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Schlieren Visualization of a Stratified Flow around a Cylinder

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***Abstract*:** Description of different modification of schlieren techniques is presented. The methods are based on Maksoutov's scheme of the schlieren mirror instrument with an illuminating slit and a different cutting diaphragm, specifically with Foucault knife, filament or grating. Depending on a slope of the slit to the vertical both black-and-white and colour schlieren images of a stratified flow are produced. Simple colour schlieren method using natural dispersion of white light in a stratified medium is described. 'Natural rainbow' schlieren image of a stratified flow is formed when an illuminated slit is placed horizontally and regular grating is used as a light cutting element. The method is characterised by a high spatial and temporal resolution and by a wider dynamic range than the traditional one. Examples of black-and-white and colour images of a stratified flow near a towing cylinder are presented.

***Keywords*:** colour schlieren technique, stratified flows.

1. Introduction

Fluids in the environment and in technology set-ups are mostly stably stratified due to non-uniformity of temperature or salinity. Stratification, even weak, inhibits a vertical component of motions and affects a flow structure, its dynamics and stability. Observations of flow patterns and probe measurements are both important for understanding physics and creating mathematical models of free stratified flows.

It is well known that different optical techniques, including shadowgraphs, schlieren and interferometry developed for visualization of compressible gas flows, can be used for studying a stratified liquid flows since changes in concentration, temperature, density of a fluid and a wave-length of light are accompanied by changes in refractive index. Disturbances in a stratified liquid will change a pattern of the refractive index which, in turn, will produce a change in the schlieren image. The application of optic methods for density stratified liquids should be based on the fact that light rays passing through the liquid are deflected even in the undisturbed medium. A tank with the vertical wall filled with a linearly stratified brine is similar to an optical prism the optic length of which is determined by the refractive index profile for a constant geometrical width of the tank. Moreover in a stratified liquid all the changes in reflected index are many times greater than those encountered in compressible gas flows. And due to the quite large changes of refractive index with the wave-length of light, dispersion effects must be taken into account. That is why the conventional methods of visualisation (interferometer, schlieren, shadow) can not be transported directly on stratified flows and should be adapted.

In practice different modifications of schlieren methods proposed by D.D. Maksoutov (1934) are mostly used in view of their sensitivity, flexibility and universality. A schlieren instrument consists of two separate parts, specifically illuminating and receiving parts. Each part contains an objective consisting of a main mirror and a compensating lens. The compensating lens with almost parallel spherical surfaces reduces aberrations of the main reflective mirror. As the Maksoutov's schlieren instrument consists of two similar objectives, their asymmetric aberrations are mutually compensated during assembling and adjustment and the total aberration of the instrument is less than the aberration of its each part. Another very important Maksoutov's improvement suggests replacing a circular illuminating diaphragm, the conventional source of light for optical measurements, by an elongated illuminating slit. To produce the schlieren effect part of the light forming the image of the light source must be cut off in the receiving part. Besides a sharp blade edge - the Foucault knife, several kinds of light cutting diaphragms, specifically, a thin filament, a narrow slit between two blade edges or a graded schlieren filter for closing part of light rays have been proposed by Maksoutov (1934). Due to a mean deflection and dispersion of light in a stratified liquid the action of cutting diaphragm depends on angular positions of the illuminating slit and of the cutting diaphragm in the focal planes. Mowbray (1967) has shown that for producing the best conventional black-and-white image of a stratified flow the illuminating slit and the cutting edge of the Foucault knife should be placed vertically.

Flexible Maksoutov's method can also be used for producing a natural 'rainbow' image of a stratified flow. The objective of this paper is to present a theory of this schlieren instrument taking into account the dispersion of light (Chashechkin 1979), to describe a simple modification of the traditional schlieren instrument enlarging its dynamic range proposed by Chashechkin and Popov (1981) and to give examples of colour patterns, visualizing all well-known conventional and some new elements of the 2D stratified flow around a cylinder.

The scheme of conventional reflector schlieren instrument is presented in Fig. 1. The light from the source *1* (mercury vapour lamp, electric lamp with spiral or plane heating body, optic laser with expander) is focused by condenser *2*. The illuminating diaphragm *3* placed in the focal plane of the condenser is used for control of the light source effective size. Typical width of the illuminated slit formed by the diaphragm *3* is (0.01...0.3) cm and its height is (0.2...2.5) cm. The diaphragm is located at the focus of main concave spherical mirror *4*. Past a small turning mirror the light comes on the fully reflecting mirror *4* and goes out from the illuminating part of the instrument through an aberrations compensator (spherical meniscus) *5* as a parallel beam. After passing through the working section of a stratified tank 6 the beam goes through the aberrations compensator of receiving part *7* and is condensed in the focus of the second mirror *8*. The image of the light sours in the illuminating part of the instrument is formed in the focal plane of the main mirror of the receiving part. Part of light is cut off by a visualising diaphragm *9* while the remainder enters through the objective *10*. The latter is focused on a plane of observation inside the working section of the tank *6*. It is important that mirrors *4*, *8* and compensators *5*, *7* are parts of larger optical details with spherical surfaces. They are cut and mounted so that their anti-symmetric aberrations mutually compensate each other. The design and use of schlieren instruments are described in details by Vasilyev (1968).

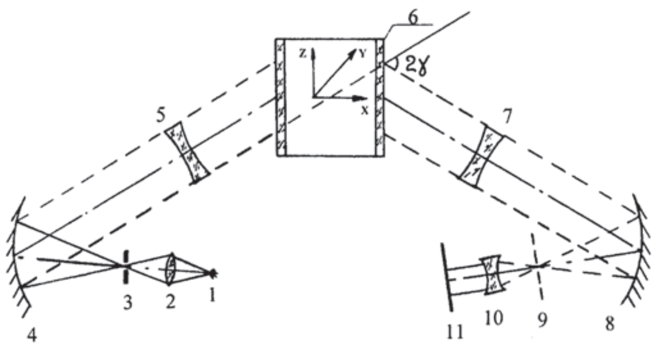


Fig. 1. Schematic diagram of reflector schlieren instrument.

The most popular schlieren instruments in Russia (IAB-458 or IAB-451) are characterised by a focal length equal to 190.43 cm and of a diameter of view field equal to 23 cm. They are constructed for registration of small deflections of the light beam (0...25') with the angular resolution of about 0.1" ($5{\cdot}10^{-7}$ rad). The spatial resolution after film processing is about 0.01 cm. The more advanced instrument IAB-463 has the aperture of 46 cm (Vasilyev, 1968). All the instruments are assembled in the rigid metallic tubes. Besides schlieren and shadowgraph techniques holographic interferometer and schlieren interferometer can be designed on their basis. All following experimental results are received by the schlieren instrument IAB-458.

Because in a stratified fluid there is a general deflection of light due to the refraction index gradient, the illuminating and receiving parts of the instrument are placed on independently adjustable foundations with the control of four degrees of freedom, specifically displacements and rotations in the vertical and horizontal planes. In experiments a linear profile of density is mostly used. In this case all light rays are deflected on the same angle to horizontal ($2\gamma^0$), so that the beam coming on the second main mirror is composed by parallel rays and the size of the image is determined by an aperture of the instrument.

For arbitrary profiles of density the height of horizontal lightened image strip is limited by the maximum registered light rays deflection angle (25' for the given instrument) from their reference value. The whole pattern of a flow can be composed step by step (or more strictly speaking strip by strip) by consequently change of the tilt of the instrument parts to the horizontal. In practice the best result is obtained when both parts of the instrument are tilted at the same angle γ.

2. Analysis

The path of light rays through a fluid with the refractive index n, that varies in a continuous manner, is given by the Euler-Lagrange equations (Mowbray, 1967). Due to large variations of the refractive index in a stratified liquid the equations must be integrated exactly taking into account the dispersion of light. The disturbance is assumed to be two dimensional so along the light rays $\partial n/\partial x = 0$.

The exact solution of Euler-Lagrange equations for monochromatic light rays traversing a fluid in which $\partial n/\partial y$ equals to zero, is (Mowbray, 1967)

$$x = -\int_{z_0}^{z} \frac{dz}{\sqrt{(\alpha n/n_e)^2 - \beta^2}}; \quad \alpha = \sqrt{1+\left[\frac{dy}{dx}\right]_e^2 \left[\frac{dz}{dx}\right]_e^2}\ ; \quad \beta = \sqrt{1+\left[\frac{dy}{dx}\right]_e^2}\ . \tag{1}$$

The subscript $\boldsymbol{e}$ refers to conditions at the inside face of the first glass wall. For the common salt brine the refractive index n is a linear function of its density ρ (Mowbray, 1967).

$$n = 1.3330 + 0.231\ (\rho - 1) \tag{2}$$

In general case the angle of ray deflection depends upon light wave length λ. Far from the lines of the light absorption the refractive index of the fluid is described by approximate equation of state

$$\frac{n^2-1}{n^2+2} = \frac{\mu A}{1-(\lambda_0/\lambda)^2} \tag{3}$$

where $\mu = \rho/\rho_0$ is dimensionless density, ρ_0 is reference density, A and λ_0 are empirical constants. One can resolve (3) relatively to n and expand the resulting expression in Taylor series. Writing only the linear term on μ we receive the expression (3) in the form

$$n = A' + (B' + C'/\lambda^2)\ \mu \tag{4}$$

with three empirical constants A'; B'; C'.

In laboratory studies the stratified water solution of the common salt is mostly used. Optical properties of the salt brine are presented by Kaufman, 1960. For diluted sea water values of coefficients in (4), calculated from tables presented by Popov et al. (1979) by the least mean squares method, are $A' = 1.14948$; $B' = 1.17478$; $C' = 0.00303$. The choice between approximations (3) and (4) can be made for any particular problem from the condition of minimum error. For the salt brine and sea water formula (4) is successfully used.

For linear profile of undisturbed density $\mu = (1+ bz)$, b = *const* calculation of (1) yields

$$x = n_0 \frac{\sqrt{(1-\mu_0 B)^3}}{\sqrt{3}\,Bb}\,[arcsin\sqrt{X} + \sqrt{X}\sqrt{1-X}\,] \qquad (5)$$

where $X = \dfrac{Bb\,(z - z_0)}{(1-\mu_0 B)}$, $\quad B = \dfrac{A}{1-(\lambda_0/\lambda)^2}$,

and for displacement and inclination of the light rays are, respectively, (taking into account smallness of $\sqrt{X} \approx 10^{-2}$ rad for typical experimental conditions):

$$z - z_0 = \frac{3Bbx^2}{4n_0^2\,(1-\mu_0 B)^2}, \quad \frac{dz}{dx} = \frac{3Bbx^2}{4n_0^2\,(1-\mu_0 B)^2}.$$

For linearized equation of state (4) integration of (1) yields

$$z = \left[\frac{n_0}{k}\right] arcch\,\frac{m + kz}{m + kz_0}$$

where $m = A' + (B' + C'/\lambda^2)$, $k = b(B' + C'/\lambda^2)$, and we receive for displacement and inclination of the light rays:

$$z - z_0 = kbx^2/2n_0;\ dz/dx = kbx/n_0, \text{ as } kx/n_0 \cong 4\cdot 10^{-2} \text{ rad.}$$

On leaving the liquid the light rays go through the glass window into the air deflecting in accordance with Snell's law of refraction. Since the differences $(z - z_0)$ and $(n - n_0)$ are small, the total deflection of ray at the point where it leaves the tank is $\delta = bkW$, where W is the width of the tank.

For equation of state (3) this angle is $\delta = 3BbW/2n_0\,(1 - \mu_0 B)^2$ and the additional widening of illuminating slit image in the focal plane of receiving system in different colours taken from the edges of visible light range, namely from blue light with wave length λ_b to the red one with λ_r is

$$\Delta = F\,(\delta_b - \delta_r) = \frac{3bFW}{2n_0}\left[\frac{B_b}{(1-\mu_0 B_b)^2} - \frac{B_r}{(1-\mu_0 B_b)^2}\right]. \qquad (6)$$

For equation of state (4) the expression for widening of slit image is more simple.

$$\Delta = FbW\,C'\,(\lambda_b^{-2} - \lambda_r^{-2}) \qquad (7)$$

From both expressions it follows that the additional widening of coloured image of illuminating slit Δ is proportional to the focal length of main mirror F, width of a tank W, density gradient value b and depends on coefficients of dispersion of light in the test fluid.

Due to the dispersion of light even for the vertical slit and knife the schlieren image of flow is coloured partially, especially if the slit is thin. The colours become brighter and more saturated when the cutting knife is replaced by a thin filament. The image of the stratified medium becomes perfectly 'rainbow' coloured if the slit is located horizontally and the knife is replaced by a grating with a regular or variable step.

As it follows from the formula (6, 7) the set of spectrally disintegrated superimposed images of the light source is formed in the focal plane of the receiving part of the instrument. When a two-dimensional grating consisting of equal transparent and non-transparent strips, is placed in parallel to the slit (horizontally and perpendicular to the direction of the mean refractive index gradient), it partially overlaps the set of source images. Due to this effect the pattern in the plane of the subject observation becomes spectrally coloured in one or several 'rainbow' bands. The height of a complete band depends on a density gradient value, a tank width and parameters of grating. The colour in a given point depends on a step and position of the grating and can be merely changed by the grating displacement.

In an undisturbed medium the refractive index gradient is directed vertically. Due to this the appropriate horizontal grading forms a stripy coloured image of a stratified fluid. The height, brightness, saturation and location of 'rainbow' bands depend on the refractive index gradient, a thickness of the grating strips (the grating step) and its location. Dynamic processes in a stratified medium change an initial distribution of the refractive index and cause displacement and distortion of coloured strips.

In the given experiments different gratings with constant and changing thickness of steps are used for producing of colour images. The choice of grating type depends also on the feature of explored process, spectral parameters of the light source and photo materials.

The grating period is selected to satisfy conditions of maximum brightness and saturation of 'rainbow' colours in the image of an undisturbed fluid, the presence of all spectral colours and the absence of visible diffraction and image doubling effects. Practically the highest quality of images is obtained when the grating period is taken equal to (1.2 ... 1.6)Δ. For typical laboratory conditions, sizes of the illuminating slit are (0.01 ... 0.15) $\times$ 1.0 cm^2, the thickness of the grating strips is (0.02 ... 0.25) cm, the number of strips is (5 ... 15), and the grating background can be transparent or black.

By displacement of the grating in the vertical direction one can change the background colour of the flow pattern and, in case of a variable density gradient, the local sensitivity of the instrument. This additional degree of control essentially enlarges the dynamic range of the schlieren instrument. Practically the dynamic range increases several times since the image of the slit does not cut completely by the knife as in the conventional schlieren instrument, but only partially covered by one or another strip of the grating.

The instrument sensitivity to the angular displacements of the light rays, caused by an optical (and density) disturbance can be also determined before each experiment. To this end, registration of an undisturbed media pattern in different positions of the cutting grating is performed. The traditional calibration procedure can also be used. In this case the image of a 'standard disturbance' namely a long focal length lens or a transparent optic wedge introduced into the working section of the instrument is registered.

3. Basic Parameters of a Stratified Flow near a Cylinder

To illustrate different schlieren images we present patterns of a flow past a cylinder, towing with constant velocity in a continuously stratified fluid. The initial dimensional parameters of the problem are velocity U and the diameter of the cylinder d, the gravitational acceleration g, the initial density ρ and its gradient $d\rho(z)/dz$, the kinematic viscosity coefficient ν and the salt diffusion coefficient k_s.

The density profile $\rho(z)$ is characterised by the buoyancy scale length $\Lambda = |d\ ln\ \rho\ /\ dz|^{-1}$, the buoyancy frequency N and period $T_b = 2\pi\ /\ N = 2\pi\sqrt{\Lambda/g}$, the z – axis is directed vertically upwards. The local buoyancy frequency value and its profile are checked by the density marker method. These markers are produced by a laminar wake past a vertically ascending small gas bubble or a free descending common salt or sugar crystal. Internal oscillations around the vertically submerging marker are observed optically or measured by the conductivity probe.

There are a set of length scales and the unique natural time scale i.e. the buoyancy period T_b in the problem. The external length scales are the buoyancy scale Λ and the diameter of the towing body d. The internal structure of a flow is characterised by several intrinsic length scales, i.e by the length of adjoined (lee) internal waves $\lambda = U/T_b$, the thickness of the velocity boundary layer $\delta u = \nu/U$, thickness of the density boundary layer $\delta_\rho = k_s/U$ on the body surface (Chashechkin, 1993).

The other group of small length scale parameters describes internal boundary currents, which are produced by a separating boundary layer or are formed directly in a continuously stratified fluid interior resulting from non-linear interaction of a larger scale processes (internal waves, vortices and jets). The internal boundary currents are characterised by two intrinsic length scales. Variations of velocity in the current are described by the scale $\delta_\nu = \sqrt{\nu/N}$ and variations of salinity (and density) are described by the length scale $\delta_s = \sqrt{k_s/N}$ (Chashechkin, Mitkin, 1998).

The conventional dimensionless parameters can be expressed in terms of direct (Fr, C) or inverse (Re, Pe) ratios of the appropriate scales to the body diameter: internal Froude number $Fr = U/Nd = \lambda/$d, length scales ratio $C = \rho/\Delta\rho = \Lambda/d$, Reynolds number $R = Ud/\nu = d/\delta_u$, Peclét number $Pe = Ud/k_s = d/\delta_\rho$.

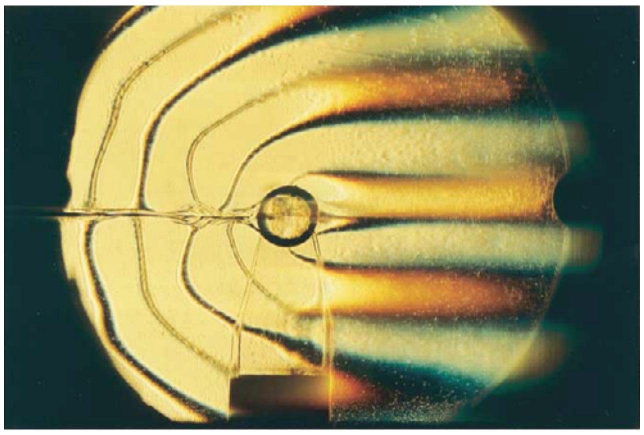
To visualise all these elements of the flow which are characterised by the set of different length scales, an optical instrument should have large aperture, high sensitivity and a fine spatial resolution. These demands are controversial and can be met only partially. That is why only the combination of different optical methods, which complement each other, can give more or less complete image of real pattern of a stratified flow.

4. Experiments

All experiments are conducted in a tank 2.2 × 0.4 × 0.6 m^3 filled from below with a stratified common salt solution using the well known two-tanks method (Oster,1965). In this technique one storage tank is filled by tap water, the second one – by the brine in the density range from 1.005 to 1.2 g/cm^3. In these experiments the buoyancy period value is changed from 5.2 s to 30 s. The plastic hollow cylinder with length equal to the tank width (40 cm) and the external diameter of 0.8, 1.5, 3.2, 5.0 or 7.6 cm is towed horizontally by means of two vertical transparent blades rigidly fastened to a carriage. The latter moves along rails mounted above the tank. The towing speed is in the range of 0.01 – 10 cm/s. The side view of the flow pattern is registered by the schlieren instrument IAB-458 (Vasilyev, 1968).

Traditional schlieren image of the stationary flow around uniformly moving cylinder is shown in Fig. 2(a). The cutting diaphragm (the knife) and illuminating slit with the width of 0.28 mm are located vertically. The sequence of wide dark and light semicircular bands past the cylinder visualises set of adjoined internal waves. Inside the density wake, originated from attached rear vortex, one can see several isolated vortex bubbles connected by thin elongated interfaces. Tilting wide bands ahead of the body show upstream disturbances, including transient internal waves and blocked liquid ahead of the body (Stevenson, 1973). Boundaries between these bands correspond to crests and troughs of internal waves. Their shapes are described by the theory rather well (Chashechkin and Makarov, 1984).

(a)



(b)

Fig. 2. Pattern of stationary stratified flow around the horizontally towing cylinder(T_b = 12.5 s, D = 2.5 cm, U = 0.3 cm/s, $Fr = U/ND$ = 0.24, Re = 76.5, C = 1550). (a) – conventional "vertical slit-knife"; (b) – "vertical slit-thread", width of slit is 0.28 mm, thread thickness is 0.16 mm.

The background colour of the image depends on the location of the knife relatively to the slit. Due to the dispersion colouring of the slit image there is the blue background of the given flow image, most clearly visible on tips of sloping bands ahead the body. If we turn the knife on 180˚ it begins to cut the other side of spectrally disintegrated slit image and the tips will be red. Thick dark bands visualising internal waves mask weaker vortex disturbances inside the wake. This method is too sensitive and does not indicate the amplitudes of internal waves.

More informative schlieren image is received when the cutting knife is replaced by a vertical filament. Pattern of motion for the same flow parameters is shown in Fig. 2(b). In this case variations of brightness on schlieren images are proportional to changes of the local radial component of the density gradient. This method visualises only lines of crests (darker ones) and troughs (double grey lines) of internal waves. Changes in colours ahead the body help to distinguish domains of strengthening and weakening of the initial density gradient. Brightness of the schlieren image ahead the body depends on amplitudes of the transient internal waves.

The main field of view remains clear. In this case the superfine structure of the density wake and fine disturbances inside the strong wave field are completely resolved. The interfaces inside the downstream density wake are formed by internal boundary layers separating from the body surface. From the distribution of mean brightness one can see zones of maximum wave amplitudes past the body and domains of their gradual attenuation ahead the body.

The typical side view 'rainbow' colour schlieren image of a stratified liquid around a cylinder at rest is shown in Fig. 3. Usually an observed image consists of a system of periodic horizontal 'rainbow' bands but for the given parameters of stratification and grating only one complete band is formed by the schlieren instrument IAB-458. It is important to mark the difference between height of spectral bands and their locations inside and outside the cylinder. Due to the break of a molecular flux on the body surface the initial density gradient becomes weaker inside the impermeable cylinder. That is why locations of the same spectral bands inside and outside the cylinder do not coincide near the poles and coincide around its central plane where the initial density gradient value is still maintained.

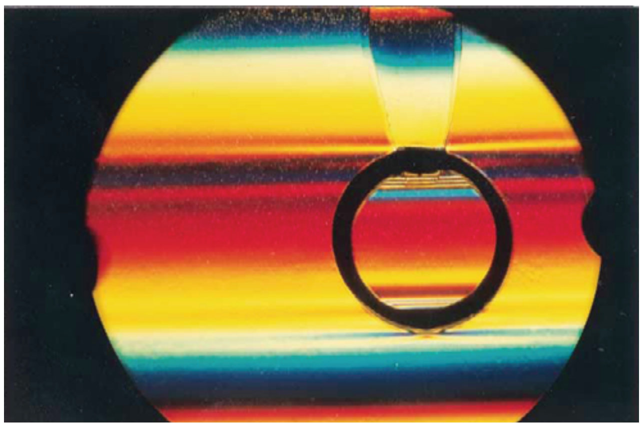


Fig. 3. Natural 'rainbow' schlieren image of stratified flow around the cylinder at rest (T_b = 6.1 s; D = 7,6 cm, slit width is 0.35 mm, grating period is 3 mm here and below).

There are small scale distortions of colour bands near the upper and lower poles of the cylinder in Fig. 3. These distortions manifest the boundary current induced by a diffusion near a motionless horizontal cylinder submerged in a continuously stratified fluid at rest.

The condition of impermeability of a matter at sloping boundaries leads to a break of horizontal homogeneity of the medium and to formation of the specific boundary current with different scales of spatial variability of density and velocity even when the fluid and the body are at rest. The flow consists of four vortices that is one in every quadrant. The velocity of the fluid directs towards the cylinder in vicinity of its central plane and outwards near its poles. The transverse size of the vortices is an order of the cylinder radius. But all variations of salinity are concentrated in thin interfaces with the thickness of order $\delta_s = \sqrt{k_s/N}$ near the poles. Distortion and interruption of blue line near the lower pole of the cylinder visualise this specific boundary current outside the cylinder. Inside the cylinder one can observe the weakening of the density gradient near the poles due to lack of the supporting molecular flux. Parameters of the diffusion induced boundary current near a motionless cylinder are calculated by Baydulov and Chashechkin (1996).

In the pattern of flow near a starting body (Fig. 4, direction of motion from left to right) one can see the formation of blocked zone ahead the cylinder (black and red domain bounded by thin line ahead the cylinder); sequence of transient and adjoined internal waves (dark patches show domains of maximum amplitudes, closed lines are iso-surfaces of wave displacements); the density wake bounded by sloping interfaces with visible vortex motion near the body. There are four singular points on the body surface. On the front part there are two points that mark intersections of the blocked zone boundaries with the body surface (points of contacts of counter flows). On the rear part of the cylinder two points of separation of the density boundary currents (points of flow bifurcation or co-flow inside and outside the wake) are presented.

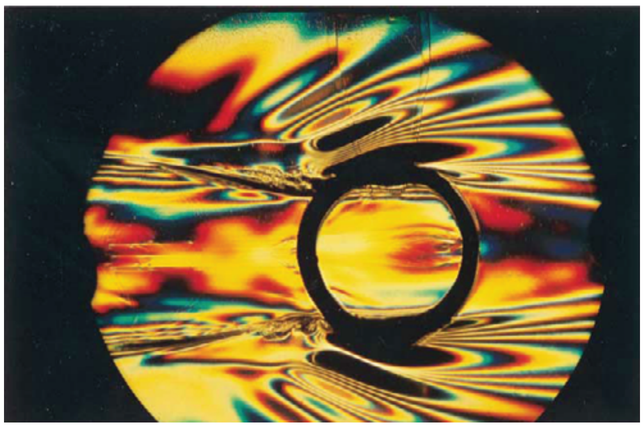


Fig. 4. Natural 'rainbow' schlieren image of stratified flow around the starting cylinder (T_b = 6.1 s; D = 7.6 cm, U = 0.24 cm/s, $Fr = U/ND$ = 0.03, Re = 182, C = 121, t = 25 s).

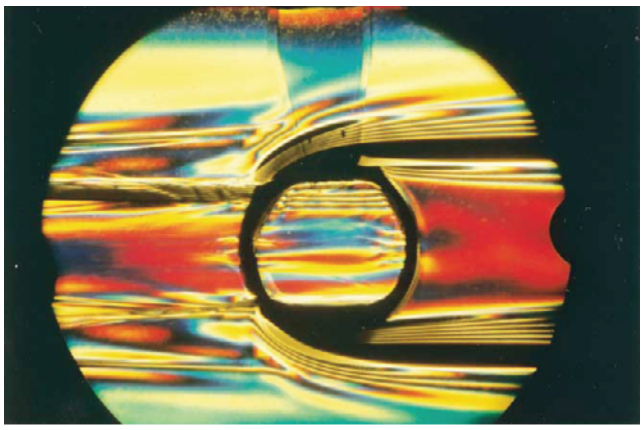


Fig. 5. Pattern of stationary flow near the horizontally towing cylinder (T_b = 5.8 s; D = 7.6 cm, U = 0.12 cm/s, $Fr = U/ND$ = 0.015, Re = 91, C = 110).

New elements of motion, i.e. isolated surfaces of density gradient discontinuity, are also visualised by the 'natural rainbow' schlieren technique in this range of the flow parameters. These soaring horizontal interfaces originate from domains of the most intensive wave motion. They are separated from the body and its wake by bands of a uniformly stratified liquid. The interfaces are uniform along all their length and have no singularities on their leading and trail edges. Earlier high gradient interfaces produced by isolated soaring vortices were observed in the wakes past a cylinder (Chashechkin, 1993). Here the internal boundary currents inside the internal wave field are presented. These interfaces result from non-linear interaction of adjoined internal waves with a mean flow of no-wave type induced in a tank by a moving 2D body (Chashechkin and Mitkin, 1998).

The pattern of flow around stationary moving cylinder is shown in Fig. 5. Ahead the body their is a portion of a blocked liquid coloured in red, that is bounded by two pronounced transient internal waves. Downstream wake past the cylinder is covered by high gradient sloping interfaces touching the body surface. Two soaring interfaces are separated from the body surface by adjoined internal waves. They are also separated from the downstream density wake by strips of fluid without any small scale inhomogeneities. The pattern of iso-surfaces in the colour schlieren image of a stratified flow and even on its black-and-white copy helps to extract additional information about pattern of vertical displacements of fluid particles from their initial positions.

The 'natural rainbow' colour schlieren method is highly informative and provides data about constant phase loci of internal waves and about distribution of the density gradient along them too. On the images besides waves, upstream and downstream wakes one can see domains of intensive small scale vortex motions on the external boundaries of the density wake.

The values of spatial resolution of all these methods are almost the same and for all experiments are less than 0.01 cm. The temporal resolution is determined by a rate of registration. In general all these methods are complementary and can be used practically simultaneously.

5. Conclusions

Advantages of schlieren methods are high sensitivity, fine spatial and temporal resolution. Comparatively large aperture, direct compatibility with other visualisation techniques, i.e. dyeing, markers, neutral buoyancy particles, electrolytic precipitation (used, for example, by Sysoeva and Chashechkin, 1992), makes them a flexible and powerful scientific instrument in studying of stratified flows. Some of their disadvantages (for example, the ones caused by an incompatibility of a narrow dynamic range of the instrument with the large value of a density gradient variations in a stratified flow) can be compensated by simple technical improvements (for example, by replacing of the cutting knife by a grating).

As the human eye is more sensitive to changes in colour than those in brightness, different modifications of colour schlieren instruments provide additional information on the flow structure. A colour slide (Merzkirch, 1974) or 'bull eye rainbow filter' (Teoh et al., 1997) are also used as a colour forming elements in a schlieren instrument. Using a simple grating one can receive perfect 'natural rainbow' colour images of a stratified flow. The method is based on natural dispersion of light in a stratified brine and does not need additional light filtering of dividing optic elements.

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