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A Visual Study on Flow Pattern Around the Strip Moving Uniformly in a Continuously Stratified Fluid

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Abstract : The flow pattern around a thin strip horizontally towed at constant velocity in a continuously stratified liquid is visualized by conventional "Vertical slit-Foucault's knife", "Maksoutov's slit-thread" and "horizontal slit-regular grating" methods. Using these sensitive high-resolution methods enables to reveal new kind of the streaky structure including a sequence of thin sloping interfaces both on the strip surface and inside its wake. When velocity or distance from the strip increases, the streaks may be turned into the sloping or nearly horizontal interfaces. Reconnections of outer edges of the streaks result in appearance of a set of symmetrical "butterfly-like" vortices, which are perturbed by a shear flow inside the downstream wake. Lift forces caused by a slope of the strip produce an asymmetry of the wake and lead to fast degeneration of the streaky structures.

Keywords : Schlieren technique, Stratified fluid, Horizontal strip, Internal waves, Streaky structures

1. Introduction

Investigations of internal waves, upstream disturbances and vortex structures around 2D smooth and bluff bodies (Chashechkin and Mitkin, 2001, a), past a singular or an array of horizontal plates (Nakamura et al., 1991; Guillaume and LaRue, 2001), uniformly moving in a stratified or homogeneous liquid, have received much attention. Apart from these elements the high-resolution schlieren methods reveal sharp horizontal interfaces in a vicinity of an impermeable surface of the obstacle regardless of whether it moves or not in a stratified fluid at rest. These interfaces indicate that an initially smooth stratification is transformed into a layered structure. From the boundary conditions (no-slip for velocity and no-flux for salinity), it follows that an interruption of the ambient molecular flux of the stratifying component on a boundary disturbs the horizontal uniformity of the density. Action of the gravity force causes a compensating current.

Exact solution of the initial value problem, describing a formation of diffusion induced current on a sloping plane (Kistovich and Chashechkin 1993) and asymptotic solutions for flows on the sphere or the cylinder (Baydulov and Chashechkin, 1996) are constructed. They describe boundary layers characterising by different length scales of velocity $\delta_b = \sqrt{\nu/N}$ and for density $\delta_\rho = \sqrt{\kappa_s/N}$, where ν is kinematic viscosity, κ_S is salt diffusion coefficient, and $N = \sqrt{(g/\rho(z))(d\rho/dz)}$ is a buoyancy frequency (g is gravity acceleration, ρ is density, the axis OZ is directed upward). The length scales do not depend on the surface slope. This time-dependent solution has no stationary limit. An available solution of the same stationary posed problem is characterized by common length scale for density and velocity boundary layers $\lambda_p = \sqrt[4]{\nu\kappa_s / N^2 \sin^2 \alpha}$ that depends on the plane slope, α, to the horizontal (Phillips, 1970).

When the obstacle starts to move the diffusion induced boundary currents separate from the surface and produce slightly sloping high gradient interfaces inside the density wake (Baydulov, et. al., 1999; Chashechkin and Mitkin, 2001, a). The singular interfaces that have no contact with the boundary layer and dynamical features on their leading and trailing edges are also observed inside the attached (lee) internal wave field (Chashechkin, 1999). All these thin interfaces are oriented in the direction of motion.

Essentially less is known about fine structure of a stratified wake past the horizontal plate. The aim of this paper is to present patterns of the flow around plane strips and to demonstrate the new types of small-scale streaky structures forming in continuously stratified brine.

2. Experimental techniques

The experiments are conducted in a rectangular 2.2 × 0.4 × 0.6 m^3 transparent tank with the optical windows. The tank is filled with linearly stratified brine through the bottom valve using the well-known two tanks method. Side view of the flow is observed by the Schlieren instrument IAB-458, whose view field diameter is 23 cm; the spatial resolution of the instrument is better than 0.1 mm. The conventional instrument with the light cutting flat knife, or with Maksoutov's visualizing thread, also with a horizontal grating giving “natural rainbow” colour Schlieren image (Chashechkin, 1999) are used.

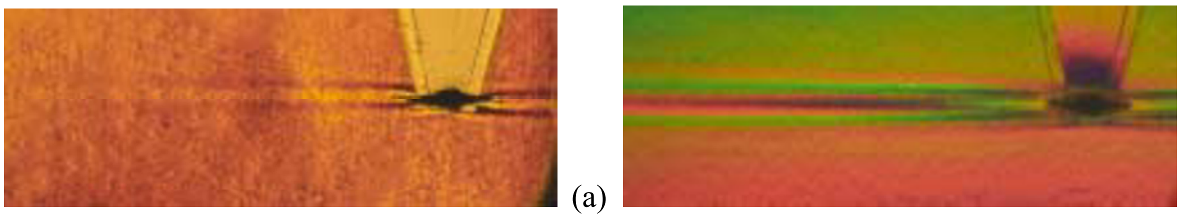
Prior to each test, the buoyancy period $T_b = 2\pi/N$ is determined (with accuracy 5%) from a marker produced salinity oscillations measured by conductivity probe. The marker is formed by a vertical wake past a free falling sugar crystal or a small vertically arising gas bubble and is observed in a quiescent environment over 200 s. The marker is also used to measure a horizontal component of the velocity. Accuracy of velocity measurements and the spatial resolution are defined by the marker thickness, which is about 0.25 mm. So both the density and the velocity fields are visualized continuously in the entire observation plane as distinct from the particle tracking methods illustrating particle displacements only in separated points.

The towing obstacle is a plastic strip of width L_c = 2.5 cm, length 36.5 cm and thickness of 0.1 cm, having the flat leading and rear edges. The strip central part is strengthened, at the both sides, with sharpened strips of width 1.5 cm, length 36.5 cm and the same thickness of 0.1 cm. The strip tips are fixed between two thin vertical transparent plastic supports attached to the towing carriage with metal knifes. The carriage is put at the rails above the tank. The horizontal position of the strip and its trajectory are carefully adjusted during the filling of the tank with respect to a free water surface. The experimental conditions (6.6 < T_b < 17.4 s, 0.1 < U < 6 cm/s, correspond to laminar and transient flow regimes.

At the beginning of each run series, the carriage is positioned in the central window, and the diffusion induced boundary currents are observed in one or two days. Then the carriage is slowly moved to the front wall of the tank. After degeneration of all dynamic and structural disturbances the buoyancy period profile is measured, whereupon the carriage holding the strip is ready to start. The flow is observed through the central window. The experiment is repeated several hours later after disappearing of the entire all the dynamic and structural disturbances.

3. Experimental results

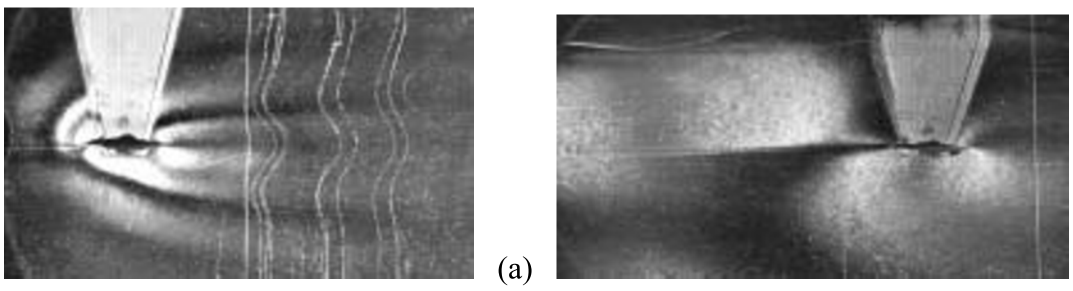
The patterns of density gradient disturbances produced by the diffusion induced boundary currents near the sloping and horizontal motionless strip in a fluid at rest are presented in Fig. 1. Conventional schlieren image in Fig. 1 (a) shows a set of high gradient interfaces outcoming from edges of the sloping strip. The length of interfaces slowly increases with time, but their thicknesses remain practically unchanged. The central interfaces, shorter of the outer ones, are smoothed under the effect of the central plane inflow. The patterns of flow around strip and the cylinder in the fluid at rest (Chashechkin, 1999) are similar. Variations of vertical component of the density gradient near the strip are rather strong; the images produced by different slits of grating are overlapped, so the pattern shown in Fig. 1 (b) looks blur near the obstacle. The observed flow pattern corresponds to the solution of the time-dependent problem (Kistovich and Chashechkin 1993) and disagrees with stationary solutions of the diffusion induced boundary currents problem (Phillips, 1970).



(a) (b)

Fig. 1. Schlieren images of the diffusion induced currents around a motionless strip in a stratified fluid at rest, T_b = 7.5 s, L_c = 2.5 cm, (a) – "slit-knife" method, $\alpha = 12.5^\circ$; (b) – "rainbow schlieren" technique, $\alpha = 0^\circ$.

Black-and-white schlieren images of the flow around the horizontally towing strip in the weak density gradient fluid are shown in Fig. 2. The sloping straight rays ahead of the obstacle visualize upstream transient internal waves. Crests and troughs of the waves are matched with the appropriate circular phase surfaces of attached (lee) internal waves past the strip. Twin grey lines past the strip (Fig. 2 (a)) show the troughs of the internal waves while dark lines mark the crests. Thin high gradient interfaces in the downstream wake outcome from the strip rear edge.



(a) (b)

Fig. 2. Pattern of flow around the horizontal strip (L_c = 2.5 cm, T_b = 14.0 s,) moving from left to right; (a) – U = 0.1 cm/s, $\alpha = 0^\circ$, "slit-thread"; (b) –U = 0.9 cm/s, $\alpha = 10.0^\circ$, "slit-knife".

Distorted vertical lines ahead the obstacle in Fig. 2 are density markers visualising vertical profiles of the velocity. The height of the central blocked liquid area is larger than the strip thickness. The vertical thread in the right part of the image in Fig. 2 (b) is the reference line to measure the markers displacements. Contours of the markers in the upper part of the Fig. 2 (a) indicate an upstream influence of both the obstacle and the vertical blades.

With the towing velocity increase, an intensity of the upstream disturbances decreases and the length of internal waves increases and a new structural component of the flow is observed. Conventional schlieren method reveals four thin short sloping interfaces in the downwind side below the sloping strip terminating with the free sharp edges (Fig. 2 (b)). Their leading edges closely attach to horizontal boundary layer on the strip. The thickness of the interfaces is less than 0.1 cm; the distance between them is about 0.5 cm. The slope of the interfaces gradually increases with the distance from the plate. The lift force distorts the thin density wake and displaces crests and troughs (Chashechkin and Mitkin, 2001, b). The density wake position is restored due to buoyancy forces and with distance it gradually comes back to the body path.

With the buoyancy frequency increase, the flow pattern becomes more complicated and a total number of transverse streaks past the strip increases (Fig. 3). Near the obstacle, their leading edges are directed horizontally, while their sharp outer edges are oriented almost vertically. The streaky wake remains rather narrow due to the buoyancy forces suppressing the vertical displacement of fluid particles. With time and distance from the strip, the slopes (with respect to the horizontal) of the individual streaks and the height of the whole structure decrease. Due to the shear flow inside the velocity wake, the streaks elongate in the horizontal direction. They are gradually smoothed by molecular diffusion and disappear.

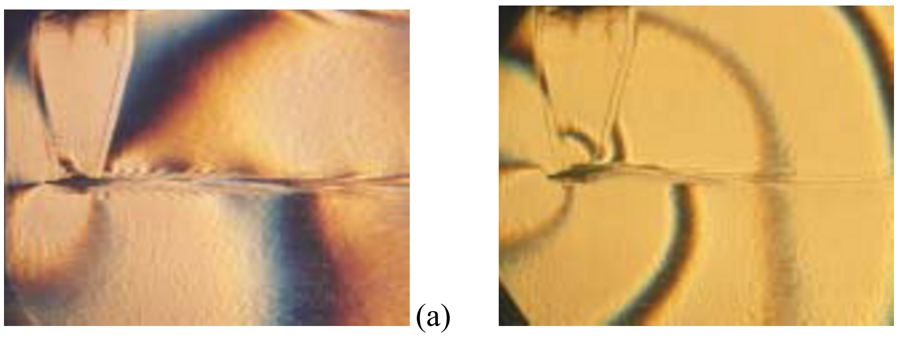

(a) (b)

Fig. 3. Pattern of flow around strip moving from right to left; T_b = 7.5s; L_c = 2.5cm; (a) – U =2.3 cm/s, $\alpha = 0^\circ$; (b) –U =1.4 cm/s; $\alpha = 12.5^\circ$; "slit-thread" method.

The lift force changes the flow pattern around the sloping strip. If the first trough and first crests in Fig. 3 (b) are located, respectively, at the strip leading edge in upper semi-space and the strip rear edge in lower semi-space, the next troughs in the both semi-spaces contact each other through the thin density wake. The central interface of the wake becomes wavy-shaped with a spatial period equal to the length of the attached internal waves $\lambda = U \cdot T_b$. In the upper semi-space, the streaks in the upwind side of the obstacle are arranged with relatively large intervals. They separate only from the rear edge of the strip.

As a contrast, in the downwind strip side the streaky structure separates along the entire surface, starting the leading edge of the strip. Their sharp trailing ends form large angles with the obstacle trajectory. The overall length of the domain occupied by the streaky structures and the thickness of individual interfaces are the same, however, the total numbers of sloping interfaces are different in the upper and the lower hemi-spaces, respectively.

The thickness of the boundary layer is small in the upwind side of the obstacle and large in the downstream side where the interfaces are merged into the uniform disturbance. Due to the baroclinicity, this domain is characterized by high level of vorticity existing in the form of superposed interfaces. Differences in the thickness and colour of curved strips, illustrating crests and troughs of internal waves in Figs. 3(a), (b). are caused by differences in wave amplitudes, mutual locations and thickness of illuminating slits and cutting threads.

Subsequent evolution of the flow structure, when increasing the strip velocity, is presented in Fig. 4. At a moderate velocity, the wave pattern is antisymmetric and the trough marked by curve grey line in upper hemi-space contacts with the crest in lower hemi-space that is marked by deep-blue curve. The pattern of the streaky structures is symmetric both in general and in individual details. The separating streaks extend horizontally with the distance from the obstacles and then gradually disappear (Fig. 4 (a)). With the body velocity increase, the streaky patterns keep the symmetry. They are arranged separately with some interval between themselves.

Sufficiently far from the strip, symmetric pairs of the streaks transform into a butterfly-like structure, presented in Fig. 4 (b). In vicinity of the central horizontal plane, a sharp pattern with thin interfaces near the body gradually turns, with the distance from the obstacle, to blur due to overlapping of slightly sloping interfaces. Separate interfaces lost their plane form and become wavy in the spanwise direction. Wavy distortions of interfaces make their images smooth in the central part of the wake. The outer edges of the streaky structures are connected between themselves with long interfaces oriented almost horizontally. The maximum vertical size of the wake is within 0.4 cm.

Substantially more complex structure is presented in Figs 4(c), (d), where two sequential photos of the same experiment illustrate evolution of flow pattern vs time, or vs distance from the strip, $x = U \cdot t$. Near the body the elongated interfaces exist, the density wake is symmetric and arranged horizontally. Next, the trailing edges of the separate interfaces are reconnected and the butterfly-like vortices are formed. The leading and trailing edges of these spanwise elongated vortices move in opposite directions and distort the shape of the wake. The central part of the wake becomes wavy. Vertical motions enhance the density variations, so the sloping interfaces inside the density wake come into particular pronounced and are visualized by short sloping black lines near the central plane in Fig. 4 (d). The vertical motion is insensibly suppressed by stratification and fluid particles relax to their neutral buoyancy horizons. As a result, the interfaces inside the density wake are oriented almost horizontally, as in the right part of Fig. 4 (d).

The disturbances caused by the supporting knifes are characterized by their own structure evolution dynamics. Initially, the sequence of vertical wavy folds is observed in the knives wake near the strip. Then the pattern sharpness increases, so, in the left part of Fig. 4 (d), we can see a set of seven vertical interfaces inceptive in the domain of the flow separation from the lower edges of the knives.

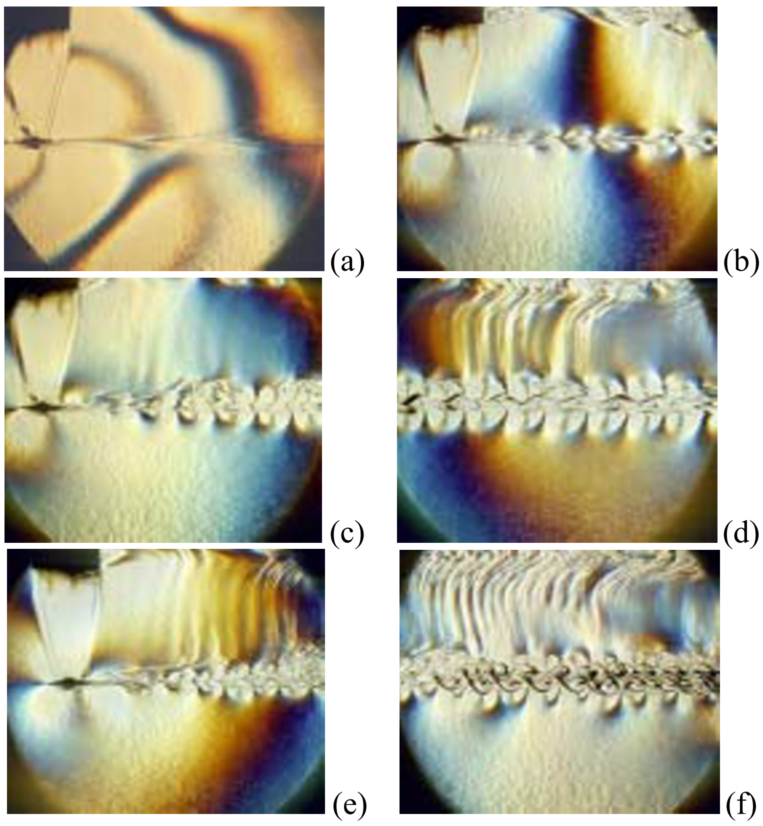


Fig. 4. Evolution of the flow pattern around the horizontal strip moving from right to left with the velocity increase, L_b = 2.5 cm T_b = 7.5 c; (a) – U = 1.38 cm/s, (b) –U = 3.2 cm/s, (c, d) – U = 4.9 cm/s, (e, f) – U = 5.25 cm/s, “slit-thread” method.

With further strip velocity increase, a general structure of the flow is conserved, but the lengths of detailed component vary. Several elongated streaky structures are observed in Fig. 4(e) on the strip sides and in the near downstream wake. With the distance, the sharp central interface past the strip starts to oscillate and, near the turning points, the vortices gradually form a set of smooth butterfly-like disturbances, and further the ones having the sharp interfaces inside. With an increase of the wake wavy oscillations, the central plane interface of the downstream wake splits into a set of interfaces. The flow come into wavy form both in longitudinal and in the spanwise direction. In the complex pattern of flow shown in Fig. 4 (f) several sets of vortices are distinguished in spanwise direction that is along the ray of observation. The flow past the 2D strip includes 3D vortex structure and gradually decays into set of interfaces. Intensively moving 3D vortices produce a big number of secondary internal waves outside the density downstream wake. Their length and slope are determined by the size and relative translation velocity of a forming vortex.

To illustrate a degree of the flow pattern reproducibility, two first images shown in Fig. 5 present the same flow pattern, visualized by the two schlieren methods in different experiments. Comparison of images in Figs. 5 (a),(b) shows that different fine structural elements are reproduced one-to-one in independent experiments. An increase of the interfaces lengths in Fig. 5 (a), comparably to Fig. 5 (b), is due to a higher sensitivity of conventional schlieren method under the given conditions of the instrument tuning. The curved dark and light strips visualising attached internal wave past the body are imperfect circular arcs, that is caused by the Doppler effect inside the velocity wake shear flow.

(a) (b) (c)

Fig. 5. Pattern of flow around a vertical strip (H_c = 2.5 cm) moving from right to left; (a, b) – T_b = 12.5 s, U = 0.1 cm/c, “slit-thread” and “slit-knife” methods; (c) – T_b = 17.4 s, U = 0.3 cm/s, “slit-knife” method.

The vertical markers indicate a profile of the velocity horizontal component. An upstream central jet representing blocked fluid is pronounced in more extent than the downstream wake. The height of the velocity wake exceeds the density wake thickness bounded by two sloping interfaces. The density wake wedge contacts the vertical strip through the single central interface whose length is about 2 cm. Due to buoyancy forces, the high gradient boundary layers separating from upper and lower edges of the strip converge to the central horizontal plane. At given regime of the flow, thin elongated interfaces occupy the whole velocity wake. The curves of attached internal waves crests and troughs penetrate through the interfaces with little distortions. The sharp edges of the strip generate their own set of upstream disturbances. Short black and white lines near the strip edges in Fig. 5 (a) indicate the areas of maximum density gradient.

With the velocity increase, the vorticity is accumulated in the rear part of the obstacle. The stationary symmetric rear vortex past the vertical strip in Fig. 5 (c) is bounded by high gradient envelope separated from the strip edges. The shedding of eddies from the rear vortices pair is suppressed by attached internal waves, so the wake past the obstacle is thin. Further the wake expands following the phase structure of the internal waves. After the first expansion, interfaces are arranged almost horizontally. Shapes of the intensive attached internal waves are only slightly disturbed by the shear downstream flow at this regime.

4. Discussion

Given data supplement numerous studies of the fine flow structure in a homogeneous fluid. Regular streaky elements have been first observed in oscillating flows around bluff bodies like a circular cylinder (Honji, 1981; Tatsuno and Bearman, 1990) or near the sloping plane (Okajima et. al., 1998). Similar transverse structures are also observed in the flows of compressible gases in the wind tunnel (Kozlov and Grek 2000). As the fields of different parameters can be visualized in stratified liquids, the features of these structures can be studied more completely. They are produced by a separating boundary layer off the strip; locate almost horizontally and are characterized by a constant transverse length scale over all the length. A horizontal slope of the streaky structures increases gradually; their outer parts can be oriented at some angle or even vertically. With the obstacle velocity increase, the trailing edges of streaky structures are reconnected and form a set of "butterfly-like" vortices. Further strip velocity increase leads to loose homogeneity in the spanwise direction, and 3D vortices are observed.

Note that these small-scale elements are the robust components of the flow. They are observed in different experiments and, under the constancy of the flow parameters, stably reproduced in general and in tiny details. All above-mentioned features allow classifying these components as internal boundary currents, which are originated from the internal boundary layers on the body surface and extend into a fluid interior. In stratified liquid there are two kinds of 3D periodic boundary layers. Their thicknesses are described by universal length scales $\delta_b = \sqrt{\nu/N}$ for velocity (Vasiliev and Chashechkin, 2003) and $\delta_\rho = \sqrt{\kappa_s/N}$ for density or salinity and different factors depending on the wave and body surface slopes. The evolutional dynamics of these elements is defined by their interaction between themselves with large-scale components of the motion: the mean flow, internal waves, singular vortices and vortex systems. This streaky structure is affected both a drag and lift forces on the strip.

5. Conclusion

The high spatial resolving schlieren methods show that the pattern of disturbances around horizontally moving plane strip in a continuously stratified fluid contains the regular streaky structure, apart well-known upstream disturbances, attached (lee) internal waves, downstream wake, soaring interfaces and vortices. The thin streaks, in domains of their separations, are arranged horizontally; with a distance their slopes to the horizon gradually increase, so their free trailing edges can be oriented even normally to the direction of the obstacle motion. At large velocities the trailing edges of the streaky structures are reconnected and form the vortex loops. The high reproducibility of the finest flow structures indicate that all variety of non-dimensional parameters should be involved in describing of the stratified flows near an obstacle, including a ratios of external flow scales and thicknesses of the boundary layers.

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