J. Fluid Mech. (1971), *vol.* 50, *part* 3, *pp.* 535–543
Printed in Great Britain

A new type of water channel with density stratification

By GARRETT M. ODELL AND
LESLIE S. G. KOVASZNAY
Department of Mechanics, The Johns Hopkins University

(Received 22 March 1971)

The novel idea is to use a disk pump to drive each fluid layer independently round a closed-return density-stratified water channel. A small-scale model was built and tested to demonstrate the feasibility of the idea. A hydrogen-bubble technique was used for both flow visualization and velocity measurement. Density measurements were made with an electrical conductivity probe developed by the authors. The tests have demonstrated the usefulness of such a facility, especially for long steady-state experiments in density-stratified flows.

1. Introduction

Owing to the increasing interest in geophysical fluid mechanical problems there is a natural demand for laboratory experiments with stratified fluids. So far the existing facilities are mainly of two types: density-stratified towing tanks (e.g. Long 1954, 1955; Pao 1968) and wind tunnels (Lin & Binder 1967; Scotti 1969). In the first case the density stratification is effected by varying the concentration of brine; in the second case by heating from above and/or cooling from below. The towing tank experiments are very clean and precise but, owing to limitations on the length of the tank, only very brief samples of steady-state phenomena are possible and the influence of end walls is a serious problem, at least in some experiments. The towed model of course disturbs the density profile, which is then difficult to restore, so usually only 'one-shot' experiments are performed. Finally, it is inconvenient to gather quantative data because probes and visualization equipment must be towed down the tank behind the model with precision. The heated wind tunnel, on the other hand, cannot attain strong density stratification effects without reducing the mean flow velocity to rather impractically small values. A good comparison between the various facilities can be made on the basis of a global Froude number defined as $F = \bar{\rho}U^2/gh\Delta\rho$, where $\bar{\rho}$ is the average density, $\Delta\rho$ is the maximum density difference across the depth h, U is the mean velocity and g is the gravitational acceleration. Lin & Binder (1967) attained Froude numbers as low as $F = 0{\cdot}01$ in their heated air tunnel; the present device easily attained $F = 0{\cdot}003$ while keeping U sufficiently high to permit its accurate measurement.

The present configuration is novel and it offers an attractive range for experimentation. The basic idea of the tunnel was conceived by one of the authors (Kovasznay) after being exposed to the intrinsic difficulties of experimentation in towing tanks. The authors thank Dr Y. H. Pao of Boeing Scientific Research Laboratories and Professor Lawrence H. Larsen of the University of Washington for pointing out many of the difficulties of existing experimental methods. Discussions with them significantly contributed an incentive to the authors' effort to find an alternate experimental method and this led to the development of the device reported here.

2. Description of the apparatus

A special pump drives the fluid around a closed circuit in such a way that the constant-density surfaces remain essentially horizontal. A schematic top view is given in figure 1. The flow can be observed from the side through a straight, 20 in. long, Plexiglas section placed in the return leg of the channel. The channel has a uniform depth of 4 in. and has turning vanes placed in the corners. For steady operation, constant values of the density can be maintained both at the upper free surface and at the lower plate boundary by supplying fresh water and salt respectively.

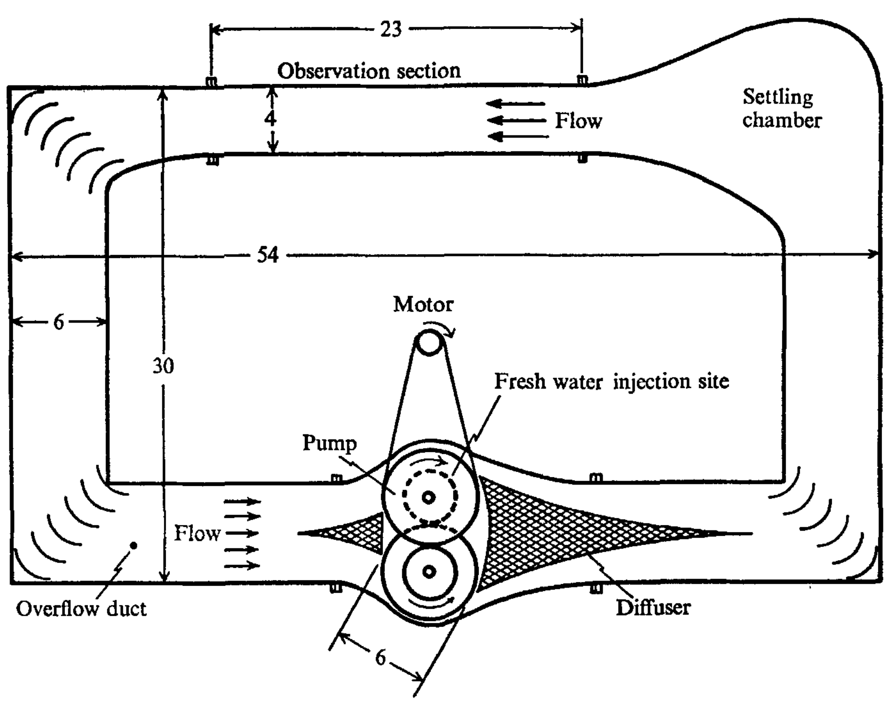

FIGURE 1. Schematic top view of the channel. Flow proceeds counterclockwise. The channel has a uniform depth of 4 in. All dimensions in inches.

The disk pump

A schematic side view of the pump is given as figure 2. The top view appears in figure 1. Two counter-rotating vertical shafts are motor-driven through a pulley, belt and a pair of gears. Each shaft turns a stack of 32 round plastic disks, each

$\frac{1}{8}$ in. thick. A typical rotation speed is 30 rev/min. The disks are of two different diameters, 3 in. and 6 in., and they alternate. The centres of the shafts are 4·5 in. apart with the two stacks arranged so that a large disk on one shaft is opposite to a small disk on the other. In this way the two stacks of disks mesh, leaving no open space between the stacks but creating $\frac{1}{8}$ in. thick and $1\frac{1}{2}$ in. wide horizontal gaps on the outside between the large diameter disks. When the two stacks rotate in opposite directions fluid is pulled around the outside channels by the viscous drag of the larger disks and is ejected as $\frac{1}{8}$ in. thick horizontal jets emerging from the gaps formed between the larger disks.

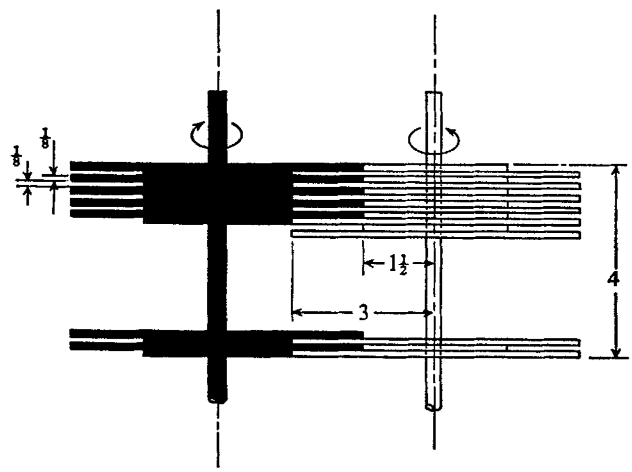

FIGURE 2. Schematic view of the pump (looking downstream). Dimensions in inches.

The effective channel cross-section (the total open cross-sectional area through which fluid is free to pass) is of course much reduced at the pump so that a diffuser is needed downstream of the pump in order to avoid flow separation from the side walls. It is formed by a shaped insert with vertical walls (the shaded area in figure 1) and it effects a gradual increase of channel cross-section.

After leaving the pump as many $\frac{1}{8}$ in. thick horizontal jets the fluid must accelerate the wakes of the disks by shear, so there is some turbulence immediately downstream of the pump. Nevertheless, if the density profile is strongly stable (i.e. $d\rho/dz$ sufficiently negative) this small-scale turbulence will be damped out rapidly. This is the key to the satisfactory operation of the device. On the other hand, without stable density stratification the turbulence will persist.

Control of the density profile

The working fluid is salt (NaCl) brine whose salinity varies from top to bottom. Molecular diffusion of NaCl in water is very slow. For example, the characteristic diffusion time in the case of a 4 in. deep layer of salt solution at room temperature is of the order of 30 days! Thus, once a stable density profile is established, it is strongly persistent. Unless large amplitude cresting, internal waves are purposely set up in an experiment the only effective mechanism for vertical salt transport is turbulent mixing associated with the pump wake. This turbulent salt transport tends to homogenize the brine and destroy the density gradient, but, as noted just above, one effect of stable stratification is to inhibit and damp out the turbulence. (More precisely, only the horizontal components of vorticity are damped, but flow with only vertical vorticity causes no vertical salt transport.) The result is that turbulence and the attendant undesirable mixing is confined to a small region downstream of the pump and is still well upstream of the observation section.

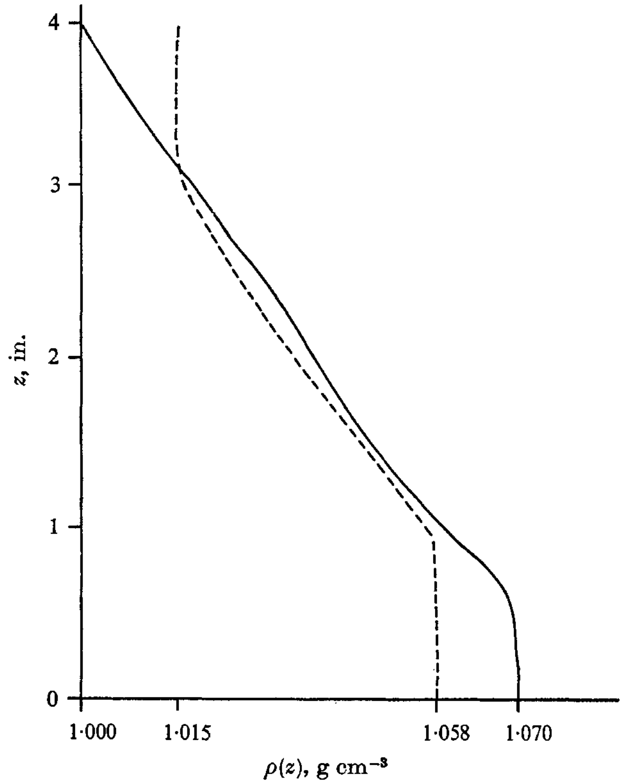

FIGURE 3. Evolution of the density profile in time when no salt flux through the upper or lower boundaries is provided to maintain steady state. ——, profile at time $t = 0$; – – –, at $t = 40$ min. The mean velocity in the observation section was 1·5 in./sec.

In order to maintain steady flow conditions a fixed value of the density is maintained at the upper free surface by the continuous slow injection there of fresh water; the excess is withdrawn at an equal rate via an overflow duct after one trip round the channel. Referring to figure 1, the water is injected at the pump disks and the overflow duct is one foot upstream of the pump. Crystalline salt is scattered in a thin layer on the flat bottom of the channel and its presence there fixes the density of the brine at the lower boundary layer at very nearly its saturation level. This lower boundary condition cannot be maintained at arbitrarily high flow velocities (and concurrent intense turbulent mixing) because the salt cannot dissolve rapidly enough. Nevertheless, for a sufficiently wide range of pump speeds the vertical salt flux through these boundaries can adjust itself to sustain a smooth monotone density profile in the face of the turbulent mixing caused by the pump. Figure 3 gives an idea of how slowly the density profile decays with time in a typical flow when no vertical salt flux is allowed through the upper or lower boundaries.

With the density fixed at the upper and lower boundaries, and at a fixed rate of pumping, the eventual development of steady-state density and velocity profiles is inevitable. (Starting with a staircase shape density profile, perhaps with five layers, a smooth steady-state profile can be established in about 2 h. Note that before the pump is turned on the density profile must have sufficiently strong stability to inhibit the pump wake turbulence, otherwise a completely turbulent flow would result.) If the pump is made to run too fast the flow will consist of two nearly homogeneous layers, both turbulent, separated by a thin highly stable layer with a high density gradient. At lower speeds a more desirable density profile is obtained; this varies linearly with height except for two thin homogeneous layers, one at the top and another at the bottom. For a sufficiently low range of operating velocities this linear profile will persist forever.† To obtain a density profile of different shape, one could fix the density at some level between the upper and lower boundaries by the slow injection there of fluid of the desired density, although this was not actually attempted.

3. Flow visualization

Two methods of flow visualization were used. Each consisted of photographing streaklines marked in one case by hydrogen bubbles, and by aluminium powder in the other. The observation section of the channel is 4 in. wide. Viscous boundary layers extended inward from the lateral walls for about 1 in., leaving an essentially two-dimensional flow region in the middle. A vertical slit of light illuminates only those streakline markers in the central half inch of the flows and, since the flows are steady, the streaklines correspond to streamlines of the central two-dimensional region of the flow.

At several different heights, horizontal (1 in. wide) sheets of small hydrogen bubbles were generated by electrolysis of the brine along fine horizontal wires (Schraub *et al.* 1965). Sheets of bubbles are used since, seen edge-on, a sheet produced by a wire is much more visible than a line from a point source of bubbles. Buoyancy, of course, causes the bubbles to rise somewhat but this occurs sufficiently slowly if fine wires and moderate electrical currents are used. The current through each bubble-producing wire depends on the conductivity of the brine surrounding it; so the bubbles are generated more vigorously near the bottom of the channel where salinity, and hence conductivity, is greatest and float upward most rapidly there. Nevertheless, the electrolysis voltage can be adjusted to generate bubbles which clearly mark streaklines at all levels but do not float more than about 0·1 in. in 10 sec. Typically, a 7 V potential above ground to 0·0008 in. diameter platinum (or even nichrome) wires gives an acceptable sheet of bubbles. Furthermore, the bubble-generating current can be interrupted by

† The experiment described below and pictured in figure 5 was left running in a steady state for 4 days and terminated only because the authors' enthusiasm waned. Average flow speed in the observation section was about 0·6 in./sec.

a timing device so that, by measuring the lengths of the broken streak segments from a photograph, the mean velocity profile can be established. Since any visible bubble does rise, this hydrogen-bubble technique cannot measure accurately very slow velocity fields, such as occur in the channel when strongly blocked flows are studied.

To record very slow velocity fields (less than 1 cm/sec) aluminium powder mixed into the brine was used to mark fluid particles. Time exposure photographs were made and used to measure the lengths of streaklines. Since the channel produced a completely steady flow, many similar photographs of different exposure times were made of the same flow. The advantage of taking many pictures of the same flow is that one is sure to find a streakline recorded in every region of interest on at least one of the pictures. A variety of exposure times is also useful when various speeds in a single flow differ by orders of magnitude since the smaller the speed, the longer the ideal exposure time to record it. Analysis of the several photographs can give the complete two-dimensional vector field of the velocity. The velocity profile and streamline data of figure 5 were obtained in this fashion.

4. Density measurements

An electronic density probe was built which permitted the measurement of either the density profiles in steady flows or time-varying density records at a fixed point. The probe is a single point-electrode device which responds to the electrical conductivity of the brine in its immediate neighbourhood. In principle it differs little from the probe described by Gibson & Schwarz (1963), however, its operating characteristics are quite different. The probe output voltage is a linear function of density (when the temperature is constant at 18 °C) in the range $1{\cdot}000 \leqslant \rho \leqslant 1{\cdot}150$, which is about the greatest density range which can be easily produced using salt and water. The probe will be described elsewhere.

To record a density profile the probe is moved vertically in the flow using a rack and pinion, the pinion gear driving both the rack and a potentiometer (whose resistance thus indicates the vertical displacement of the probe). A signal derived from the potentiometer drives the vertical input of an X–Y recorder, the probe voltage drives the horizontal input and an accurate linearly scaled plot of the density profile results. Since very good steady-state flows were generated, density profiles were leisurely recorded at many stations along the flow direction and a complete map of the entire density field was obtained.

5. The upstream velocity profile

For strongly stratified low-speed flows (i.e. low Froude number) an obstacle placed in the observation section has almost as much effect in determining the shape of the upstream velocity profile as the pump and channel geometry. This, of course, is one of the interesting features of stratified fluid flows. For an example of this blocking effect see figure 5. Experiments indicate that a stack of horizontal drag plates, with varying vertical spacings, placed in the channel at either end of the observation section can control and modify the velocity profile so that a broad variety of profiles can be generated.

One drawback of the present configuration is that a viscous boundary layer at the channel bottom is unavoidable. For obvious reasons (the blocking effect) a contraction in channel depth is not a good way to remedy this problem. One method of minimizing the lower viscous boundary layer is to float the entire brine flow on a layer of higher density fluid of sufficiently low viscosity which in addition is immiscible with brine. One of the heavy freons is a good example. The boundary layer on the bottom still exists, of course, but the maximum shear will occur in the lower immiscible layer and, furthermore, if the density jump is sufficiently great across the interface it will remain essentially undisturbed. The idea is to approximate a traction-free lower horizontal boundary for the brine flow studied.

6. Examples of observed flows

Figure 4 (plate 1) shows three samples of flow, each produced at nearly identical pumping speeds with flow from left to right. Horizontal white lines are streamlines made visible by sheets of hydrogen bubbles; vertical black lines mark 1 in. intervals. On the right of each photograph is shown the velocity profile measured at the upstream end of the observation section, at the far left, by measuring the lengths of the pulsed hydrogen-bubble streaklines. On the far right the basic upstream density profile is given as measured by the conductivity probe. This was essentially identical for all the three flows shown. It may be pointed out here that in these preliminary experiments the density was not fixed at the boundaries as described above, so that the density profile was slowly decaying over a period of hours. The three sample flows shown here were produced and recorded within a few minutes. The top picture shows a train of lee waves behind a 'Gaussian bump' obstacle. The middle one shows how the disturbance produced by the same 'mountain' is absorbed in a shear layer beneath a 'stagnant' blocked region created by an aerofoil-shaped obstacle on the right. Note that the sheet of bubbles shed directly into the layer blocked by the aerofoil simply floats up until it finally reaches the moving fluid above; the blocked region is virtually stagnant. The bottom picture shows the same configuration but with a slightly increased pumping speed (by only about 5 %). Now one can see 'quasi-steady eddies' formed upstream of the blocking aerofoil. These seem to be due to the breaking of internal waves generated by the 'mountain' below. In all three flows of figure 4 the average Brunt–Väisälä frequency was $\{(g/\rho)(d\rho/dz)\}^{\frac{1}{2}} = 2{\cdot}1\,\text{sec}^{-1}$, and the typical mean velocity was 1 in./sec. The average Froude number F based on the channel depth was about 0·025.

Figure 5 presents a more thorough study of the blocked flow upstream of an aerofoil obstacle, again the flow is from left to right. Note especially that the blocked region is also a region of nearly constant density. At the trailing edge of the obstacle there was no discontinuity in the density profile. The 'blocked' layer of significant velocity defect extended all the way upstream to the pump. The Froude number F based on channel depth was 0·0023 and Brunt–Väisälä

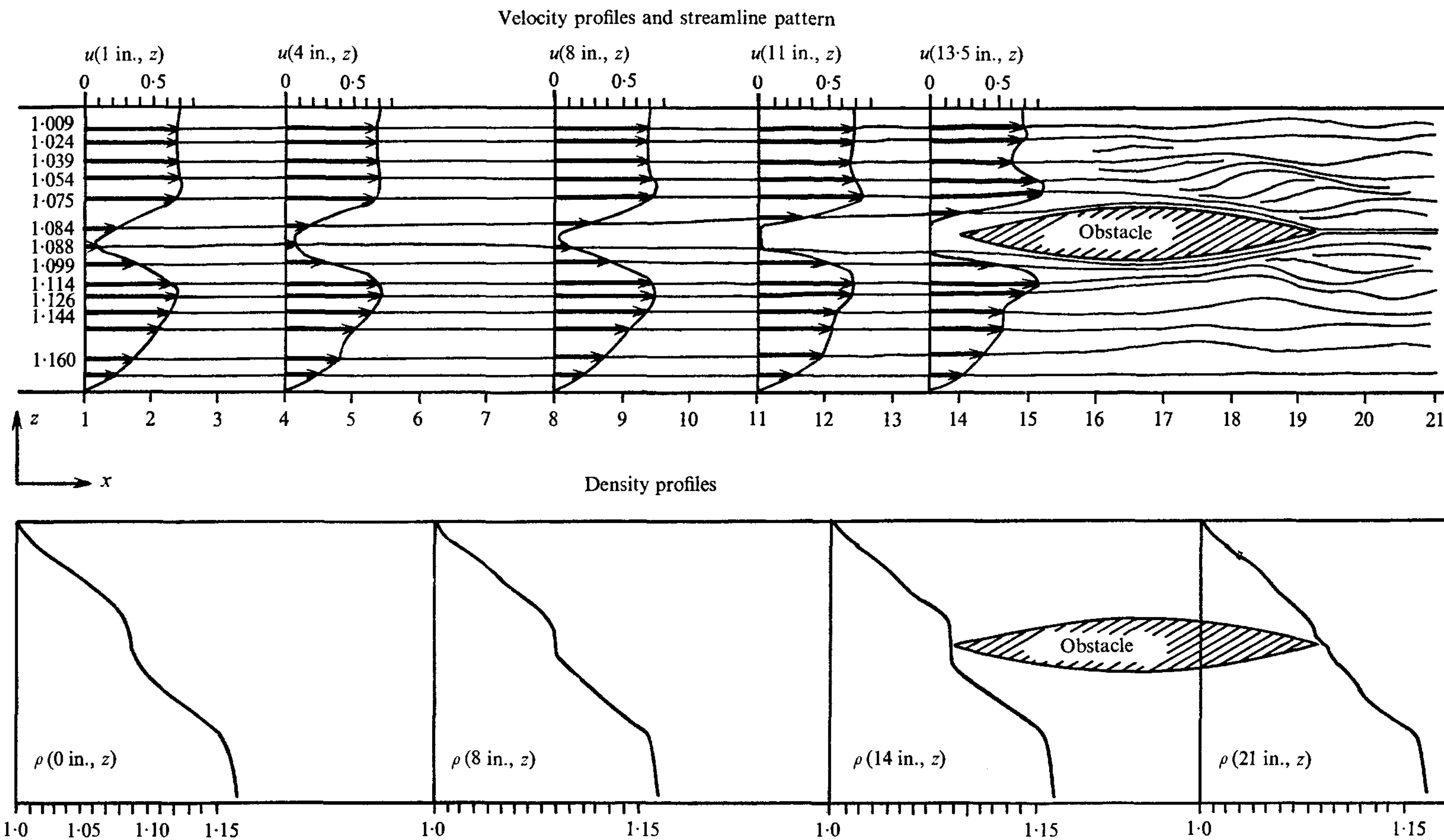

FIGURE 5. Detailed data for a blocked flow. $u(x, z)$ is the x component of the velocity field for which profiles are superimposed on the streamline pattern at five different values of x. The value of the density is recorded at the upstream end of each streamline. Four density profiles, $\rho(x, z)$, are given below. x is measured in inches, u in in./sec and ρ in g/cm^3.

frequency was about 4 sec^{-1}. The constant density lines coincide with the streamlines because the density of a fluid particle cannot change during a time interval characteristic of the flow, so the streamline pattern in figure 5 was obtained by analysis of both streakline and density field data. This is a good example of a flow which would be very difficult if not impossible to generate in a towing tank, because such a flow must be maintained for a rather long time before steady conditions are achieved, perhaps 15 min. (In fact, the flow had been running steadily for six hours before the data were collected.) The collection of the detailed data presented here required about one hour, a time which would require a prohibitively long towing tank. The same flow would be equally difficult to produce in a heated-air wind tunnel for the different reason that rather strong stratification effects would be necessary to create the strongly blocked flow shown here.

The examples shown in figures 4 and 5 illustrate the point made earlier that the obstacle in the observation section plays a significant part in determining the upstream velocity profile.

7. Conclusion

The prototype device constructed and tested has demonstrated that a continuous steady flow with significant density gradients can be obtained in the fashion outlined above. Such a facility, especially a scaled-up version of it, would be eminently suitable for observation of phenomena such as blocking by obstacles or turbulent wakes, which require longer periods of observation than are practically available in towing tanks and where stronger stable density stratification is desired than can be obtained in heated air tunnels. The convenience of having a truly steady and easily visualizable flow need hardly be emphasized.

This research was supported in part by the National Science Foundation under grant GA-641 X.

REFERENCES

Gibson, C. H. & Schwarz, W. H. 1963 Detection of conductivity fluctuations in a turbulent flow field. *J. Fluid Mech.* **16**, 357–364.

Lin, J. T. & Binder, G. J. 1967 Simulation of mountain lee waves in a wind tunnel. *College of Engineering, Colorado State University. Int. Tech. Rep.* no. CER 67–68 JTL–GJB 24.

Long, R. R. 1954 Some aspects of the flow of stratified fluids. II. Experiments with a two-fluid system. *Tellus*, **6**, 97–105.

Long, R. R. 1955 Some aspects of the flow of stratified fluids. III. Continuous density gradients. *Tellus*, **7**, 341–357.

Pao, Y. H. 1968 Laminar flow of a stably stratified fluid past a flat plate. *J. Fluid Mech.* **34**, 795–808.

Schraub, F. A., Kline, S. J., Henry, J., Runstadler, P. W. & Little, A. 1965 Use of hydrogen bubbles for quantitative determination of time-dependent velocity fields. *A.S.M.E.* series D, **87**, 429.

Scotti, R. S. 1969 An experimental study of a stratified shear layer. *Aeronaut. Sci. Division, University of California, Int. Tech. Rep.* AS–69–1.

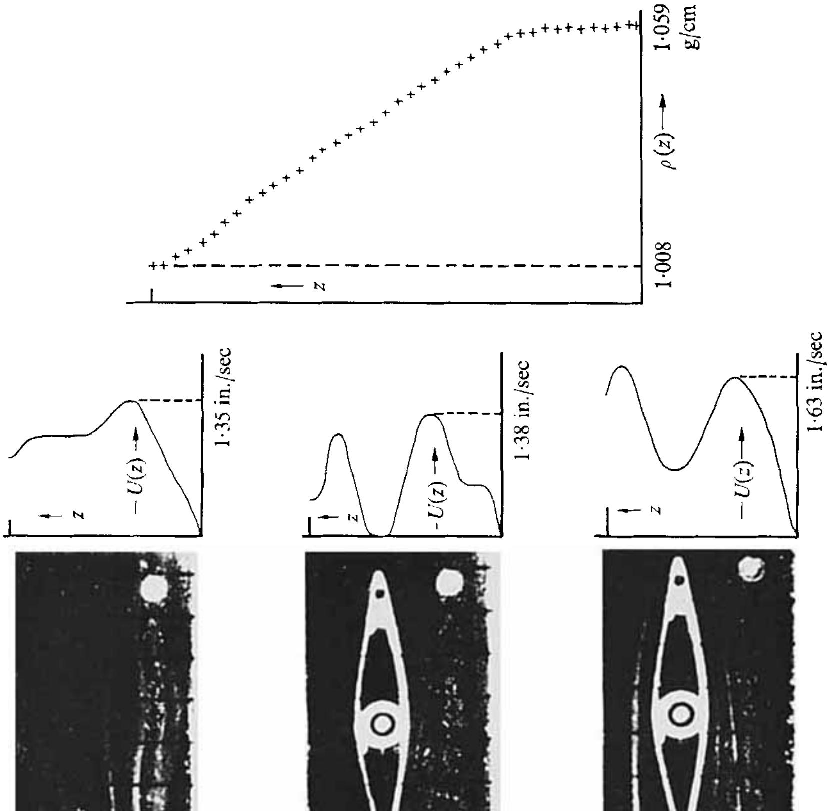

FIGURE 4. Three typical samples of flow. The flow is from left to right. The white lines are streaklines, marked by hydrogen bubbles. Vertical black lines show 1 in. intervals. On the right of each flow the upstream velocity profile is shown. At the far right, the density profile is shown with the vertical scale expanded.