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ВЛИЯНИЕ ПУЛЬСАЦИЙ ИСТОЧНИКА НА СТРУКТУРУ И ВНУТРЕННЮЮ ДИНАМИКУ ИНТРУЗИОННОГО ТЕЧЕНИЯ

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Структура и внутренняя динамика интрузионного течения изучалась при помощи двумерной численной модели стратифицированных по плотности течений в вертикальной плоскости. Течение в модельном пространстве формировалось за счет притока жидкости промежуточной плотности в двухслойную среду. Приток осуществлялся в виде двух импульсов фиксированного объема с заданным интервалом времени между ними. Начальная стратификация определялась перепадом плотности между слоями равной толщины и толщиной промежуточного слоя. Для идентификации водных масс отдельных импульсов в расчетах использовались индивидуальные поля пассивной примеси. Предложен набор безразмерных параметров, определяющих начальные и граничные условия задачи. Численные эксперименты показали существенное влияние пульсаций расхода источника на эволюцию интрузионного течения. В зависимости от параметров затока может происходить как ускорение, так и замедление горизонтального распространения объема второй интрузии. Приведены примеры различной динамики объема второго импульса при закритических и докритических начальных числах Фруда. Расчеты показывают, что импульсный характер источника в наибольшей степени модифицирует течение при коротком интервале времени между импульсами.

Ключевые слова: стратифицированные течения, плотностные течения, численное моделирование.

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INFLUENCE OF THE SOURCE PULSATIONS ON THE STRUCTURE AND INTERNAL DYNAMICS OF THE INTRUSION

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A 2-dimensional numerical model of stratified fluid dynamics in the vertical plane was used to investigate the structure and internal dynamics of density stratified intrusive current. The intrusion was formed by the pulsed inflow of two identical volumes of water of intermediate density into the two-layer stratified environment with a given time interval. Inflowing volumes of water were marked by different passive tracers. Initial stratification was defined by the density difference between the layers of equal thickness and the thickness of the intermediate layer. A set of dimensionless parameters is proposed which define the initial and boundary conditions of the problem. Numerical experiments showed that the evolution of the intrusive current is significantly influenced by pulsations of the inflow, particularly in the case when the time interval between the pulses is short. Depending on the intrusion parameters both is possible the acceleration and slowdown of horizontal propagation of the second intrusion volume. Dynamics of inflow of the second inflow volume is different for flows with supercritical and subcritical initial Froude number. Calculations show that the pulse nature of the source modifies the flow to the greatest extent when a short time interval between pulses.

Keywords: stratified current, density current, numerical simulation.

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Density stratified currents in lakes and reservoirs, the atmosphere, and the ocean have been an object of study over a long time [1, 2]. Field observations showed ubiquitous inconstancy of these currents' parameters and their sources in time.

High level of variability is discernible in observations of inflows through the straits to a water body with lower water density: there is the Mediterranean Sea waters inflow to the Bay of Cadiz [3–5]; there is an inflow of waters of the Marmara Sea to the Black Sea [6–8]; there is the Red Sea water inflow to the Gulf of Aden [9], and there is an overflow through the Denmark Strait [10–12]. Sources of these flows – the bottom currents of more dense water in the strait – are markedly non-stationary, in particular, the well-known blockage of the Mediterranean waters inflow to the Black Sea correlating with storm events [6–8]. Field observations in various areas provide an insight of spatial and temporary variability of thermohaline structure, velocity and turbulence parameters along paths of density currents propagation. The analysis of observations' data and theoretical modelling show that the effect of the inflow non-stationarity may have an effect only within a limited distance from the source (for example, 25–50 km from the strait for inflow of the Red Sea waters in the Gulf of Aden [9]).

At the same time, laboratory and numerical studies of a variable discharge effect on the evolution of vertical structure and the density stratified current dynamics are deficient. Of these, there is a study [13] which is dedicated to laboratory experiments with density intrusions into a two-layer liquid initiated one after another with time intervals between them extensive enough for large-scale motions in the pool ceased. It enabled authors to trace an indirect effect of the previous and following impulse of an inflow through the changes in stratification caused by them and also through the associated changes of the flow pattern [13, 14]. In the study [15] that deals with the numerical experiment on the subsurface current propagating through the stratified water body (an analogue of a river discharge to a fiord, see [16]) and compares the results of modelling of the forced, free-flowing and pulsating sources; it is shown that the pulsing character of an intrusion increases the thickness of a flow and can intensify mixing with surrounding liquid.

Thus, some propagation features of the intrusion-type currents observed in-situ can be related to abrupt changes of a discharge (at least under some circumstances and within a limited range from a source), however, the interrelationship of a source parameters with flow features is not sufficiently studied. The purpose of the presented study is the research of the effect of pulsing source discharge on the propagation of an intrusion current depending on parameters of an inflow.

Problem formulation. The study of intrusion currents from the pulsing source is executed using the following assumptions. The two-dimensional current of the density stratified waters in the rectangular $H_x x H_z$ area is considered (fig. 1, *a*). It is supposed that H_x is vast enough that the wave perturbations caused by an inflow of liquid through an inlet in the left boundary are not able to reach the right boundary of the area. Horizontal boundaries are specified as impermeable surfaces; the left vertical boundary is also impermeable except for an entrance inlet of H_0 height, through which time-varying water flow is injected. The value of H_0 is a model analogue of the vertical measurements of a plume near a source. For the compensation of an inflow through the inlet, liquid flows freely through the right boundary.

Intake of liquid through an inlet is described by step function of discharge variability (fig. 1, *b*) which allows consideration of two scales of time, which are features for a source: the duration of events and the interval between them. The presented model of a variable inflow source depends on H_0 and on three other parameters: the value of a two-dimensional discharge Q_0 (or a characteristic speed of a fluid inflow $U_0 = Q_0/H_0$), and the intervals Δt_0 and Δt_1, where Δt_0 is the duration of each of the two impulses of a fluid inflow, and Δt_1 is an interval between the moment of the termination of the first impulse and the beginning of the second.

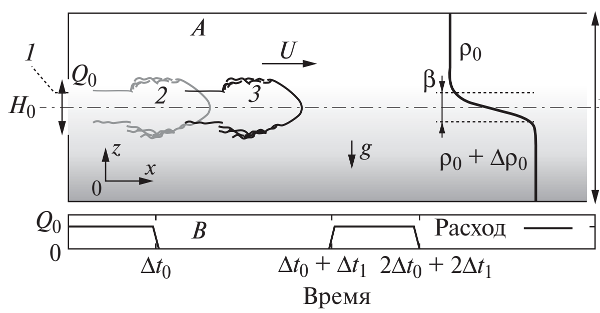

Рис. 1. Схема задачи.
а – структура модельного пространства,
б – временная диаграмма расхода через входной створ. Цифрами обозначены: *1* – входной створ, *2* и *3* – контуры объемов воды, поступивших через входной створ, которые в расчете определяются по полю трассера. Символьные обозначения соответствуют таковым в тексте.

Fig. 1. Schematics of the problem.
a – the structure of the model space,
b – the time pattern of the inflow. In the picture: *1* – inlet, *2* and *3* – contours of the water volumes entering through the inlet; each of them marked by a separate tracer. Symbols correspond to those in the text.

Initial vertical density stratification is modelled by the function of a hyperbolic tangent that is schematically shown in fig. 1, *a*. Initial stratification is described as two-layer and symmetrical in the vertical direction with an interface layer of thickness β and homogeneous in the horizontal direction. The density of the upper and lower stratified layers are equal ρ_0 and $\rho_0 + \Delta\rho_0$, respectively. The liquid entering from an inlet has density $\rho_0 + {}^1/_2\Delta\rho_0$.

Assuming uniformity of a current on one of horizontal coordinates (namely, on "*y*") and plausibility of Boussinesq approximation, for the flow evolution description, the equations for viscous fluid dynamics for density stratified waters are employed with variables: vorticity $\omega = u'_z - w'_x$, excess density $\sigma = \rho - \rho_0$, and stream function ψ [17, 18]; for separate volumes of liquid tracking the equations of passive tracers *c* transfer are used [17]:

$$\frac{\partial\omega}{\partial t} + u\frac{\partial\omega}{\partial x} + w\frac{\partial\omega}{\partial z} = \frac{g}{\rho_0}\frac{\partial\sigma}{\partial x} + \nu_T\Delta\omega, \quad (1)$$

$$\Delta\psi = \omega, \quad (2)$$

$$\frac{\partial\varphi}{\partial t} + u\frac{\partial\varphi}{\partial x} + w\frac{\partial\varphi}{\partial z} = D_T\Delta\varphi, \quad (3)$$

where t – time, $u = \psi'_z$, $w = -\psi'_x$ – the velocity components on x and z axes, respectively, g – acceleration of gravity, ρ – density, ρ_0 – density of the top layer of liquid (characteristic density), as shown in fig. 1, v_T, $D_T = Sc^{-1}\, v_T$ – coefficients of turbulent viscosity and diffusion, Sc = 2 – turbulent Schmidt number, Δ – Laplace's operator, φ is a substitute for the characters σ or c.

The model of turbulence [19] is defined by expression $v_T = v_0 + v_1\, c\,(t, x, z)$ where v_0 and v_1 – coefficients of inner and outer momentum exchange in an intrusion plume, respectively, and $c \in [0.1]$ – dimensionless concentration of a tracer which marks the intrusion liquid. For further analysis, it is convenient to express the equation for turbulent viscosity as $[v_0\,(1 + (v_1/v_0)\,c]$ and to consider the relation ν_1/ν_0 as the parameter of the turbulent model.

Assigning $g' = g\Delta\rho_0/\rho_0$, $U_w = \sqrt{g'H_0}$, $U_0 = Q_0/H_0$ the scaling of model variables is executed, using classical approach of the dimensional analysis [20]. It is possible to suggest the following form of the dimensionless parameters, which define the initial and boundary conditions of the model: H_0/H_z, β/H_0, $U_0/U_w = Fr_0$, $\Delta t_0 U_0/H_0$, $\Delta t_1/\Delta t_0$. One more parameter – Reynolds number, $\mathrm{Re} = U_0H_0/v_0$ – arises upon transition to dimensionless variables in the equations (1, 3). Thus, using H_0, H_0/U_w, and $\Delta\rho_0$ as scales of length, time and density difference, respectively, it is possible to formulate the equation of vorticity transfer in dimensionless variables:

$$\frac{\partial\omega}{\partial t} + u\frac{\partial\omega}{\partial x} + w\frac{\partial\omega}{\partial z} = \frac{\partial\sigma}{\partial x} + \frac{Fr_0}{\mathrm{Re}}\left(1 + \frac{\nu_1}{\nu_0}c\right)\Delta\omega. \quad (4)$$

The calculations simulate the case of turbulent intrusion current ($\mathrm{Re} > 10^3$) [1] in the deep ($H_0/H_z \ll 1$) two-layer stratified waterbody ($\beta/H_z \ll 1$, $\beta/H_0 < 1$) [21, 22]. Also, it is assumed that the inner and outer intensity of velocity fluctuations of an intrusion current differs by several times. Variation of Fr_0 and $\Delta t_1/\Delta t_0$ values presented an opportunity for both: the different hydraulic modes intrusions [23], and to trace the impact of a time interval variation between intrusions' generation. In this study, the values of $\Delta t_0 U_0/H_0 > 10$ are not considered as they do not lead to a change of the discussed features of an intrusion current. As for geophysical hydrodynamics problems' applications, the carried-out calculations are valid for intrusion currents ($\Delta\rho_0/\rho_0 = 10^{-6}$–$10^{-5}$), which velocity pulsations time scales are of hours to days, with characteristic current velocities of 1–10 cm/s, and with space (vertical) scales of 1–10 meters. The horizontal scale is limited to the radius of Rossby as the model does not include rotation. Information on the parameters' ranges of simulated currents is integrated into the table.

Table

Значения безразмерных параметров расчетов
Values of dimensionless parameters of calculation

H_0/H_z	β/H_0	Fr_0	$\Delta t_0 U_0/H_0$	$\Delta t_1/\Delta t_0$	Re	v_1/v_0
1/7	0.8	0.35–1.6	4–10	$^1/_4$–2	$5 \cdot 10^3$	30

Calculation algorithm. The solution of the problem is based on the implementation of the explicit finite difference scheme on a uniform rectangular grid with the number of nodes up to 10^6. For approximation of convective components in dimensionless analogues of the equations (1) and (3), the Gentry–Martin–Daly scheme with upwind differences was used [24, page 113], for the solution of a discrete analogue of the Poisson equation (2) the iterative method of a successive over-relaxation [25] was used. The system of numerical algorithms applied here is thoroughly tested (e.g., [17, 26]). No-slip conditions were set on the horizontal boundaries [24, page 217], while on the inflow boundary (the left boundary, fig. 1) beyond the inlet, numerical equivalents of impermeable and slip conditions were specified using the Newmann's boundary conditions set to zero [24, page 232]. On the outflow boundary (the right boundary, fig. 1, *a*), a free boundary condition was imposed [24, page 239]. Values ω and σ at the inflow inlet were defined as to correspond to a parabolic profile of horizontal velocity components, which integral on the interval of H_0 is equal to a two-dimensional discharge (fig. 1, *b*) at a current moment in time.

Results. 20 calculations were performed with parameters' ranges indicated in the table. The simulation results for various inflow parameters were visualized in the form of graphs of density and tracers isolines at different points in time. Their analysis showed that within the considered range of values Fr_0, $\Delta t_0 U_0/H_0$, $\Delta t_1/\Delta t_0$, a qualitative structure transformation of the flow occurs, which can be described as a transition between two modes of a passive contaminant (tracer) propagation, which marks the water volumes of each of the two successive flows.

The top row of images in fig. 2 corresponds to an intrusion from a pulsating source with a high Froude number $Fr_0 = 1.5$ at various points in time. Note, that the figure shows only part of the model space. In addition, there is a significant difference in the scales along the vertical and horizontal axes of coordinates. The inlet opening is located between marks 3.0 and 4.0. Values on the axes correspond to dimensionless coordinates. Apparently, already at $t = 35$ (fig. 2, *b*) a portion of the second inflow volume, identified by its own tracer field (red dashed line), penetrated the volume of the first inflow. Thus, the volume of water, which is injected at a later time $\Delta t_0 + \Delta t_1$ after the injection of the first volume, propagates in the horizontal direction almost as far as the first volume (arrows in fig. 2, *c*).

The second row of images in the fig. 2 corresponds to the calculation with a low Froude number $Fr_0 = 0.4$. In this case, the volume of the second inflow quickly loses speed and does not reach the head of the first. In addition, the slowing of the second volume front in time leads to its almost complete stop, while the disturbance in the density field continues to spread in the direction away from the source (fig. 2, *e*). A similar phenomenon is found in laboratory experiments [14], in which a symmetric intrusion propagates within pycnoclines of different thickness. The effect is characteristic of a thick pycnocline, and this is precisely the interpretation of the propagation of the second inflow volume in the wake of the first inflow. This comparison confirms the physical validity of the above calculations.

Differences in the structure of the flow with variable $\Delta t_1/\Delta t_0$ are manifested in each of the two series of calculations. An example is shown in fig. 3. A decrease in $\Delta t_1/\Delta t_0$ intensifies the penetration of the second inflow volume into the first volume (fig. 3, *a–c*) or, on the contrary, slows down its horizontal distribution (fig. 3, *d–f*). Also in fig. 3, *d–f*, it can be seen that the amplitude of the second perturbation in the density field (the crest of the wave is shown by an arrow in fig. 3, *d*) is smaller than the first when parameter $\Delta t_1/\Delta t_0$ is equal to 0.25 and 0.5, and almost coincides with the first amplitude at $\Delta t_1/\Delta t_0 = 1.0$ (fig. 3, *f*). A further increase in $\Delta t_1/\Delta t_0$ does not result in significant changes in the second pulse dynamics. This leads to a suggestion, that impulse intrusions can be considered a system of interacting components at small $\Delta t_0/\Delta t_0$ (for example, < 1), and as independent intrusions at other times.

Thus, the analysis of the calculation results shows a significant effect of inflow parameters on the propagation of the intrusion flow from a pulsating source. There can be both a slowdown and an intensification of the horizontal propagation of the inflow volume following the initial inflow. However, the structure of the current depends on the value of all three parameters in the presented set (Fr_0, $\Delta t_0 U_0/H_0$, $\Delta t_1/\Delta t_0$). Quantitative analysis of this relationship is beyond the scope of this work.

Conclusion. Numerical simulations were made for of a symmetric intrusion current in a fluid with a two-layer density stratification using a two-dimensional numerical model of a vertically stratified fluid dynamics. The initial stratification was determined by the density difference between the layers and the thickness of the intermediate layer. Intrusion in the model domain was formed by an injection of a fixed volume of fluid through the inlet opening of a given height. The inflow of fluid was injected in the form of two identical pulses. The volume of each injection was marked by a specific passive tracer, which provided visualization of the internal structure of the current. The main parameters of the problem were: the height of the inlet H_0, the characteristic velocity at the inlet opening of the U_0, the wave velocity $U_w = \sqrt{g'H_0}$ etermined by the initial density difference between the stratification layers, the time of each pulse Δt_0 and the time between pulses Δt_1. Of these, the dimensionless ratios of parameters $\mathrm{Fr}_0 = U_0/U_w$, $\Delta t_0 U_0/H_0$, and $\Delta t_1/\Delta t_0$ were derived, the values of which then varied between the calculations.

The results of numerical experiments indicate a significant effect of source discharge pulsations on the evolution of the intrusion flow and the dependence of the flow structure on the flow parameters. The analysis of passive contaminant transfer in calculations with different Fr_0 and $\Delta t_0 U_0/H_0$ detects a flow regime in which the volume of the second pulse propagates faster and further in the horizontal direction due to partial mixing with the first intrusion volume. For the formation of this effect, high values of the Froude numbers are needed, in particular, it is conspicuously presented at $Fr_0 = 1.5$, while at $Fr_0 = 0.4$ a slowing down of the horizontal propagation of the second pulse is observed. In addition, the pulsed nature of the source determines the current's structure in the case of short time intervals between pulses (generally, when $\Delta t_1/\Delta t_0 < 1$) and has almost no effect when it is not the case. Further work can be dedicated to a more precise definition of these effects' boundaries.

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Isachenko I. A. Influence of the source pulsations...

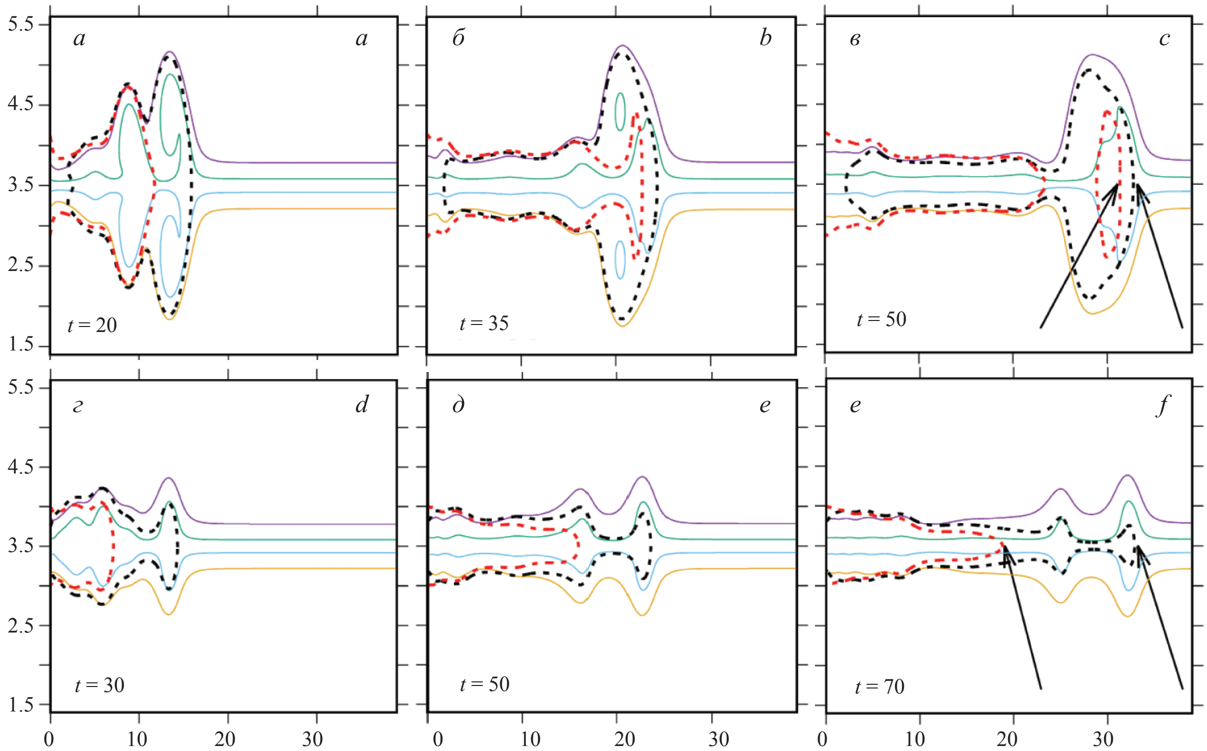

Fig. 2. Example of two distinct flow regimes.

Solid lines are dimensionless excess density contours (values 0.2, 0.4, 0.6, 0.8), *dashed lines* are isolines (value 0.1) of the tracers of the first (*black*) and second (*red*) inflow. Each row corresponds to the individual run of the model and the dimensionless time t increases from left to right. The parameters of the calculations are as follows: *a*—*c* — $Fr_0 = 1.5$, $\Delta t_0 U_0/H_0 = 8.5$, $\Delta t_1/\Delta t_0 = 0.25$ и *d*—*f* — $Fr_0 = 0.4$, $\Delta t_0 U_0/H_0 = 4.5$, $\Delta t_1/\Delta t_0 = 0.25$. The arrows mark the points farthest from the inlet, which are located at the isolines of the tracers.

Рис. 2. Пример двух режимов развития течения.

Показано распределение изолиний безразмерной избыточной плотности (*сплошные линии*, значения 0.2, 0.4, 0.6, 0.8) и трассеров (значение 0.1) первого (*черная штриховая линия*) и второго (*красная штриховая линия*) затоков. В каждой строке изображения слева направо соответствуют последовательно увеличивающимся моментам безразмерного времени t (значения указаны на графиках) внутри одного из двух расчетов с параметрами *а*—*в* — $Fr_0 = 1.5$, $\Delta t_0 U_0/H_0 = 8.5$, $\Delta t_1/\Delta t_0 = 0.25$ и *г*—*е* — $Fr_0 = 0.4$, $\Delta t_0 U_0/H_0 = 4.5$, $\Delta t_1/\Delta t_0 = 0.25$. Стрелками отмечено положение наиболее удаленных от источника точек на изолиниях трассеров первого и второго затоков.

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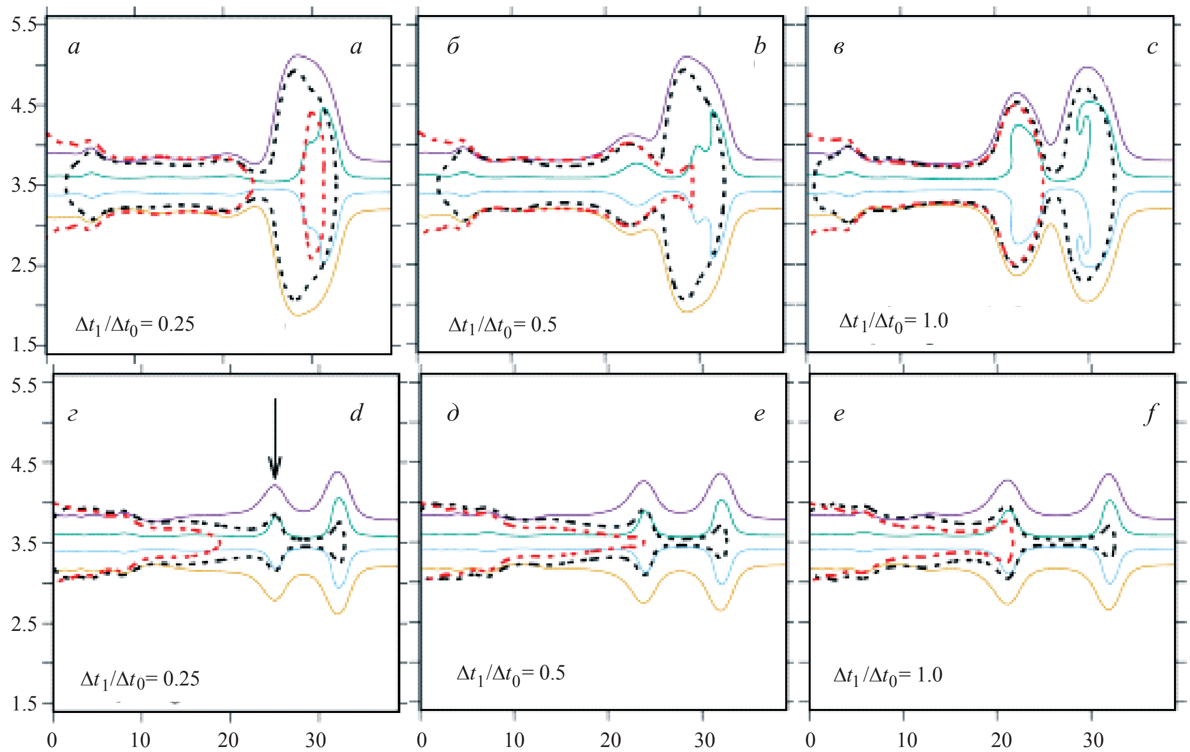

Fig. 3. Flow structure at different $\Delta t_1/\Delta t_0$.
The images in the each row correspond to different values of the parameter $\Delta t_1/\Delta t_0$ (from left to right) at time t = 50 for the series *a*—*c* and t = 70 for *d*—*f*. Remaining parameters are the same as in the examples shown on fig. 2. The arrow marks the position of the wave crest emerged from the second inflow.

Рис. 3. Иллюстрация изменения структуры течения в полях избыточной плотности и трассеров при изменении $\Delta t_1/\Delta t_0$.

Описание изолиний дано в подписи к рис. 2. В каждой строке изображения соответствуют различным значениям параметра $\Delta t_1/\Delta t_0$ (указаны на графиках) в один и тот же момент безразмерного времени t = 50 для серии *а*—*в* и t = 70 для *г*—*е*. Значения остальных параметров такие же как в примерах на рис. 2. Стрелкой на рис. *г* отмечено положение гребня волны от второго импульса.