NATURAL UNSTEADINESS OF THE FLOW PATTERN AROUND A PLATE IN NUMERICAL SIMULATION AND LABORATORY MODELING

Yuli D. Chashechkin¹, Iaroslav V. Zagumennyi²

¹ Laboratory of Fluid Mechanics, Ishlinsky Institute for Problems in Mechanics RAS, 101/1 prospect Vernadskogo, Moscow, 11926, Russia
² Department of Hydrobionics and Boundary Layer Control, Institute of Hydromechanics of the National Academy of Sciences of Ukraine, 8/4 Zheliabova St., 03057, Kyiv, Ukraine

Abstract

The paper presents numerical and experimental study of 2D stratified flow around a strip based on the system of incompressible viscous fluid mechanics equations taking into account stratification and diffusion effects and neglecting heat transfer. The computations show the flow structure is essentially unsteady and multiscale with space-time scales, manifestation degree and attenuation rate of the flow structural elements being significantly affected by variations in values of the basic parameters of the moving body, i.e. size, shape, angle of attack, and movement velocity. For all the problem parameters considered, the laboratory and calculated instantaneous flow patterns indicate a complex unsteady nature of mutual interaction of all the flow components, including waves, vortices, and ligaments, and show a good qualitative agreement of the results of numerical and laboratory modeling.

Keywords: flow structure, plate, vortices, fine structure, drag and lift coefficients, OpenFOAM

1 Introduction

Studies of flows around a plate are a traditional object of experimental and theoretical investigations in hydro and aerodynamics due to the fundamental nature of the problem and the importance of practical applications. Since the first systematic studies carried out at the end of the 19th century, the flow pattern and the nature of the forces acting on an obstacle have been studied as functions of many parameters, including plate size, its angular position, density and free stream velocity of a fluid or a gas [1].

The development of computer technology and programming methods enabled to calculate flows past obstacles based on the system of fundamental equations, which are such derived relations of the “first principles of mechanics” for subsonic [2] and supersonic flows [3]. A review of works on analytical and numerical studies of the vortex flow over plate in a wide range of angles of attack is given in [4].

In addition to the traditional studies of the boundary layer and wake past a strip in a homogeneous fluid, the influence of stratification, always existing in the environment and industrial devices, where the fluid density is not constant due to the non-uniformity of the concentration of dissolved substances or suspended particles, temperature and pressure, has been studied during recent years. The density variability in the system of equations allow to calculate the dynamics and structure of convective flows and wakes in a single statement within the whole range of velocity values available for study, to conduct a scale invariant classification of structural components, including traditionally studied waves, vortices, and ligaments determining the flow fine structure, and to develop methods for direct comparison of data of mathematical (analytical and numerical) and experimental studies of flows [5].

As one can see from the previous papers by the authors [6 – 9], instantaneous patterns of stratified and homogeneous fluid flows around bodies have a number of noticeable differences which depend on a flow regime under consideration [6]. At low Reynolds numbers, the stratification and diffusion effects on the flow structure and dynamics are the strongest [7], but, in the unsteady vortex regime, their influence is getting weaker and manifest mainly in a suppression of the vortex dynamics [8]. The present paper is a logical continuation of the previous studies, focusing at a natural non-stationarity of stratified flow patterns around a plate both in numerical simulation and laboratory modeling [9].

2 Problem formulation and solution

Mathematical modeling of the problem on flows around a sloping plate is based on the fundamental system of equation for multicomponent inhomogeneous incompressible fluid in the Boussinesq approximation [10]. The buoyancy and diffusion effects of stratified components are taken into account,
while the effects of heat-conductivity and heating due to dissipation are neglected. Thus, the governing equations take the following form,

\[ \frac{\partial \mathbf{v}}{\partial t} + \nabla \cdot (\mathbf{v} \mathbf{v}) = -\frac{1}{\rho_0 \Omega} \nabla P + \nabla \cdot (\mathbf{v} \nabla v) - s \cdot \mathbf{g}, \quad \frac{\partial s}{\partial t} + \nabla \cdot (s \mathbf{v}) = \nabla \cdot (\kappa_S \nabla s) + \frac{v_z}{\Lambda}. \]  

(1)

Here, \( s \) is the salinity perturbation including the salt compression ratio, \( \mathbf{v} = (v_x, v_z) \) is the vector of the induced velocity, \( P \) is the pressure except for the hydrostatic one, \( v = 0.01 \text{ cm/s} \) and \( \kappa_S = 1.41 \times 10^{-5} \text{ cm}^2/\text{s} \) are the kinematic viscosity and salt diffusion coefficients, \( t \) is time, \( \nabla \) and \( \Delta \) are the Hamilton and Laplace operators respectively, \( \Lambda = |d \ln \rho / dz|^{-1} \) and \( N = \sqrt{g/\Lambda} \) are buoyancy scale and frequency. Physically valid initial and boundary conditions are no-slip and no-flux on the surface of the obstacle for velocity components and total salinity respectively, and vanishing of all perturbations at infinity,

\[ v_0 \big|_{z \leq 0} = v_1 (x, z), \quad s_0 \big|_{z \leq 0} = s_1 (x, z), \quad P_1 \big|_{z \leq 0} = P_1 (x, z), \quad v_x \big|_{z \rightarrow \infty} = 0, \quad v_z \big|_{z \rightarrow \infty} = 0, \]  

(2)

where \( U \) is the uniform free stream velocity at infinity, \( \mathbf{n} \) is external normal unit vector to the surface, \( \Sigma \), of a plate with length, \( L \), and maximal thickness, \( h \). \( P_1 \), \( v_1 \) and \( s_1 \) are initial perturbations of the fields under consideration which are generated by the diffusion-induced flow due to interruption of the molecular transport of the stratifying agent by impermeable surface of the obstacle. A schematic draft of the problem under consideration is shown in Fig.1a.

Numerical solution for the governing system of equations (1) with the boundary conditions (2) is constructed in the framework of the open source computational utility OpenFOAM using original program codes based on the finite volume method [11]. The convective terms and time derivatives in the governing equations are interpolated with a limited TVD-scheme and the second-order implicit asymmetric three-point scheme with backward differencing, respectively. For solving the resulting system of linear equations, the conjugate (PCG) and bi-conjugate (PBiCG) gradient solvers are used together with DIC and DILU preconditioning for symmetric and asymmetric matrices respectively. An iterative procedure for pressure-velocity coupling is implemented using PIMPLE algorithm which has proven its high efficiency for unsteady flows.

The optimal dimensions of the computational domain in the horizontal and vertical directions were chosen to be about 10 and 5 lengths of a body respectively. The mesh type used in the calculations is a block structured one with a high grading arranged towards the surface of a body. A fragment of the computational grid around a tilted plate is shown in Fig.1b.

The spatial and temporal discretization of the numerical simulation is based on the condition of an adequate resolution of the finest flow components associated with the stratification and diffusion effects, which impose significant restrictions on the minimum spatial dimensions of the computational mesh and time step. In the most perturbed flow regions around and past the body, at least one computational cell must fit the minimal linear scales of the problem, such as Prandtl and Peclet scales [12]. The programs developed resolve all the components of multiscale stratified flows, including upstream perturbations, internal waves, vortices, and ligaments, in a wide range of Reynolds number for all types of media in a single formulation. The approach enables calculating velocity, pressure, salinity, density fields...
and their gradients, that expands the representation of the physical process under study, in contrast to the traditional approaches. The numerical simulation provides uniform convergence to the case of homogeneous fluid by tending the buoyancy frequency to zero, when the fundamental system is degenerated on the part of the singular components [12].

The numerical calculations were carried out in parallel using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University and the computing resources of the federal collective usage center Complex for Simulation and Data Processing for Mega-Science Facilities at NRC “Kurchatov Institute”.

3 Computational results

Stratified flow is a combination of multiscale flow components, such as internal waves, vortices, and ligaments, i.e., fine flow structure components, interfaces, shells, fibers, etc., which are simultaneously formed at the leading edge of the plate and are in an active mutual interaction. The greatest practical interest lies in visualization and analysis of stratified flow structure and dynamics in unsteady vortex regime when, in the vicinity of the plate’s edges, intensive multiscale vortices are formed, which, particularly in this case, are a dominant flow structural component. In this flow regime, temporal and spatial scales, manifestation level and dissipation rate of the vortex elements are essentially dependent on geometrical configuration of the plate edges.

![Image](image1)

![Image](image2)

![Image](image3)

![Image](image4)

Figure 2: Instantaneous patterns of vorticity field around a tilted plate,

\[ U = 100 \text{ cm/s}, \quad N = 1.2 \text{ s}^{-1}, \quad L = 10 \text{ cm}, \quad h = 0.5 \text{ cm}, \quad \alpha = 1^\circ, 5^\circ, 10^\circ, 20^\circ (a-d). \]

Blue, green and red colours of the colour spectrum correspond to negative, zero and positive values of the vorticity field, respectively.

In the unsteady vortex regime, at a certain set of parameters of the problem, some flow components can prevail over others, and the general flow structure seems to be more or less stable, but, at another one, an essential flow non-stationarity is observed in the form of multiple interactions of multi-scale vortex elements with each other and even with attached internal waves which, in this case, go far beyond the observation area.

At small angles of attack, the flow vortex structure past the plate consists of two quasi-steady chains of leading-edge vortices, which drift along the upper and lower sides of the plate with frequency of about 4 Hz and intensively interact with the primary vortex street past the trailing edge of the plate (Fig.2a). At larger angles of attack (Fig.2b), the flow pattern at the windward side of the plate is significantly suppressed by the oncoming free stream, so that the flow perturbations are observed only in the shear layer in the form of a wavy structure with decaying amplitudes downstream, while at the leeward side of the plate, the vortex chain increases in scales and gets off the plate surface, before being engaged in an intensive interaction with the primary vortex street past the plate. At \( \alpha \geq 10^\circ \), the vortex chain at the leeward side of the plate is engaged into a more extensive vortex motion composed of a set of two or three leading-edge vortices which then drift downstream as a single clockwise rotating system (Fig.2c).

Further increase in the angle of attack leads to growth in number of leading-edge vortices engaged in the large-scale vortex motion, as well as more complex and intensive interaction with the primary vortex street as approaching the trailing edge of the plate (Fig.2d).

By visualizing gradients of the physical variables included into the governing system (1), e.g., horizontal component of density gradient field, \( \partial \rho / \partial x \), an additional information on the flow structure can be extracted. Fig.3 shows patterns of the horizontal component of the density gradient field in the vicinity of
the leading and trailing edges of a tilted plate. This physical parameter is in a linear relation to the light refraction index, which is visualized in laboratory experiments using schlieren instruments [9]. As can be seen from all the flow patterns in Fig.3, stratified flow fine structure comprises a wide diversity of thin multi-layered flow structural elements with alternating signs, which outline vortex shells, demarcate flow regions with intensive non-linear interactions and interfaces between different large-scale flow elements. The fineness of the horizontal component of density gradient field structure is a result of the large value of the Schmidt number, being the ratio between the viscosity and diffusion coefficients, for the types of stratified fluids under consideration.

![Image](image1)

**Figure 3:** Instantaneous patterns of horizontal component of density gradient field in the vicinity of the leading and trailing edges of a tilted plate,

\[ U = 100 \text{ cm/s}, \quad N = 1.2 \text{ s}^{-1}, \quad L = 10 \text{ cm}, \quad h = 0.5 \text{ cm}, \quad \alpha = 1^\circ, 5^\circ, 10^\circ, 20^\circ (a - d). \]

At small angles of attack of the plate, the finest structural elements are localized mostly on the shells of the leading-edge vortices and in the vicinity of the plate corners, while at the larger angles, complex sets of multilayered fine-scale structures appear at the leeward side of the plate as a result of intensive non-linear interactions of the leading-edge vortices and large-scale vortex elements with each other and with the plate surface. The visualized results show that ligaments, together with waves and vortices, are an important fine-scale and high-gradient structural element of stratified flows, which appear in flow regions with intense non-linear mutual interactions of all the flow components.

### 4 Experimental techniques

The experiments were conducted at LMT stand from HPC IPMech RAS setup [13], which contains a rectangular transparent tank \(220 \times 40 \times 60 \text{ cm}^3\) with installed optical windows of a high quality, schlieren instrument IAB-458 (I), towing carriage (II), internal wave generator (III), controller (IV), shown in Fig.4.
The hydraulic and optical schemes of the stand are shown in Fig.5. The working tank 14 is filled with linearly stratified brine through the bottom valve 15 using two-buckets procedure supported by vessels 13 connected by tubes with individual regulating cranes.

Prior to each test, the buoyancy period $T_b = 2\pi/N$ is determined with accuracy better than 5% by measurement of salinity oscillations using conductivity probe near a density marker [15]. The marker is formed by a vertical wake past a free-falling salt/sugar crystal or a small vertically arising gas bubble, and is also used for measurement of horizontal velocity component and buoyancy period profiles [16]. Accuracy of the velocity measurements and the spatial resolution are defined by the marker thickness, which is about 0.25 mm. In a quiescent environment, the density marker is observed over 200 s. It should be emphasized that both the density and velocity fields are visualized continuously in the entire observation plane in contrast to the particle tracking methods illustrating fluid displacements only in separated points.

As a towing obstacle a stainless plate is used with flat leading and trailing edges. The plate sides are fixed between two thin vertical transparent plastic supports attached to the towing carriage with metal knives.
The carriage is put on the rails above the tank. The horizontal position of the plate and its trajectory are carefully adjusted during the filling of the tank with respect to a free water surface. The experimental conditions \((6.6 < T_p < 17.4 \text{ s}, 0.1 < U < 6 \text{ cm/s})\) correspond to laminar and transient flow regimes.

At the start of each run series, the carriage is positioned in the central window, and when the strip is in rest the diffusion induced boundary flows are observed [17]. 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 and the carriage holding the plate is ready to start. The flow is observed through the central window. The next experiment is started several hours later after all the dynamic and structural disturbances have disappeared.

Figure 6: Images of flow around uniformly moving horizontal plate of length \(L_x = 7.5 \text{ cm}\), moving from right to left in the stratified fluid with \(T_p = 7.6 \text{ s}\): a) \(-U = 0.27 \text{ cm/s},\) conventional “vertical slit-knife diaphragm”, b) \(-U = 0.39 \text{ cm/s},\) “vertical slit-thread diaphragm”, c) \(-U = 0.29 \text{ cm/s},\) “horizontal slit-grating diaphragm” – “rainbow schlieren method”

Typical schlieren images of flow patterns produced by different combinations of illuminating slit – visualizing diaphragms are shown in Fig.6. Boundaries between black and white bands in Fig.6a correspond to crests and troughs of upstream unsteady and attached downstream internal waves. The oblique line of fracture of the phase surfaces is the result of the interference of independent wave systems created by the leading and trailing edges of the plate. The colour schlieren image produced by Maksutov’s method is shown in Fig.6b. The image is more informative since strong internal wave disturbances in it do not obscure weaker fine-structure details. Here, the dark lines correspond to crests of waves, and troughs are shown as grey curve lines. The wave interference region is represented by a dark inclined band. A pair of thin winding vertical lines in front of the plate are density markers. Deviations of their shape from the local initial vertical line are proportional to the magnitude of the horizontal velocity component. In Fig.6a and 6b the density wake, which slightly perturb the phase surfaces of contacted internal wave fields in upper and lower half-spaces, is visualized by a thin horizontal line.

The “natural rainbow” colour schlieren method, where changes in the colours and positions of the isoplets are proportional to variations in the vertical component of the density gradient (Fig.6c). Here, the wave and wake patterns enable to highlight important flow features, which are absent in the previous images. The internal structure of density perturbations is rather complex and maximum gradient lines are located at outer low and high boundaries of the wake.

5 Comparison

Comparison of the numerical simulation results and the laboratory schlieren visualization data is conducted for the vortex flow regime when the shedding vortices are a predominant flow component and the wake flow pattern seems to be more or less regular (Fig.7). Both the laboratory modelling and the numerical simulation show the wake flow consists of a sequence of mushroom-like structures formed at some distance downstream from the plate’s trailing edge, which are gradually expanded and distorted as drifting further downstream. The wake vortex structures coexist with fine structural ligaments localized mainly on the vortex shells and past the leeward side of the plate. There are phase surfaces of attached internal waves observed at a number of locations around the plate and in the wake flow, which length, in this case, is commensurate with the size of the observation area. The laboratory and calculated flow patterns are in a good agreement with each other.
Figure 7: Comparison of the schlieren image (light refraction index) (a) and calculated flow patterns (horizontal component of density gradient (b) and vorticity (c) fields) of stratified flow around a tilted plate, $U = 3.6 \text{ cm/s}$, $N = 0.83 \text{ s}^{-1}$, $L = 2.5 \text{ cm}$, $h = 0.2 \text{ cm}$, $\alpha = 16^\circ$.

Integral values of drag and lift coefficients of the tilted plate as functions of time are shown in Fig. 8 for the angle of attack of the plate, $\alpha = 16^\circ$. The both values have a periodic structure vs time with oscillation frequency of about $0.8 \text{ Hz}$, but the drag coefficient seems to have a noticeably less regular nature of dependence on time due to influence of the fine structural ligaments.

Figure 8: Integral drag (a) and lift (b) coefficients of the tilted plate as functions of time, $U_0 = 3.6 \text{ cm/s}$, $N = 0.83 \text{ s}^{-1}$, $L = 2.5 \text{ cm}$, $h = 0.2 \text{ cm}$, $\alpha = 16^\circ$.

In all the considered cases of flow conditions and parameters, the laboratory and calculated instantaneous flow patterns indicate a complex unsteady nature of mutual interaction of all the flow components, including waves, vortices, and ligaments.

4 Conclusion

2D problem on stratified flow around a strip is studied numerically and experimentally on the basis of the system of fundamental equations of incompressible viscous fluid mechanics taking into account diffusion effects and neglecting heat transfer. Analysis of the results obtained shows the unsteady problem does not have a stationary limit over the entire range of flow parameters due to its internal multiscale structure. Variations in values of the basic parameters of the medium and the moving body have a significant impact on space-time scales,
manifestation degree and attenuation rate of the flow structural elements. A system of multilayer fine flow elements is formed on the envelopes of vortex elements and in the areas of mutual interaction of different-scale components of the vortex flow, visualized in laboratory experiments by schlieren instruments and calculated numerically in the density gradient field structure.

The calculated field patterns, being specific for the basic physical variables and their gradients, are in a qualitative agreement with the laboratory data. The laboratory and calculated flow patterns show an essential unsteady nature of mutual interaction of waves, vortices and ligaments for various flow conditions and parameters.

Acknowledgments

The work by Yu.D.C. was partially supported by the State task АААА-А20-120011690131-7. The experiments were conducted at the stand of LMT at the Unique Research Facility "Hydrophysical complex IPMech RAS (HPC IPMech RAS)" with partial support by Program of Presidium RAS №1.2.49 (project AAAA-A17-117121120015-8). The computations were performed using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University and the computing resources of the Federal Collective Usage Center Complex for Simulation and Data Processing for Mega-Science Facilities at NRC “Kurchatov Institute” with partial financial support by RFBR (grant 18-05-00870, AAAA-A18-118011990267-5).

References