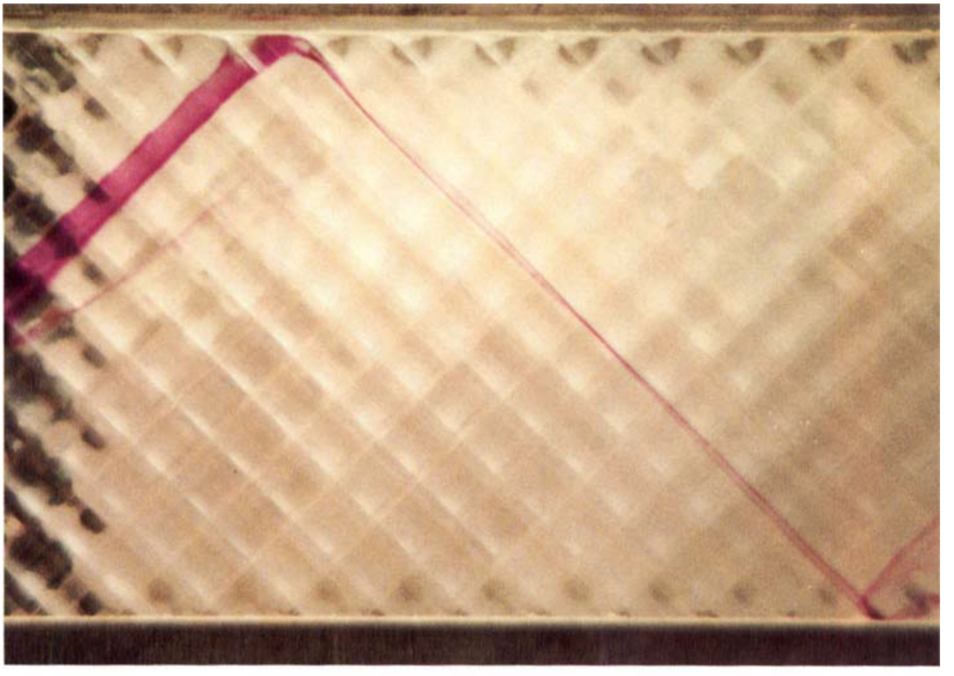
We found that *o*-cresolphthalein comes closer to fulfilling the requirements of the ideal indicator, especially as far as the reaction rate of the reverse reaction is concerned. The rate at which the colour of the activated indicator fades depends on the local pH and therefore also on the rate at which the autoprotolysis equilibrium is restored. The latter process occurs by means of diffusion of the highly mobile hydronium ions from the bulk of the solution. The equilibration is further enhanced by convective mass transfer (shear fields or turbulent diffusion), and as a result the indicator colour fades more quickly at higher fluid velocities. *o*-Cresolphthalein is a reversible indicator but the kinetics of the reverse reaction (red-purple to colourless transition) are intrinsically slow. Consequently this indicator can be used also at fluid velocities above those at which thymol blue can be used. In addition accurate adjustment of the pH of the solution becomes unnecessary.

As *o*-cresolphthalein is only slightly soluble in water, a 50:50 ethanol–water mixture was used as the solvent. Potassium nitrate was added as it was found to be a suitable inert salt of sufficient solubility (0.5 M was used). The pH of the solution was ≈ 6, adequately below the colour-change interval. The *o*-cresolphthalein concentration was 0.02 mass %.

3. Experimental

The experiments were done in an acrylic cell forming a rectangular channel with a total length of 1250 mm and cross-section of 100 mm × 10 mm. Two plates simulating the corrugated walls of a plate heat exchanger were fitted into a test section 440 mm long. The inlet was provided with wire-mesh screens, a converging section and an entrance length of 600 mm to ensure a fully developed velocity profile upstream of the test section.

The corrugations, which were machined into the acrylic test plates, were approx-

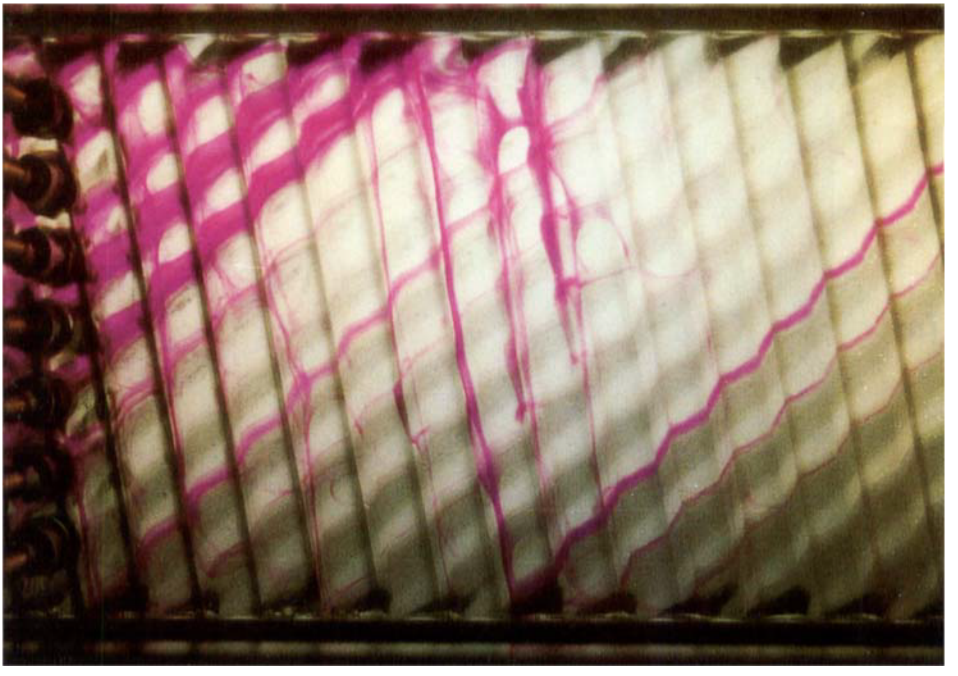


(a)

(b)

FIGURE 1. *(a)* Flow between two 45° plates. Dye is produced at a circular electrode ($Re = 70$). *(b)* Flow between two 80° plates. Dye is produced at a circular electrode ($Re = 80$).

(c)



(d)

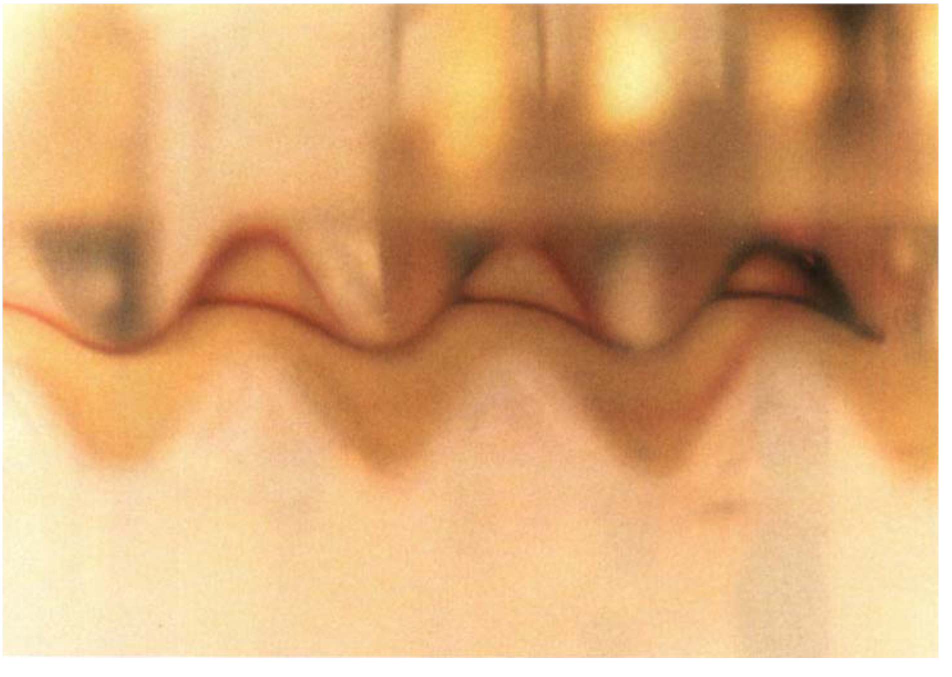
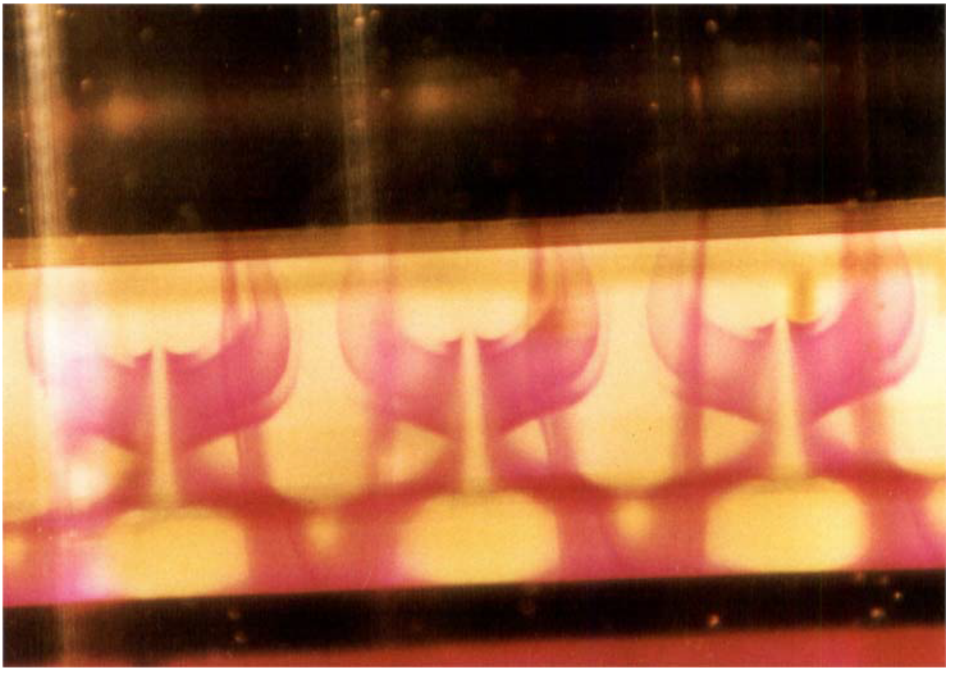


FIGURE 1. *(c)* Flow between 45° and 80° plates. Dye is produced at six circular electrodes ($Re = 125$). *(d)* Flow between two 90° plates (side view). Dye is produced at the strip electrode at the top of the 'eye' to the right. Main flow is from right to left ($Re = 90$).

FOCKE & KNIBBE

(e)



(f)

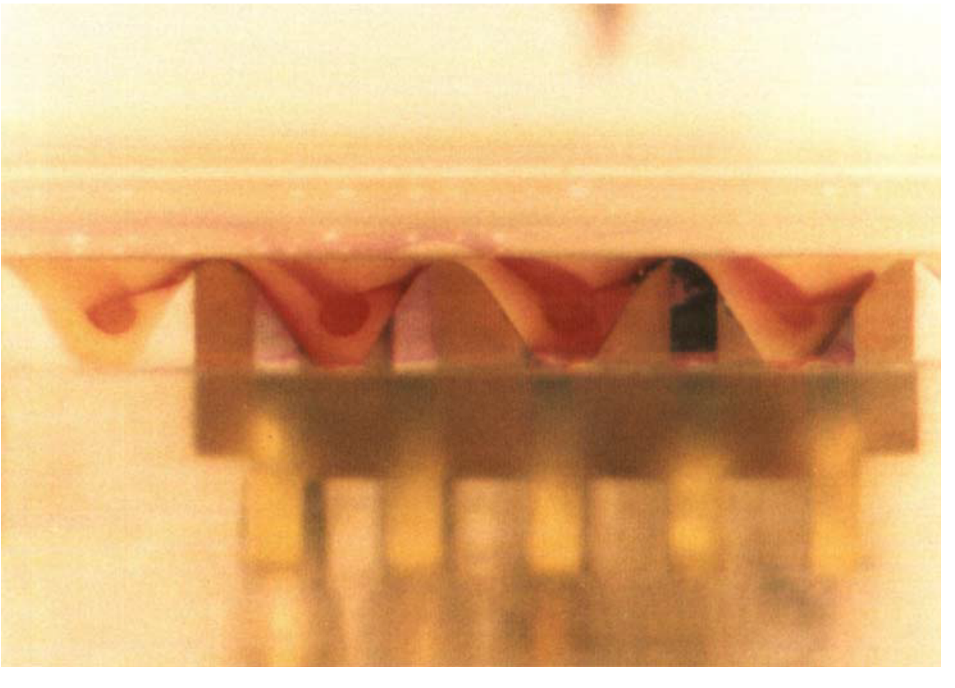


FIGURE 1. *(e)* Flow between 90° and 0° plates showing ox-horn vortices. Dye is produced along the strip electrode. Flow is from bottom to top of picture ($Re = 80$). (Converging streaks correspond to upstream vortices.) *(f)* Side view of pattern in figure 1*(e)*.

FOCKE & KNIBBE

imately sinusoidal with a pitch of 10 mm and an amplitude of 2.5 mm. The plates were assembled with the corrugations abutting in a criss-cross pattern as is common in plate heat exchangers.The test plates contained integral graphite electrodes which were either circular (made from 10 mm diameter cylinders) or rectangular (extending over the width of the flow channel and 1 mm or 10 mm long). These electrodes could be used as cathodes or anodes depending on the location at which dye production was desired.

Fluid was pumped through the cell with a centrifugal pump. The flow rate was determined with a set of rotameters, and the fluid temperature with a mercury thermometer situated at the cell outlet. Viscosity was measured with Ubbelohde viscometers and density with a pycnometer. Reynolds numbers were calculated conventionally using the maximum distance between the plates (four times the amplitude of the corrugation) as the characteristic length. The experiment was designed so as to allow for measurements in the range of *Re* numbers that is of particular interest to the industry in this field, i.e. *Re* 10–1000.

With regard to buoyancy, it was found that the density of the coloured solution after the dye had been produced was slightly higher than that of the coloured solution itself. However, the effect is very small, as observed in a beaker under quiescent conditions.

4. Results

Plates with the corrugations running at angles of 0°, 45°, 80° and 90° relative to the duct axis were tested. The resulting flow patterns were photographed [figure 1 (*a*)–(*f*), plates 1, 2 and 3] and are schematically explained in figure 2 (*a*)–(*f*).

With the corrugations running at an angle of 45° with respect to the duct axis, the flow was found to follow mainly the furrows on each wall (figures 1 *a* and 2 *a*). On reaching the side wall the flow returns along the furrow on the opposite wall. The flow in each furrow spirals, as can be expected from the interaction of the flows in the two sets of crossing furrows.

When the corrugations on both plates are at an angle of 80° (figures 1 *b* and 2 *b*), the flow does not follow a single furrow along the whole width of the plate. Instead it is 'reflected' close to a node (the intersection of two plate crests) by transfer of fluid from a furrow on one wall to a furrow on the opposite wall; overall a 'flattened' helical flow-pattern results. For this angle the flow becomes turbulent above $Re \approx 160$. When one plate has corrugations at 45° and the other corrugations at 80°, the resulting flow pattern is similar to that obtained with two 45° plates (figures 1 *c* and 2 *c*).

With the corrugations on both plates at 90°, so that a sinusoidal channel is formed (figures 1 *d* and 2 *d*), the main flow is undulating in the direction of the duct axis. At very low flow rates no flow separation is observed; flow separation first takes place at $Re \approx 20$. The separated region increases in size with the *Re* number until the reattachment point almost coincides with the top of the downstream crest. At this point the free shear layer becomes unsteady and turbulence ensues ($Re \approx 260$).

A striking ox-horn vortex pattern was observed (figures 1 *e, f* and 2 *e, f*) with the 0° to 90° plate combination in the range $10 < Re < 200$. The 'horns' were formed by vortex pairs occurring in the 90° furrow over the width of a 0° furrow. The interpretation of the observed pattern is that fluid is sucked from near the edges of the 0° channel and flows (close to the top and along the leeward side of the 90° crest) towards the middle of the 0° channel. The flow then enters the vortices and is

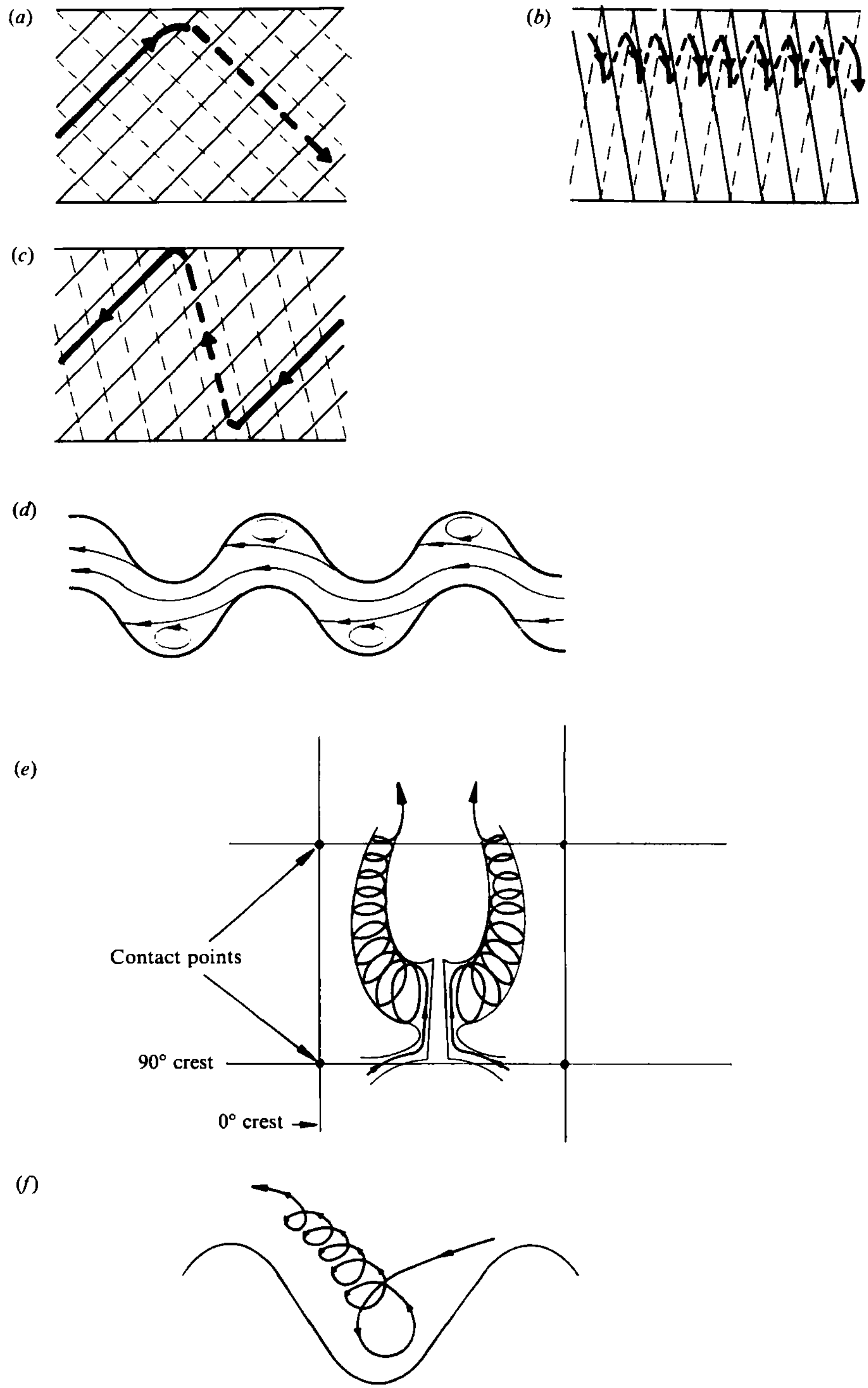


FIGURE 2. (a) Schematic explanation of figure 1 (a): ——, flow along furrows of upper plate; ----, flow along furrows of lower plate. (b) Schematic explanation of figure 1 (b): ——, flow along furrows of upper plate; ----, flow along furrows of lower plate. (c) Schematic explanation of figure 1 (c): ——, flow along furrows of upper plate; ----, flow along furrows of lower plate. (d) Schematic explanation of figure 1 (d). (e) Schematic explanation of figure 1 (e): ——, flow along upper part of the 90° furrow; ----, flow in the lower part of the 90° furrow. (0° and 90° channels above and below plane of paper respectively.) (f) Schematic explanation of figure 1 (f).

eventually pumped out again at the edges of the 0° channel, slightly above the flow sucked up by the next 90° furrow. The flow from thc two horns then continues along a converging path along the 0° channel. The region in the 90° furrow directly below a 0° crest appears to be fairly stagnant. It may contain an additional set of vortices, but this could not be ascertained beyond doubt in the present work.

5. Conclusions

o-Cresolphthalein in an ethanol–water medium was found to be superior to thymol blue for flow-visualization purposes. The electrode-activated pH-indicator technique was used to study the flow mechanism in a model of an industrial plate heat exchanger of which the corrugation angle of the top and bottom plates could be varied independently. The observed flow pattern is one of spiralling flow in the furrows on each wall. At low angles this flow continues to the sidewalls of the cell, where it is reflected. At high angles the interaction between the flows in the crossing furrows is so high that 'reflection' is observed at intermediate positions. When plates with corrugations at 0° and 90° respectively are used, ox-horn vortices are formed; with two 90° plates, flow separation occurs.

REFERENCES

Baker, D. J. 1966 A technique for the precise measurement of small fluid velocities. *J. Fluid Mech.* **26**, 573–575.

Merzkirch, W. 1974 *Flow Visualization*. Academic Press.