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ANALYSIS OF EXPERIMENTS ON DETERMINING THE TURBULENT MIXING CONSTANT ON THE BASIS OF TWO-DIMENSIONAL CALCULATIONS

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Based on numerical calculations, the experiments on mixing at the interface of gases are analyzed. Single-mode and random disturbances of the interface and superposition of random disturbances onto long-wave perturbations are considered. Possible reasons for the higher value of the mixing constant obtained in the experiments are discussed.

Key words: *interface of gases, stability, mixing constant.*

Introduction. A large class of problems in hydrodynamics is associated with the study of evolution of interfaces between fluids, which are often unstable, and all initial perturbations available at the boundary increase infinitely in time. The Rayleigh–Taylor instability (RTI) is caused by acceleration acting orthogonally to the boundary of fluids with different densities and arises if the density and pressure gradients are directed to different sides from the interface. In the case of pulsed acceleration corresponding to shock-wave passage, the interface is always unstable [Richtmyer–Meshkov instability (RMI)].

A specific feature of hydrodynamic instability is a strong dependence of interface evolution on the initial and boundary conditions. In experiments, this is manifested in such factors as the method of imposing the initial disturbance of the interface (in particular, the influence of the film separating the fluids), compressibility, viscosity, surface tension, etc., which makes interpretation of experimental information more difficult. Therefore, the analysis of experimental results should involve data of numerical simulations.

The results of experiments in a shock tube where the decelerating shock wave passed from the heavy to the light substance are described in [1, 2]. After the shock wave passed, the interface became unstable, since it experienced a consecutive action of the shock acceleration (RMI) and, then, quasi-steady acceleration generated by the unloading wave in the direction from the less dense gas to the denser gas (RTI). Regular (single-mode) perturbations of the interface were set in [1]; the interface in [2] was flat, but because of the use of a destroyed film, this is equivalent to setting a certain random disturbance onto the interface. It was noted that the evolution of disturbances rapidly passes the nonlinear stage and reaches a regime presumably corresponding to the turbulent stage.

In [1, 2], the experimental data were processed with the help of the dependence proposed in [3]:

$$\sqrt{L} = \sqrt{L_0} + \sqrt{\hat{L}}. \tag{1}$$

Here L is the mixing-zone width, L_0 is the width of the initial turbulized mixing zone, and $\hat{L} = \alpha \mathrm{A} 2S$ is the self-similar width of the mixing zone, where α is the mixing constant, $\mathrm{A} = (\rho_1 - \rho_2)/(\rho_1 + \rho_2)$ is the Atwood number (ρ_1 and ρ_2 are the densities of the contacting gases), and S is the deceleration path determined as $S = Ut - \hat{x}$ [U is the increment of velocity of the interface between the gases after shock-wave (SW) passage, t is the time relative

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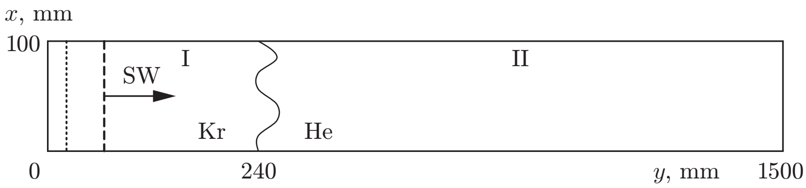

Fig. 1. Geometry of the problem.

to the moment the SW reaches the interface, and $\hat{x}$ is the distance covered by the interface relative to its initial position]. For a constant acceleration g, we have $S = gt^2/2$.

Processing of the results in [1, 2] yielded the mixing constant $\alpha \approx 0.31$ determining the growth of the mixing-zone width for the case of experiments with a sine-shaped initial interface and for a flat initial interface. This value was two or three times higher than that obtained in the experiments of [4–6], where $\alpha = 0.11$–0.14. It should be noted that the correct determination of this constant is very important for verification and determination of constants in the existing semi-empirical models of turbulent mixing.

This difference has been much discussed, but the reason is not completely clear. It was assumed in [1, 2] that the process of development of turbulent mixing in liquid media [4–6] is affected by surface-tension forces, whereas this factor is invalid in experiments with gases. The effect of conditions of disintegration of the film separating the gases was also implied.

It was noted in [2] that the data on mixing intensity in experiments with a flat interface coincide with the results of experiments with a sine-shaped boundary [1], which, in the opinion of Vasilenko et al. [1, 2] improves reliability of the result obtained. This coincidence, however, involves a number of questions that have to be studied.

For the Rayleigh–Taylor instability, the development of a multimode or randomly disturbed interface is analyzed theoretically and numerically in [7]. It is shown that a constant value of $\alpha = dL/d(\mathrm{A}gt^2)$ is established after a long time, and the value of α strongly depends on the spectrum of initial disturbances. Only the long-wave part of the spectrum exerts a significant effect, and there exists a threshold value of the initial amplitudes of long-wave components of the spectrum. If the amplitude of long-wave disturbances is lower than the threshold value (spontaneous case in terminology of [7]), a self-similar value of the mixing constant $\alpha \approx 0.1$ is reached at high values of t in numerical calculations. If the amplitude of long-wave disturbances is higher than the threshold value (stimulated case in [7]), the long-wave harmonics reach the nonlinear stage much earlier than the remaining harmonics. The value of α obtained in this case strongly depends on the amplitude of long-wave harmonics: it can be several times higher than that in the spontaneous case.

Hence, an assumption arises that a certain long-wave component with an amplitude higher than the threshold value is always present in the spectrum of disturbances in the experiments of [2] with an initially flat interface, which can significantly increase the mixing constant obtained in experiments.

In the present work, this issue is studied with the use of two-dimensional calculations by the vortex method [8, 9] and by the TIGR technique [10] with markers for interface description. Previously, the vortex technique made it possible to find the asymptotic regimes of development of single-mode disturbances of the interface at the nonlinear stage for steady and pulsed types of acceleration [8] and their joint action [9]. The method of markers in the TIGR technique allows one to trace the development of interfaces of compressible media (including those with a prescribed multimode or random initial disturbance) for a long time.

Formulation of the Problem and Calculation Techniques. The formulation of experiments is described in detail in [1] for the case of regular disturbances of the interface between the gases and in [2] for the case with a flat boundary. Here, we give only the necessary information and formulation of the problem for calculations. Note, several combinations of gases were considered in [2]; among them, we will involve only one combination, the same as in [1].

The geometry of the problem is shown in Fig. 1. Region I is occupied by krypton. The initial density is $\rho_0 = 3.36 \cdot 10^{-3}$ mg/mm^3, the initial pressure is $p_0 = 0.984$ bar, and the ratio of specific heats is $\gamma = 1.689$. Region II is occupied by helium ($\rho_0 = 1.6 \cdot 10^{-4}$ mg/mm^3, $p_0 = 0.984$ bar, and $\gamma = 1.63$). The gases are initially at rest. The length of the domain occupied by the gases is $y = 1500$; rigid walls are imposed at the coordinates $x = 0$ and

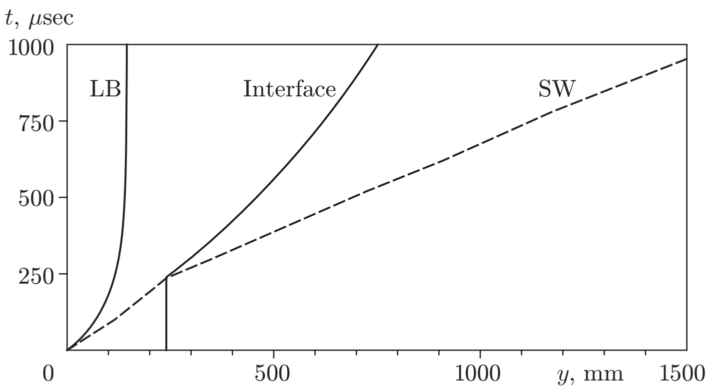

Fig. 2. Motion of boundaries and shock wave in the case of an undisturbed interface.

$x = 100$ mm. The velocity $u = U_0 \exp(-t/\tau)$, where $U_0 = 0.948$ mm/μsec and $\tau = 153.56$ μsec, is set at the left boundary (initially located at $y = 0$). The absence of heat fluxes through the boundaries is additionally prescribed.

As a result, a decelerating shock wave with a Mach number M ≈ 3 is generated at the left boundary (LB); the wave passes from krypton into helium (i.e., from the heavy to the light gas) and is followed by an unloading wave. The pattern of motion of the boundaries and shock wave in the case of an undisturbed interface of the gases is shown in Fig. 2. In this regime, the interface first experiences pulsed acceleration and then is smoothly decelerated with the Rayleigh–Taylor mixing arising at the interface.

In the experiments, the perturbation of the interface between regions I and II is determined by the shape of the film separating the gases at the initial time. In [1], the interface is set in the form $y = y_0 + a_0 \cos(2\pi x/\lambda)$, where $y_0 = 240$ mm, $\lambda = 50$ mm, and $x \in [0; 100]$ mm; a_0 is the amplitude of the initial disturbance (the experiments in [1] were performed for $a_0 = 1$ and 2.5 mm).

In the experiments of [2], the initial shape of the film separating the gases was flat; under the conditions of a disintegrating film, however, this is equivalent to imposing a certain random disturbance caused by inhomogeneous thickness of the film.

The numerical calculations were performed by the vortex technique and with the use of markers in the TIGR technique. The variation of the shape and total width of the interface between the gases (determined as $|y_{\max} - y_{\min}|$) in time was monitored in calculations.

TIGR Technique. In the implicit finite-difference technique TIGR [10] designed for numerical solution of two-dimensional problems of gas dynamics, the interfaces between the substances remain Lagrangian lines in the course of computations, and the motion inside the layers is described in moving Eulerian coordinates. In the case of strong deformations of the medium, however, it is not always possible to retain the Lagrangian form of the interfaces. In such cases, the chosen interface is indicated by particles-markers, which further travel over the moving Eulerian grid as Lagrangian particles. This allows one to localize the interface position with accuracy to one cell of the difference grid and to trace the detailed evolution of the interface with considerable deformations within a rather large time interval. Shock waves are smoothed by artificial viscosity of the von Neumann type.

The TIGR technique was used to calculate the development of the disturbed interface of ideal gases in the adiabatic approximation (with thermal conduction neglected). The development of single-mode disturbances of the interface was calculated, as well as the variant where a random disturbance with the maximum level of initial perturbations of about 0.3 mm was imposed onto a flat interface ($y = 240$ mm and $x \in [0; 100]$ mm). To check the effect of interaction of long-wave disturbances with random disturbances, calculations were also performed for the case where the above-described random disturbance was imposed onto a single-mode interface.

In the system under consideration, we constructed a regular quadrangular difference grid formed by horizontal and vertical families of lines. In the calculated system, we identified a region containing the disturbed interface, where a curvilinear difference grid was constructed (the grid outside this region was orthogonal). After the shock wave passed, the interface was indicated by markers placed into nodes of the difference grid; three markers were also placed inside each cell between the nodes. The number of markers automatically increased in the course of calculations as the interface described by the marker line was deformed. Uniform reconstruction of the grid for sustaining orthogonality was used behind the SW front in the region containing the marker line. The recalculation zone was expanded with increasing deformation.

In the calculations described below, the horizontal and vertical families contained 80 and 300 lines, respectively. The time step was 0.05 μsec until the interface was indicated by markers, and then it was increased to 0.1 μsec. Convergence was verified by refining the grid (up to 240 horizontal lines and up to 900 vertical lines) and by reducing the time step. Such a change of the grid had practically no effect on the numerical solution obtained.

Vortex Technique. This method is based on representation of the interface of ideal incompressible fluids by a vortex layer. The flow description reduces to determination of the interface shape and intensity of vortices distributed over the interface. During discretization, the interface is represented as a set of point vortices. Instead of the initial-boundary problem for nonlinear equations with partial derivatives, the method requires the Cauchy problem for a finite-dimensional system of ordinary differential equations to be solved. In particular, this removes the problem of grid construction for describing complex-shaped interfaces.

The vortex technique made it possible previously to determine the asymptotic regimes of development of single-mode disturbances of the interface at the nonlinear stage for steady and pulsed types of acceleration [8] and their joint action [9]. The applicability of the technique for RMI description for compressible media was demonstrated in [9]. Compressibility of gases is essential only at the moment when the SW passes through the interface and is taken into account as a change in the amplitude of the initial disturbance.

In the experiments of [1, 2], the unloading wave generates quasi-steady acceleration responsible for flow deceleration at the interface. Thus, the total acceleration of the interface is

$$\hat{g}(t) = \begin{cases} U\delta(t) + g, & t \geqslant 0, \\ 0, & t < 0, \end{cases}$$

where $\delta(t)$ is the Dirac function, U is the velocity increment generated by pulsed acceleration, g is the acceleration generated by the unloading wave, and $t = 0$ is the time when the shock wave passes through the interface between the gases.

The velocity of the shock wave incident onto the interface is $D = 0.81$ mm/μsec and $U = 0.94$ mm/μsec. After the shock wave passes through the interface, the Atwood number becomes $\mathrm{A} = 0.864$. It was noted in [1] that the acceleration generated by the unloading wave has a quasi-steady character, i.e., changes weakly; hence, for convenience of calculations, it can be assumed to be constant ($g = -9 \cdot 10^{-4}$ mm/μsec^2 for $t > 0$). The values of A, U, D, and g were borrowed from [1] and were confirmed by the one-dimensional calculation of the gas-dynamic problem.

Compressibility of gases is essential only at the moment when the shock wave passes through the interface and is taken into account as a change in the amplitude of the initial disturbance $a_0^+ = a_0(1 - U/(2D))$ [9].

A regular interface of the form $a_0 \cos(2\pi x/\lambda)$ was calculated. In contrast to the TIGR technique, the vortex technique allows separate consideration of constant and pulsed types of acceleration and their joint action in order to determine the influence of each type of acceleration on the evolution of the flow pattern.

In the present calculations by the vortex technique, we used 200 vortex points per wavelength and a time step of 0.05 μsec (note, in studying convergence of the method, we found that a rather exact result is obtained already when 50 vortices are used).

Analysis of Numerical and Experimental Results. In what follows, in the description of numerical and experimental results, the time $t = 0$ is the moment when the shock wave passes through the interface.

Single-Mode Interface. The calculated (by the TIGR technique) shapes of the interface at certain times are shown in Fig. 3 for regular initial disturbances of the interface. The time evolution of the total width of the interface between the gases (numerical and experimental curves) are plotted in Fig. 4.

We consider the case of a single-mode interface of the form $a_0 \cos(2\pi x/\lambda)$ with $\lambda = 50$ mm and $a_0 = 2.5$ mm. Figure 3a shows the interface positions calculated by the TIGR technique for $t = 310$ and 670 μsec. Figure 4 shows the experimental [1] and numerical dependences (calculated by the vortex technique and TIGR technique) of the total width of the mixing zone on time. Note, the shock wave passes from the heavy substance to the light substance; therefore, the phase of interface disturbances changes when the SW passes through the interface. The method of markers allows one to trace interface evolution much further in time than the vortex technique; the results obtained by two methods are in good agreement but predict slightly lower values as compared with the experiment.

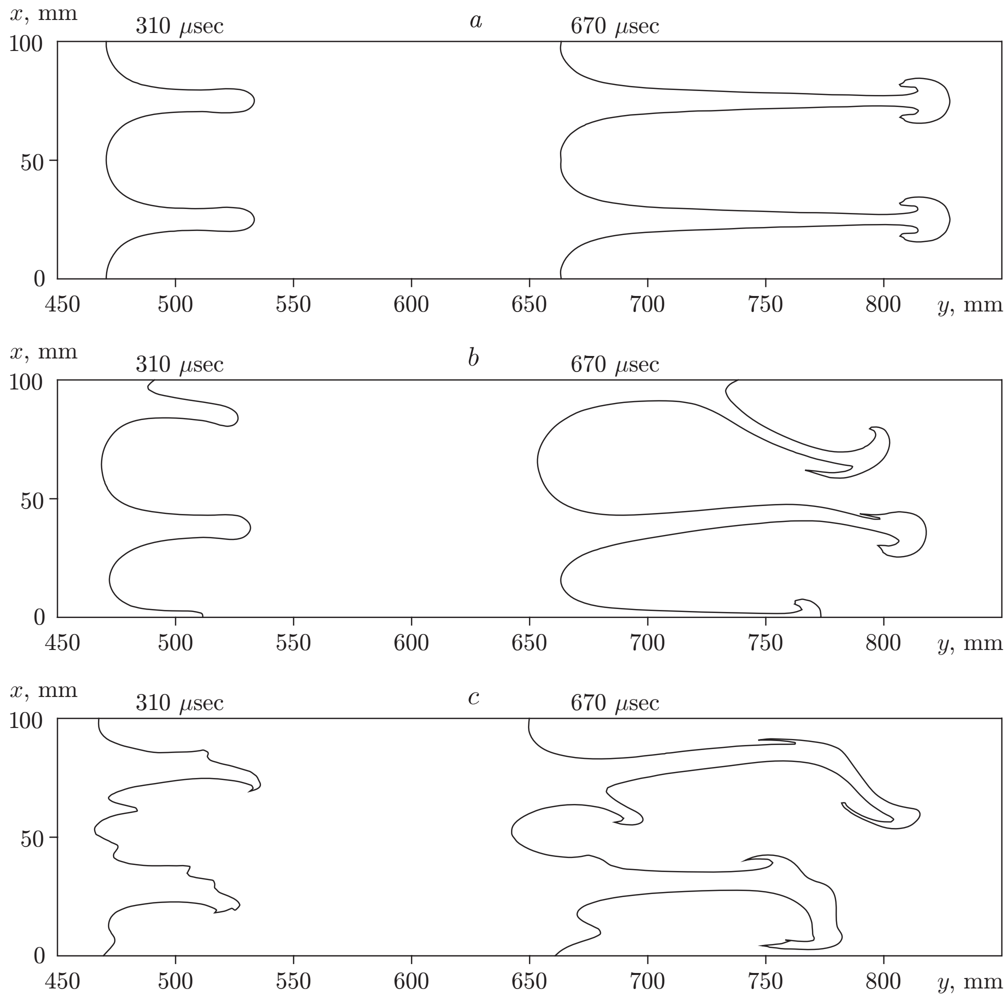

Fig. 3. Interface position at the times $t = 310$ and 670 μsec ($a_0 = 2.5$ mm and $\lambda = 50$ mm). The calculations were performed by the TIGR technique: the initial disturbances were $a_0 \cos(2\pi x/\lambda)$ (a) and $a_0 \sin(2\pi x/\lambda)$ (b), and a random disturbance imposed onto the initial disturbance a (c).

For preliminary investigations of ear-wall effects, we considered the case with a varied angle of contact between the regular interface and the rigid wall; in this case, the interface had the form $a_0 \sin(2\pi x/\lambda)$. The calculation results for $\lambda = 50$ mm and $a_0 = 2.5$ mm are plotted in Figs. 3b and 4. The total width of the mixing zone L almost coincides with the case of the initial disturbance $a_0 \cos(2\pi x/\lambda)$. The difference is manifested in distortions of the interface shape in the region of peaks of the heavy gas and asymmetry of these peaks. The depths of penetration of the fluids into each other are also slightly different (in the case of a sine-shaped disturbance, the depth of penetration of the heavy fluid into the light fluid decreases, and the depth of penetration of the light fluid into the heavy fluid increases, which is seen from the positions of the interface at the final time).

The possible influence of other near-wall effects on the evolution of the mixing-zone width deserves an individual detailed study.

Let us now discuss the value of the mixing constant α obtained in [1] by processing experimental data.

The development of interface instability is usually divided into three stages: regular (including linear and nonlinear stages), transitional, and turbulent. The linear stage was identified by comparing the experimental and numerical results with the analytical solution (also shown in Fig. 4) obtained in [1] in the linear approximation for the case of ideal fluids with a consecutive action of pulsed and constant types of acceleration onto the interface:

$$L(t) = 2a_0^+\Big(\cosh(\omega t) - \frac{U}{W}\sinh(\omega t)\Big), \qquad \omega = \sqrt{\mathrm{A}gk}, \quad W = \sqrt{\frac{g}{\mathrm{A}k}}, \quad k = \frac{2\pi}{\lambda}.$$

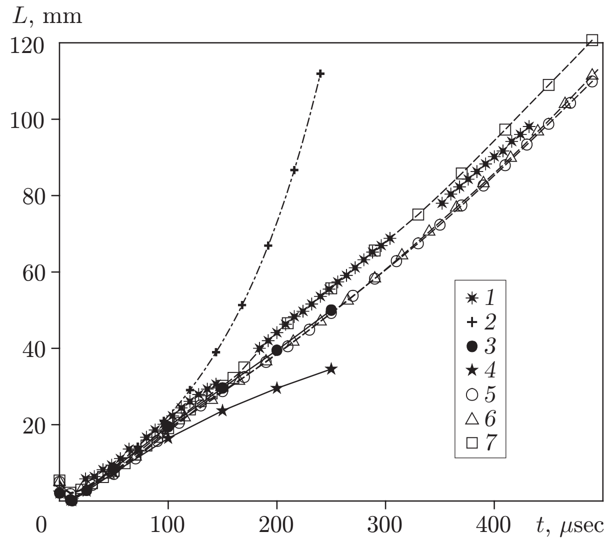

Fig. 4. Mixing-zone width versus time (regular disturbance with $a_0 = 2.5$ mm and $\lambda = 50$ mm): experiment [initial disturbance $a_0 \cos(2\pi x/\lambda)$] (1); linear theory [1] (2); calculation by the vortex technique [initial disturbance $a_0 \cos(2\pi x/\lambda)$] (3); vortex technique [initial disturbance $a_0 \cos(2\pi x/\lambda)$, only pulsed acceleration] (4); TIGR calculations [initial disturbance $a_0 \cos(2\pi x/\lambda)$] (5); TIGR calculations [initial disturbance $a_0 \sin(2\pi x/\lambda)$] (6); TIGR calculations [initial disturbance $a_0 \cos(2\pi x/\lambda)$ + random disturbance] (7).

For the case considered, we can assume that the linear stage is extended up to the time $t \approx 120$ μsec; the results of experiments, calculations, and the linear theory are in good agreement. The nonlinear stage begins from interface-shape distortion and leads to formation of clearly expressed vortex structures. In the transitional stage, the initial spatial structure of the interface is destroyed because of vortex interaction, and then the turbulent stage is reached.

The process of transition to the turbulent stage depends on particular test conditions, but the limiting stage of turbulent mixing should be independent of initial conditions. Though it is recognized in [1] that it is almost impossible to ensure an asymptotic stage of mixing in the experiment because of the finite size of the setup and short duration of acceleration, it is assumed, nevertheless, that the transition to the turbulent stage has already occurred in the experiments described, and the test results are analyzed on the basis of dependence (1). The coefficient $d\sqrt{L}/d\sqrt{2S} = \sqrt{\alpha \mathrm{A}}$ is found to describe the process of gravitational turbulent mixing. The value of the mixing constant α was obtained in [1] by the least squares technique for $t > 150$ μsec ($S > 10$ mm).

It should be noted that the formulas mentioned are valid only for the asymptotic stage of gravitational mixing characterized by randomness in the flow. However, both the photographs of the mixing zone [1] and the calculations (see Fig. 3) clearly display mushroom-shaped structures of the heavy gas even at the last time instants; the number of these structure is unchanged. Such a shape of interface evolution is typical of the deep nonlinear stage. The calculated width of the mixing zone increases almost linearly in time, which is typical of the nonlinear stage of development of single-mode disturbances in the Rayleigh–Taylor instability.

Thus, we can assume that, in the case of a single-mode interface, the nonlinear stage of instability that has not passed to turbulence yet is observed at the final time.

If we take into account formula (1), formally process the results of calculation of the mixing-zone width in the variables $\sqrt{L}$ and $\sqrt{2S}$, and evaluate the change in the parameter α in time, this parameter does not reach a constant value even at the last time instants calculated and behaves as a decreasing function of time. Thus, incorporation of the nonlinear stage into processing of test results significantly increases the averaged value of the parameter α obtained in [1].

There is one more factor in the experiments, which has a significant effect on mixing-zone development and is ignored in processing the results in [1], namely, the development of the Richtmyer–Meshkov instability after SW passing through the interface. The results for $a_0 = 2.5$ mm ($\lambda = 50$ mm) under the action of pulsed acceleration only, which were obtained by the vortex technique, are also plotted in Fig. 4. The contribution of the pulsed component of acceleration in the case of the total width of the mixing zone for the times considered is commensurable with the influence of constant acceleration. The shock wave imparts some initial kinetic energy to the layer, which accelerates the development of the latter. For the existing relation of the parameters U and g in the time intervals considered, the initial pulse significantly increases the value of α obtained by processing the test results.

In addition, it was shown in [2] that, under the test conditions, the nitrocellulose membrane separating the gases burns down before the shock wave is incident onto the interface. Because of the admixture of combustion products, part of the thermal radiation from a hotter krypton is absorbed in the mixing zone, which, possibly, leads to a more intense increase in the mixing-zone width.

The evolution of the mixing-zone width can also be affected by initial random disturbances imposed onto the interface, which are caused by the variable thickness of the film and conditions of its disintegration.

We considered the case where random disturbances of $\sim$0.3 mm corresponding to the test conditions of [1, 2] were imposed onto the above-described regular initial disturbances of the interface of the form $a_0 \cos(2\pi x/\lambda)$. It was not possible to obtain an exact quantitative estimate of this influence by the vortex technique, but the method of markers in the TIGR technique allows this kind of calculations. For the case $\lambda = 50$ mm and $a_0 = 2.5$ mm, the time evolution of the mixing-zone width is shown in Fig. 4; the interface shape at the times of 310 and 670 μsec is shown in Fig. 3c. The influence of random disturbances is manifested in a noticeable distortion of the interface shape (see Fig. 3c) and offers an adequate description of experimental data on the mixing-zone width, though the long-wave component of the disturbance is the governing factor.

As in the case described above, if we process the calculated width of the mixing zone in the variables $\sqrt{L}$ and $\sqrt{2S}$, the value of the parameter α is also a slowly decreasing function, which has not yet reached a constant value.

For all cases described, calculations were also performed with different amplitudes of the initial disturbance a_0. The qualitative pattern of interface evolution, however, remains unchanged, and the results of these calculations are not described here.

Experiments with a Flat Interface. In the experiments with a flat interface [2], the destruction of the film initially separating the gases corresponds to a certain random disturbance imposed onto the film. The mixing intensity obtained by processing experimental data for a flat interface [2] coincides with the results of experiments with a sine-shaped interface [1]; Vasilenko et al. [1, 2] believe that this improves reliability of the data obtained. Taking into account the results of [7] and the above-described results of numerical investigations of the behavior of single-mode interfaces, however, we can assume that a certain long-wave component is present in the spectrum of the initial disturbance in experiments with a flat interface, which exerts a significant effect on mixing evolution.

The assumption was verified by TIGR calculations with the use of markers for the interface description. Figure 5 shows the calculated dependences of the mixing-zone width on time for different variants of the initial disturbance.

In [2], in analyzing the results of experiments with a flat interface for the gas combination considered, it was assumed that the flow is laminar before the time $t = 100$ μsec and becomes turbulent at $t \geqslant 150$–200 μsec. The calculated width of the mixing zone almost coincides for the case of single-mode and random disturbances, but is still lower than the experimental data at the stage corresponding to turbulence in [2]. In the case of superposition of the initial single-mode and random disturbances, the contributions of the random and regular components are almost identical. The calculated result almost coincides with the experimental one (see Fig. 5) for $t > 200$ μsec, but there is some difference at the initial regular stage.

If, as previously, we estimate the calculated intensity of mixing α, the value of this parameter at late times is a slowly decreasing function of time. At the time $t = 500$ μsec, we have $\alpha \approx 0.23$ for the regular or random initial disturbances and $\alpha \approx 0.27$ for the case of superposition of the random disturbance onto the regular one, which is in good agreement with the experimental value. The amplitude of the long-wave component of the disturbance exceeds the threshold value [7] and significantly increases the mixing intensity α.

Conclusions. The capabilities of the vortex technique and TIGR technique with the use of markers for description of interfaces in gases are demonstrated. The cases of single-mode and random disturbances of the interface and superposition of random disturbances onto long-wave perturbations are considered.

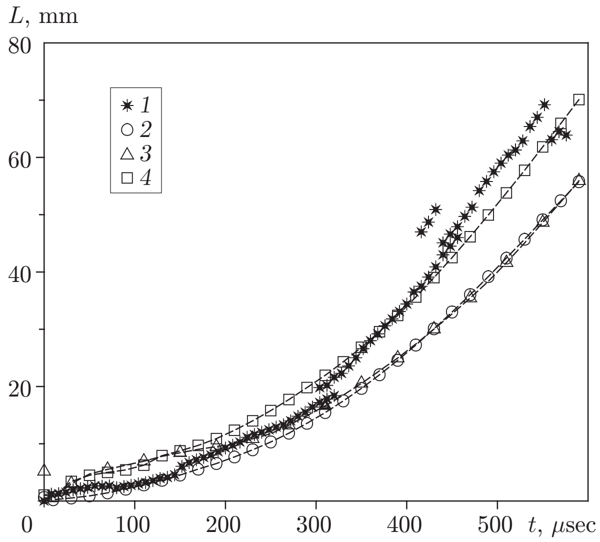

Fig. 5. Mixing-zone width versus time: experiments with a flat interface (1); calculations by the TIGR technique [initial disturbance $a_0 \cos(2\pi x/\lambda)$, $a_0 = 0.3$ mm, and $\lambda = 50$ mm (2), random initial disturbance (3), and regular initial disturbance with $a_0 = 0.3$ mm + random disturbance (4)].

Based on calculations by these techniques, the results of experiments [1, 2] on instability and mixing at the interface of two gases are analyzed. It is shown that some factors that are ignored in processing of experimental data can significantly increases the mixing intensity in the time intervals considered.

In the case of a single-mode initial interface, the allowance for additional random disturbances offers an adequate description of the increase in the mixing-zone width. The nonlinear stage of instability that has not yet passed to turbulence is observed at the final calculation times. The higher value of the experimentally obtained mixing constant can be caused by incorporation of the nonlinear stage into processing of results and by the presence of initial kinetic energy of the layer owing to SW passage through the interface, which significantly affects the process evolution during the time interval under consideration.

For experiments with an initially flat interface, it is shown that the higher value of the mixing constant can be caused by the presence of a certain additional long-wave component in the spectrum of the initial disturbance.

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