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Experimental and Numerical Evolution Studies for 2-D Perturbations of the Interface Accelerated by Shock Waves*

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The evolution studies for the perturbations of interfaces between two gases or fluids accelerated by the shock wave started after the emergence of papers [1],[2]. The shock tube experiments [2]–[5] studied the evolution of 2D single-mode perturbations (like $y = a_0 \cos x$) of the interface between two gases under the acceleration driven by one shock wave. The reference [6] considers the case of a 2D disturbance with a complex shape ("saw","step"). Because of great difficulties to generate such interface shapes (when the gases are separated by a thin film about 0.5μm thick) the perturbation in these experiments was set such that a half-wave lengths of such perturbation fits the channel cross–section. When analyzing the experiment results one should keep in mind the potential influence of near-wall effects.

In addition to experimental studies, numerical investigations of this process are very extensive in recent years which is explained by both the importance of the subject itself and the fact that the problem is perfect for method testing. While the investigations of small perturbations can be considered the passed stage, the studies of nonlinear phases is far from being completed. This is explained by the complexity of the process itself in late phases that include turbulent mixing and by the imperfect existing numerical and experimental capabilities.

The evolution of sinusoidal perturbations of the air-helium interface crossed by a series of shock wave was numerically studied in [7],[8].

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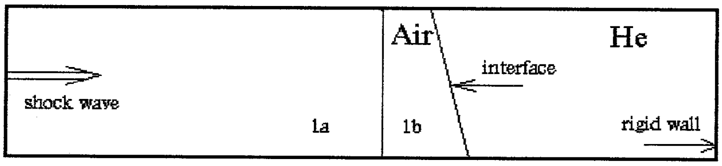

Figure 1: Initial experimental and computational geometry.

This paper presents the results of experimental and numerical studies of the perturbations such as "step" and "saw" in the geometry similar to [9] (air-helium-rigid wall) that is the interface is initially accelerated by the incident shock wave and then decelerated by a series of shock waves reflected from the rigid wall at the end of the channel.

The experiments used the shock tube described in [2]. The initial experimental and computational geometry is given in Figure 1. The end of shock tube channel with the cross-section $120 \times 40\,\text{mm}$ with transparent side walls was composed of mountable units and the face was covered by a plug (rigid wall). The unit at the channel end was separated by a thin organic film with the specific mass $\sim 4{-}10^{-5}\,\text{g/cm}^2$ forming a closed volume filled with helium. The remainder of the channel confound air at atmospheric pressure. The interface between the gases initially experienced the perturbations like "saw" or "step". The distance from the mid line of the perturbed interface to the rigid wall was 200 mm. The initial perturbation amplitude was $\Delta_0 = 0.1\lambda_0$, $\lambda_0 = 240\,\text{mm}$.

The flow pattern in the measurement section was recorded with the shadow system IAB-451 optically connected with the camera VKF-13.

The numerical simulation of the above mentioned problems used several methods from EGAK and MIMOZA codes.

The EGAK codes [10] are intended for numerical simulation of time-dependent compressible 2D flows of multicomponent medium with strong deformations including turbulent mixing ($k - \varepsilon$ model [11]). The codes use a regular quadrangular grid whose nodes may move in a relatively arbitrary way during the computations. In partial cases it can move with material (Lagrangian grid) or remain fixed (Eulerian grid) [12]–[14]. To distinguish the components, we use the full set of thermodynamic parameters. The method of concentrations was used to avoid the smearing of the interface between the components [15].

The MIMOZA codes [16] are intended for numerical simulations of wide spectrum of 2D and 3D time-dependent gas-dynamic applications with heat conduction using various Lagrangian- Eulerian methods. The computations described bellow use the Eulerian method including the Young's scheme [17] computing the convective terms with the second-order accurate approximation in smooth solutions retaining the monotonicity. The MIMOZA codes also include the 2D VKL method where the interface between materials is selected by the curved grid- independent lines whose motion is computed separately from that of the grid.

The evolution computations of the perturbations corresponding to the above described experiments were performed using each of four methods till $t = 3\,\text{msec}$. The initial geometry for all computations is identical and schematically shown in Figure 1. At initial time the parameters behind the shock front were applied to the domain 1a while the domain 1b experienced non-perturbed state.

The computational results are presented as raster patterns of volume concentrations for the MIMOZA, EGAK and EGAKT computations and as the interface position for VKL computations in Figures 2 and 4 for the saw perturbation and in Figures 3 and 5 for the step perturbation. The computational results for EGAK and EGAKT codes are given in comparison with the experimental pattern and give clear idea of the agreement between computational and experimental data. The comparison used the computer matching of images. To avoid the overlapping of the computational lines of the same level and the experimental patterns, the experimental images are slightly darkened and the isoline itself has a triple width (white color inside and black border). The time given in the frames was counted since the time of the incident shock wave arrival to the mid-line of the initial perturbation.

The qualitative evolution pattern of the large scale “saw” perturbation is as follows. After the interface is crossed by the incident shock wave the perturbation changes the sign (the shock wave passes from the heavy to light gas) and continues to grow. After the deceleration by the shock waves reflected from the rigid wall the perturbation form changes. Note that the shock wave always moves in $L \to H$ direction and the perturbation grows without changing the sign. Near the upper edge of the spike point of the heavy gas a jet forms with evolving vortex at the end. And a bubble emerges at the spike of the light gas. At later times an additional series of vertices of various size forms that also grow with time. From the very beginning the interface demonstrates the formation of the turbulent mixing zone (TMZ) against these large-scale perturbations.

In the case of the initial “step” perturbation the perturbation changes the sign immediately after the shock wave arrival and a vortex forms at the interface curvature front, further growing. Its size becomes comparable with that of the measurement section with time. In addition to large scale perturbations, the TMZ forms at the interface.

At the interface fragments parallel to the front of the shock waves crossing the interface, the TMZ width is considerably greater as compared to the interface fragments normal to the shock front (tangential mixing). The figures shows that till the computation completion the computational date agree well in describing long wave perturbations. The comparison with the experiment also indicate an acceptable agreement.

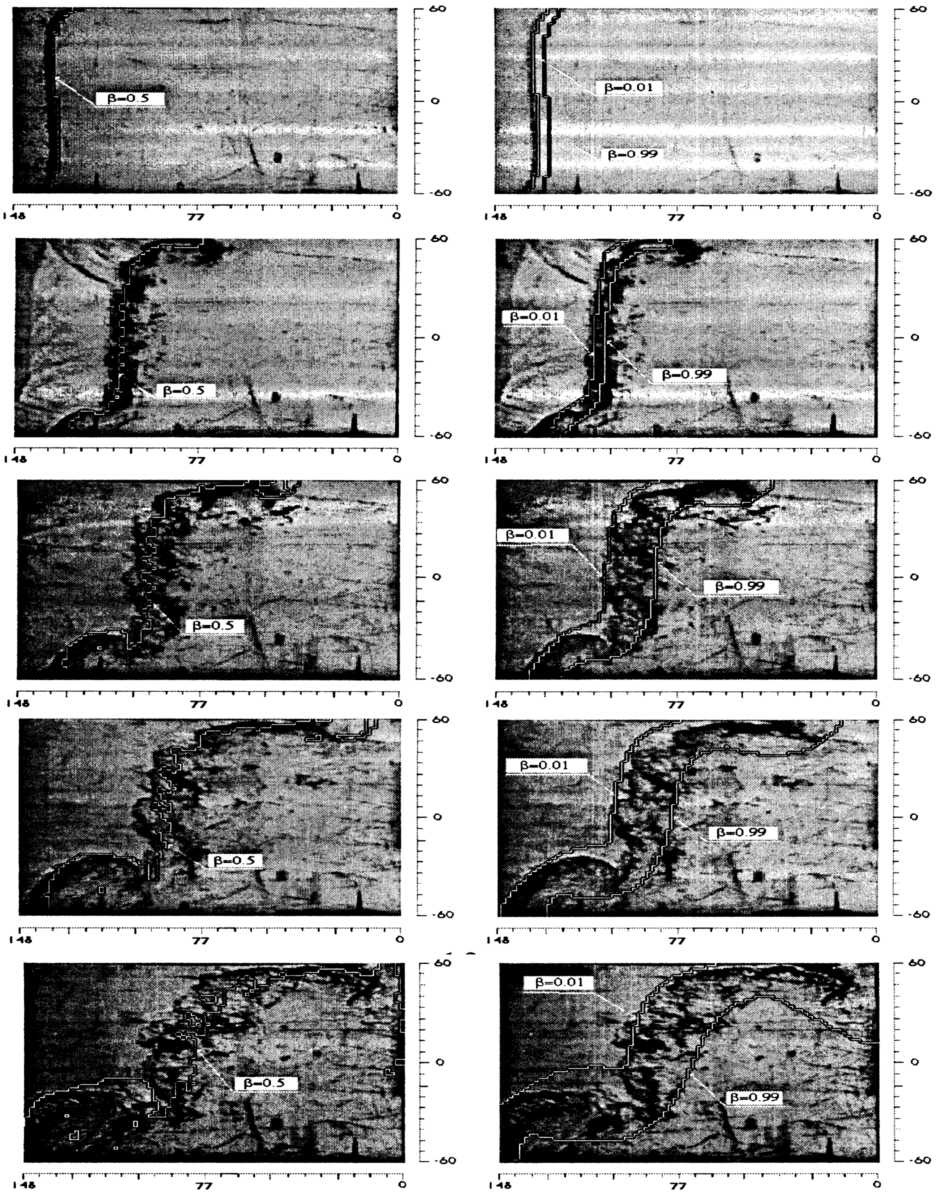

Figure 2: Evolution of saw-shaped perturbation. Comparison between experiment photochronograms and 2D EGAK (left) EGAKT (right) calculation results at times $t = 0.3, 0.6, 0.9, 1.2, 1.8$ms from top to bottom.

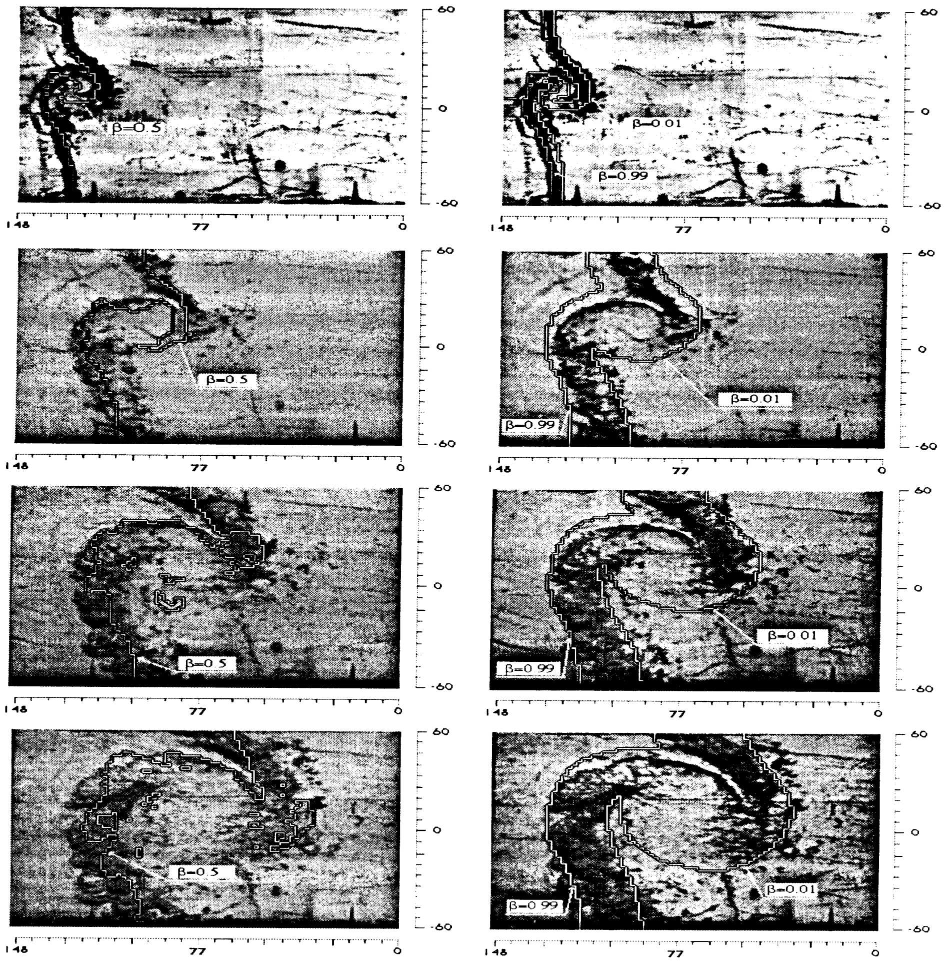

Figure 3: Evolution of step-shaped perturbation. Comparison between experiment photochronograms and 2D EGAK (left) EGAKT (right) calculation results at times $t = 0.3, 0.6, 0.9, 1.2$ms from top to bottom.

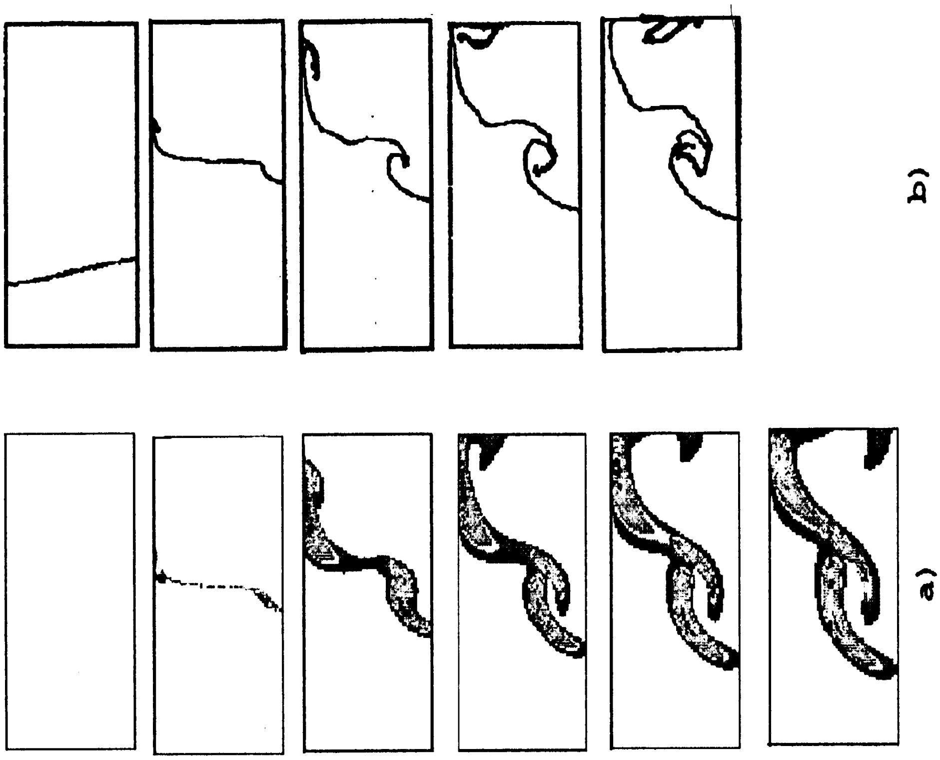

Figure 4: Evolution of saw-shaped perturbation. a) EGAKT simulation (shadow photographs), b) VKL simulation (interface).

However the "saw" perturbation demonstrates some differences in describing bubble dynamics in the lower part of the image. For the fragment with dominating tangent mixing, the computational methods yield a greater TMZ width as compared to the experiment. There are also the differences at the upper interface represented by a higher computational jet velocity along the wall. Possibly, this is due to the boundary effects associated with the boundary layer in the experiment. Note that the computations used the perfect sliding condition.

The step perturbation did not demonstrable significant differences in large scale flow characteristics since the basic dynamic processes for this problem occur in the middle of region far from the walls.

However the description of the small-scale computational fluctuations indicates the differences for both problems. First, note that these three gas-dynamic codes do not allow the comprehensive simulation of small-scale spectrum of turbulent fluctuations

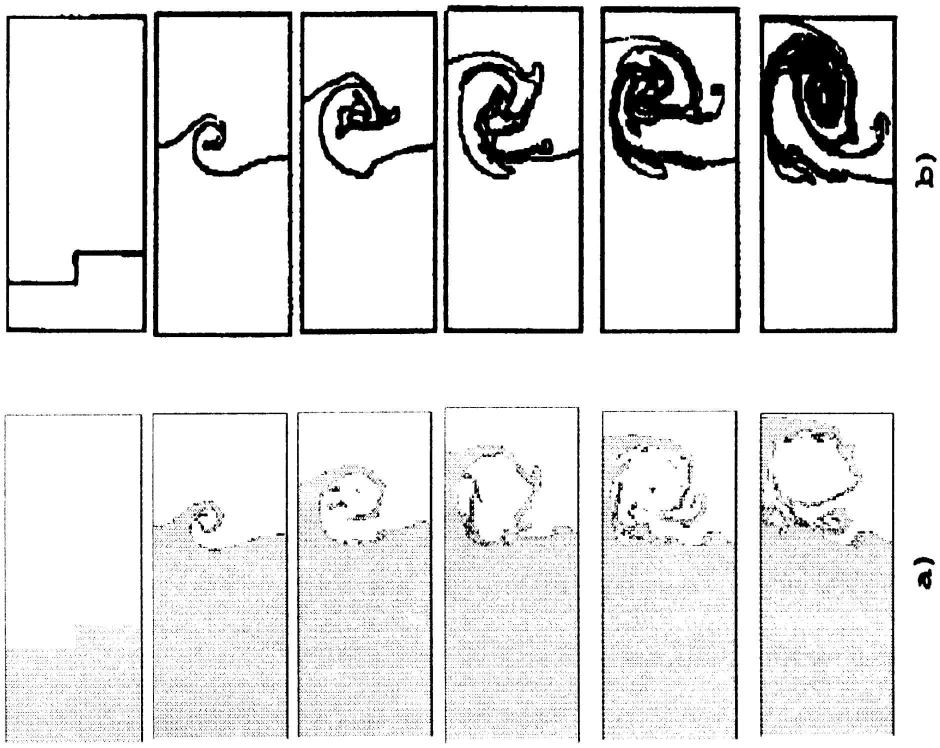

Figure 5: Evolution of stepped perturbation. a) MIMOZA simulation (volume concentrations), b) VKL simulation (interface).

and yield a smaller TMZ width as compared to the experiment especially where the main contribution to the turbulence is made by gravitational mixing. For these fragments the lowest TMZ width is given by VKL computations. The TMZ width is considerably greater in MIMOZA and EGAK computations. The computations with $k - \varepsilon$ model give the TMZ width value that is closest to the experiment.

Generally, the representation of 2D computation results uses the display of spatial distribution of the corresponding quantity, for example, density or mass concentration of a gas component that are compared with the experimental photographs. However this comparison may not be quite correct since the experiment usually yields some "translated" pattern of the thermodynamic medium state, for example, shadow image. Therefore, It is interesting to try to obtain the analogs of the shadow photograph, corresponding to the experiment from 2D computations.

For the shadow visualization of transparent inhomogeneities, the light from a light source passes through a narrow hole impacting the mirror with the focal distance $f \cong 2m$ which forms a plane parallel light beam.This beam moves through the flow region in the shock tube and then impacts another mirror with the same $f \cong 2m$ and is focused. Then an intermediate lens was installed that in combination with the second mirror generates the image of the region studied on a film. In the focus of the second mirror the Foucault knife was installed. It cuts the beams with the negative refraction angle α_0 actually without diffraction. The angle α_0 means the refraction only in the direction perpendicular to the Foucault knife line.

If the flow contains the optical non-uniformities such as the refraction index gradients, the light beams will decay. As a result, the photographs will contain a light spot where α_0 is positive and a dark shot where α_0 is negative.

The known refraction indices for the gases are used, to evaluate the light beam decay angle. Thus the isolines of the vertical refraction angle α_0 must yield the shadow photograph similar to the experiment. The processing of EGAK and EGAKT results in the assumption of homogeneous mixing of helium and air showed that the numerical shadow photograph agrees well with the conventional data processing and with the experiment (see Figure 3b).

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