PROPAGATION OF VORTEX RINGS IN STRATIFIED FLUID

V. I. Boyarintsev, A. I. Leont'ev, S. Ya. Sekerzh-Zen'kovich, and V. I. Sysoev

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Numerous theoretical and experimental studies have been made on the propagation of vortex rings in stratified fluids (see, e.g., [1-5]). The problem of vortex ring propagation in stratified media, in particular with density discontinuities, has received much less attention. The motion of vortex rings exhibits a whole range of characteristic features in between these two conditions [6-10]. The characteristics of vortex ring propagation in fluids with density discontinuity are investigated in this paper.

Experiments were conducted in the test setup shown in Fig. 1. The container walls 1 were made of Plexiglas and measured 1500 × 500 × 300 mm. A vortex generator 2 was mounted on one of the walls. A pulse generator in the form of a membrane 3 and electromagnet 4 were located at the top and a cylindrical nozzle 5 was mounted at the bottom of the vortex generator. The electromagnet was connected to an electric circuit through a transformer. When the electric circuit was closed by the starter knob, the coils in the electromagnet produced a pulse across the membrane. This resulted in the injection of a fluid jet through the nozzle in the form of a fluid jet from the cylindrical part of the generator. The impulse and the forward velocity of the vortex ring were controlled by the voltage across the electromagnet. A tube 6 with a dye was attached to the vortex generator in order to visualize the process of growth and propagation of the vortex ring. The tube had a graduated scale to introduce a known amount of the dye. Mixing tanks 7 were mounted on top of the test stand. A known concentration of common salt (NaCl) solution was prepared in these tanks. The salt solution from these tanks entered the test section through the settling chamber 8, moved along the bottom, and pushed up the previously poured less dense water. The height of the salt solution was adjusted such that the boundary separating the layer of water and the salt solution coincided with the axis of the vortex generator. A movie camera was used to record the movement of the vortex ring and to establish the flow parameters.

Experiments were conducted in the Reynolds number range $Re = D_0U_0/\nu = 3 \times 10^3$ to 1.5×10^4, which corresponds to turbulent conditions in the vortex ring (according to [2, 5], $Re_{cr} \sim 10^3$); D_0 and U_0 are the initial parameters of the vortex ring; in the experiments D_0 = 32 mm, U_0 = 0.1-0.43 m/sec.

The vortex ring motion in a triple layered liquid is shown Fig. 2. In this figure, the upper layer is pure water (ρ_1), and the middle layer (ρ_2) and the lower layer (ρ_3) are salt solutions with different concentrations ($\rho_1 < \rho_2 < \rho_3$). The difference in the densities was 1.25% between water and the salt solution and 1.9% between the two salt solutions. The diffusion coefficient of salt in water was extremely small ($D_m = 1.1 \times 10^{-5}$ cm/sec) and hence the density discontinuity in all the experiments was always sharp (variation in density took

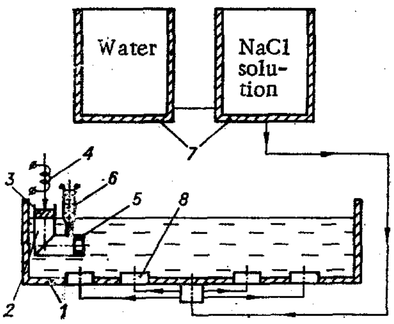

Fig. 1

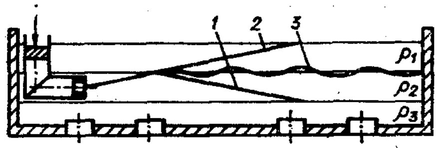

Fig. 2

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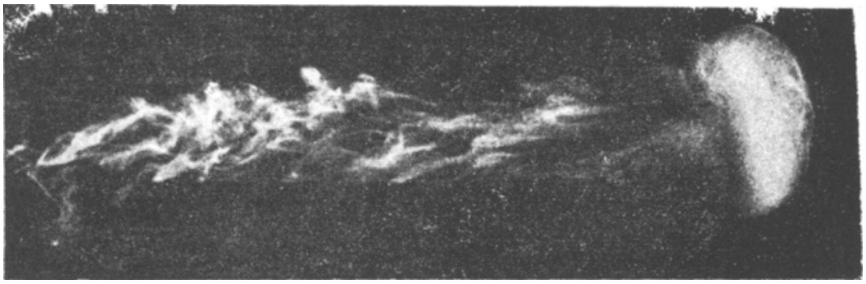

Fig. 3

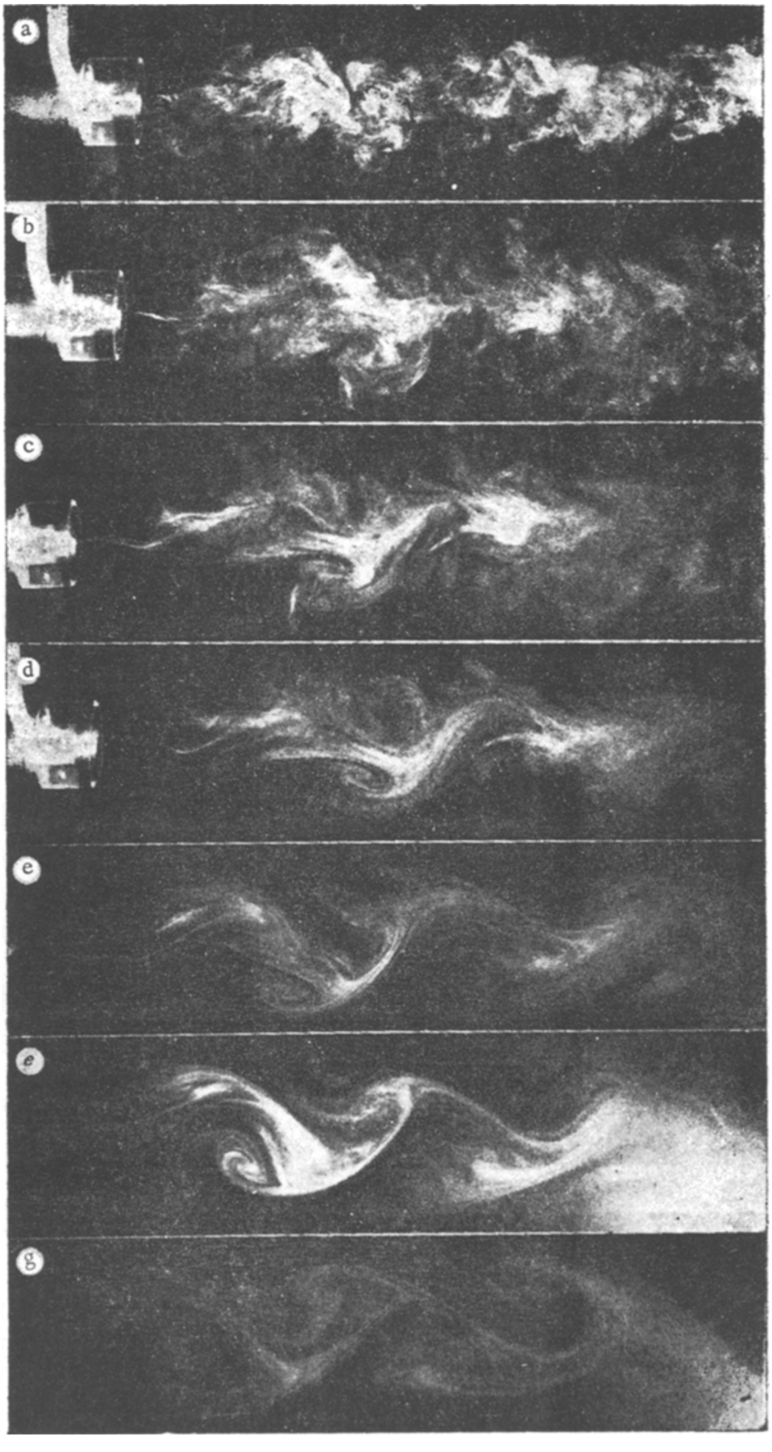

Fig. 4

place with a jump). It was also confirmed by the addition of a small amount of the dye in in the upper and lower layers of the media (marked variation in color while moving from one layer to another).

In the present experiment, the following principal types of vortex ring motion were observed: 1) the vortex ring was deflected from the interface; 2) the vortex ring passed through the interface, went to the free surface (or reached the bottom), and was destroyed; and 3) the vortex ring gave rise to an internal wave after breaking down.

The vortex rings were directed at the interface with speeds of 0.2 and 0.4 m/sec in these experiments. It was established that for a speed of 0.4 m/sec, the maximum angle of inclination of the vortex ring axis to the interface was 7° from the moment the ring passed through the interface. The deflection type resulted in lower angles. When the vortex ring moved at 0.2 m/sec, the maximum inclination became higher and reached 10°.

When the speeds were less than 0.1 m/sec, vortex ring breakdown was observed at the density discontinuity; in this case, weak internal waves appeared at the interface. Observations indicate that the internal waves generated by the vortex ring breakdown were far from being stabilized. The maximum inclination was not determined in this case.

At large angles of inclination (see, e.g., [9], below 45°) the vortex ring was slowly displaced upwards after interaction with the interface, and later it collapsed. Thus, apparently, under given experimental conditions (density variations in the media, vortex ring speed) there is a maximum angle of inclination of the vortex ring axis to the interface of the density discontinuity when the ring remains stable. Appreciable variation in the shape of the vortex ring while moving across density discontinuities was not observed in the experiments.

In the experiments with two layers of liquid, the vortex ring axis remained at the density discontinuity. There was a 1% difference in the densities of water and the salt solution. The vortex ring motion was observed with a movie camera.

Photographs of the vortex ring in motion indicate that the dye, which was initially contained within the "atmosphere" of the ring, was quickly left behind by the ring as it moved. The spatial structure of the vortex ring wake was thus observed (Fig. 3). However, after the passage of the vortex ring, this spatial structure is transformed into a vortex street, similar in external form to the Karman vortex street, along the plane of the density discontinuity. The sequence of the development of the vortex street is shown in Fig. 4. Such a vortex structure was stably maintained in the experiments for a period of a few hours. The order of magnitude of velocities in the wake was not estimated in the present experiment. A similar vortex structure was observed while studying the motion of a solid sphere in a fluid with linear variation in density [10].

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STABILITY OF VISCOUS WALL JET

O. S. Ryzhov

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An incompressible, viscous plane jet along a rigid wall is considered. The theory of free interactions between the boundary layer and the external potential flow is used to study its stability. The dispersion equation relating the frequency of free oscillations to the wave number is identical to the equation that governs the stability of Poiseuille flow in an infinite channel. The properties of the solution to the problem of harmonic disturbances generated by the oscillator used in the test setup depend on the location of the roots of the dispersion equation. It is observed that the analysis of the temporal amplification of disturbances can be carried out using Prandtl's boundary layer equations with self-induced pressure.

1. Consider an incompressible, viscous plane jet along a rigid wall. The entire jet thickness can be treated as a boundary layer whose dimensionless velocity distribution U_1 at any section is shown in Fig. 1. It is significant that the velocity, as well as its derivative with respect to the normal coordinate Y_1, are zero at the outer edge of the boundary layer. Such velocity profiles are typical not only for jets; as is well known, similar velocity profiles are obtained in steady flow on a heated vertical plate [1] and on a rotating disk [2]. The theory of free interactions between the boundary layer with the external potential flow has been used to study the characteristics of these flows near the leading and trailing edges of solid bodies [3]. More examples are considered in [4], in which a solution of Prandtl's equation has been obtained to describe the separation of the jet and the subsequent development of the recirculating zone. This theory is applied to analyze the stability of the jet with respect to large wavelength disturbances, with the critical layer of neutral disturbances close to the wall [5, 6]. These disturbances determine, in the linear approximation, the asymptote of curves relating wave number to Reynolds number, as the latter goes to infinity [7].

The whole velocity field is divided into two regions to achieve this objective. According to the principles of free interaction theory [8, 9], the effect of viscosity on the structure of the disturbed flow in the upper region 1 is negligibly small. Let us introduce a small parameter $\varepsilon = \mathrm{Re}^{-1/4}$, where the Reynolds number $\mathrm{Re} = \rho^* U_M^* L^*/\lambda^*$ is expressed in terms of density ρ^*, the coefficient of viscosity λ^*, the maximum U_M^* in the jet, and its characteristic length L^*. The time t^*, and cartesian coordinates x^*, y^* are given by the following equations:

$$t^* = \frac{L^*}{U_m^*}(t_0 + \varepsilon^4 t_1),\ x^* = L^*(x_0 + \varepsilon^6 x_1),\ y^* = \varepsilon^7 L^* y_1, \tag{1.1}$$

where t_0 and x_0 are arbitrary constants. The pressure p^* and the velocity components v_x^*, v_y^* are expressed by the asymptotic series:

$$p^* = p_\infty^* + \rho^* U_m^{*2}[\varepsilon^4 p_1(t_1, x_1, y_1) + \ldots],$$
$$v_x^* = U_m^*[U_1(y_1) + \varepsilon^2 u_1(t_1, x_1, y_1) + \ldots],\ v_y^* = U_m^*[\varepsilon^3 v_1(t_1, x_1, y_1) + \ldots], \tag{1.2}$$

where p_∞^* is the pressure at the outer edge of the jet and the quantity $U_1(Y_1)$ is the velocity profile in the initial undisturbed flow.

Equations (1.1) and (1.2) are substituted into the Navier–Stokes equations and only the principal terms in the resulting equations are retained; we obtained [3, 4]

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