

APPLICATION OF VARIOUS METHODS OF VISUALIZATION IN THE STUDY OF TURBULENT MIXING IN A SHOCK TUBE EXPERIMENTS

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Introduction

The interface between two media of different density moving with acceleration directed normally to the boundary can be unstable at some certain conditions. Initial perturbations of the unstable boundary grow; and as a result a growing turbulent mixing zone is formed. Depending on nature of acceleration two basic types of instability are differentiated.

In the first case, when acceleration is constant or changes weakly in time and is directed from light medium to heavy, the interface turns out to be unstable. Such type of instability is called Rayleigh-Taylor instability (RT) [1,2]. The interface is stable, if acceleration is directed from heavy medium to light.

In the second case when acceleration has pulse nature or, when the interface is accelerated by a stationary shock wave, instability develops irrespective of acceleration direction. This type of instability is called Richtmyer-Meshkov instability (RM) [3,4].

For over forty years by the author or with his direct participation several studies of the RM instability - the instability of the two gases accelerated by a shock wave experiments on shock tubes was carried out. The results of these studies have been described in reviews [5,6], the monographs [7] and in a number of articles and reports. This review describes examples of applications in experiments of different methods of flow visualization: shadow method [8-10], laser sheet method [11], a method of defocused filament (Ronchi method) and defocused lattice [12]. These methods have been used in the study of turbulent mixing zone that develops at the interface of two gases accelerated by shock waves.

1. Specific features of turbulent mixing zone structure at gas-gas interface.

The phenomenon of turbulent mixing at the interface of two gases of different density accelerated by shock waves was discovered experimentally by the author of this paper in 1968 and published in [8-11]. Experiments [8-11] were performed in a shock tube in the following geometry (Fig. 1): *air* ($\rho_0=1.2$ g/l) – *helium* ($\rho_0=0.178$ g/l) – *rigid wall*. The shock tube channel cross section was 4×12 cm², the helium portion length was 16.6 cm. Mach number of the initial stationary shock wave in the air was $M=1.3$. The experiments in such a formulation optical recording of flow was carried out by the following methods: a) visualization of the mixing zone by the shadow method with high-speed movie camera recording SFR [8-10], and b) visualization by the laser sheet with the registration of the flow in the single-frame mode [11].

In these experiments the flat interface between air and helium separated by a thin film is first accelerated unevenly by a stationary shock wave and moves further with a constant speed by inertia. Since helium is much lighter than air, then after discontinuity decay a rarefaction wave goes into air, and a shock wave with the amplitude much lower as compared to an incident wave, goes into helium. This wave is reflected from a rigid wall at the end of the channel as a shock wave, which in its turn is reflected from the helium-air interface also as the shock wave,

and so on. As a result the interface is decelerated by a series of shock waves with the sequentially decreasing amplitude. The flow pattern is illustrated by shadow streak photographs of the experiment (Fig. 2).

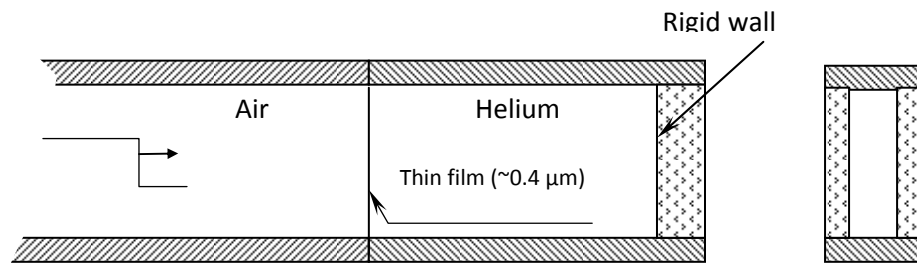


Fig. 1 Scheme of a shock tube test section in experiments on development of the turbulent mixing zone at air-helium flat interface accelerated by shock waves.

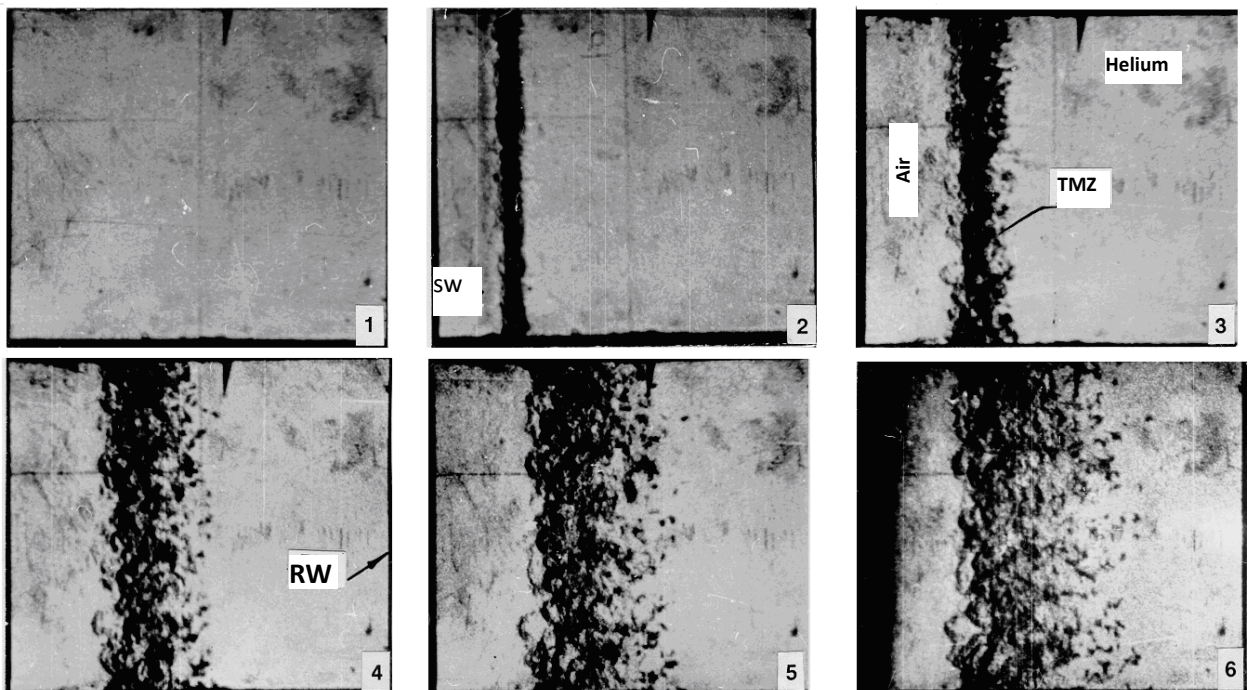


Fig. 5. Turbulent mixing zone (TMZ) development at the air-helium interface [8]. Abbreviations: SW is shock wave, RW is rigid wall. Shadow method is used.

In experiments the part of initial perturbation was played by natural thickness variation (hence, mass variation) of the film; thickness distribution had random nature and could reach about $\pm 50\%$ of the average value. After the first shock acceleration of the interface, it moves some time by inertia with a constant speed. However in the experiment gases are separated by a thin film with a low, but finite mass, so the interface accelerates up to the predicted flow rate at the short, but finite distance. During this time there is the pressure difference on each side of the film. The film portions with different mass accelerate differently, that results in the boundary shape distortion. If acceleration exceeds the elastic strain limit of the film, it tears into fragments, and micro-jets of compressed air flow in gaps between these fragments [10]. As a result of these processes the seed perturbation is formed (frame 2 of Fig. 5), and one can observe the fast

development of the mixing zone, whose image has a cell structure, typical for shadow photos of turbulent flows. Mixing zone boundaries are perturbed, and the perturbation scale grows in time.

In fig. 3 shows a photograph of a turbulent mixing zone at the air-helium interface, obtained by defocused filament [12].

Fig. 4 present photo of turbulent mixing zone at the air-helium interface, obtained by laser sheet [11].

Schlieren photography [8] and the photograph obtained by defocused filament [12], provide an integral picture of the turbulent mixing zone, such photos allow you to define the width of the zone and no more. Photographs obtained by the laser sheet [11], in addition, provide information about the structure of the mixing zone. An experimental set-up with a shock tube is similar to the one provided in Fig. 1 with the exception that cigarette smoke is added to the air bordering with helium. At the set time a flat thin laser beam (~ 1 mm) was passed through the mixing zone along the shock tube channel axis (the beam was passed through a transparent rigid wall at the end of the channel). The laser sheet light was scattered on smoke particles in air, including the air in the mixing zone. Thus, the instant image of the distributed air in the mixing zone in the laser sheet plane was formed.

The mixing zone pattern in scattered light (fig. 4) differs significantly from the pattern obtained by using shadow method (fig. 2,3). A typical feature of this pattern is the presence of a clearly defined boundary between the air («heavy» gas) and the mixing zone, at the same time the boundary between the mixing zone and the helium (“light” gas) is not observed. Thus, *between the heavy gas and the mixing zone there is heavy gas concentration (and density) discontinuity, i.e. concentration jump between the heavy gas and the mixing zone, and at the same time there is no discontinuity (jump) between the mixing zone and the light gas.*

In the mixing zone the air concentration gradually falls down to zero. The photo In Fig. 4 discloses the mechanism of turbulent mixing zone development at a later stage, when film fragments initially separating gases basically shift to the zone edge, and their effect on the zone development becomes practically ignorable. At this stage the mixing zone development is determined basically by the effects occurring at the interface between the heavy gas and the mixing zone. As is mentioned above, density jump continuously exists at this interface. The heavy gas penetrates into the mixing zone in the form of relatively narrow jets. Eddy zones at the ends of these jets are exactly the source of heavy gas penetration into the mixing zone and the further mixing of this gas with the light gas. It should be noted that the interface between the heavy gas and the mixing zone at other portions (beyond jets) remains reasonably smooth. Thus, at the stage of the developed flow one can observe in the mixing zone the combination of ordered flow components at the interface with the heavy gas (the interface between the heavy gas and the mixing zone is perturbed, but not turbulized) and turbulent mixing of gases in the remaining portion of the zone.

The photo negative obtained in one of the experiments at the time $800\mu\text{s}$ was photometrically measured over 25 lines in the direction of the shock tube channel axis (negative processing procedure and photometric measurements results were described in details in [11]). As a result air concentration distribution over each line was obtained. Fig. 5,a provides the photo fragment with the lines. Fig. 5,b provides the air concentration plot in the turbulent mixing zone after processing over line №5. Based on these photo measurements the air concentration at the air/mixing zone interface drops down by a jump from 1 to ~ 0.15 . At the same time the averaged

(over every line) distribution of air concentration has smooth nature and agrees with the results of mixing zone calculations according to Nikiforov model [13] (Fig. 6).

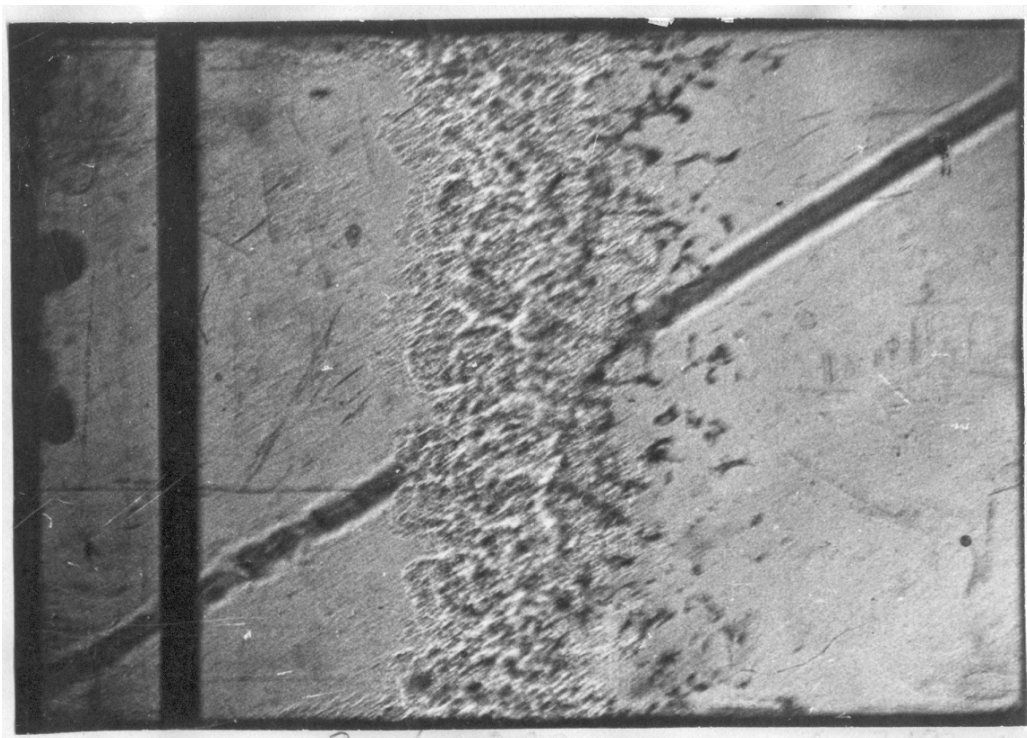


Fig.3. Photo of turbulent mixing zone (ITP) at the air - helium experiments, obtained by defocused filament at time $t \approx 900$ ms after the beginning of the movement of the interface. [12].

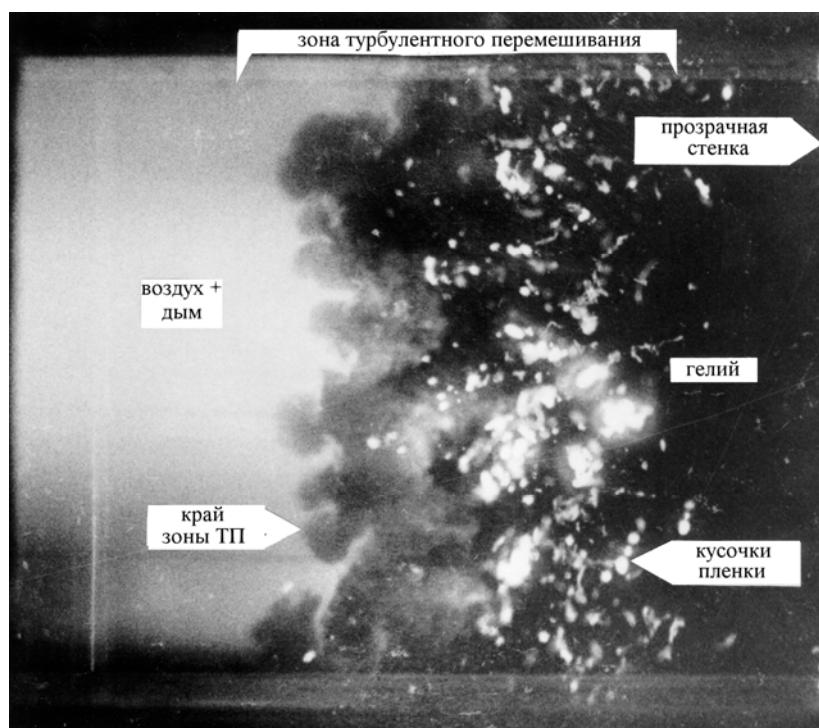


Fig. 4. Photo of turbulent mixing zone obtained by a laser sheet method at the interface between air (with smoke impurity) and helium at the time $t \approx 890 \mu\text{s}$

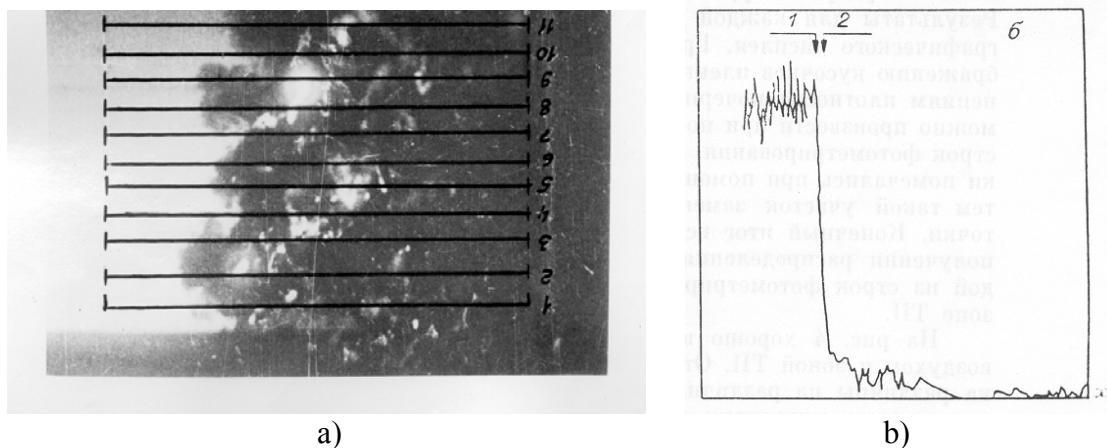


Fig. 7 a) Mixing zone photo fragment ($t \approx 800 \mu s$) subjected to photometric measurements over lines contoured on photos; b) air concentration distribution (1) in the mixing zone (2) based on the results of photometric measurements over line №5

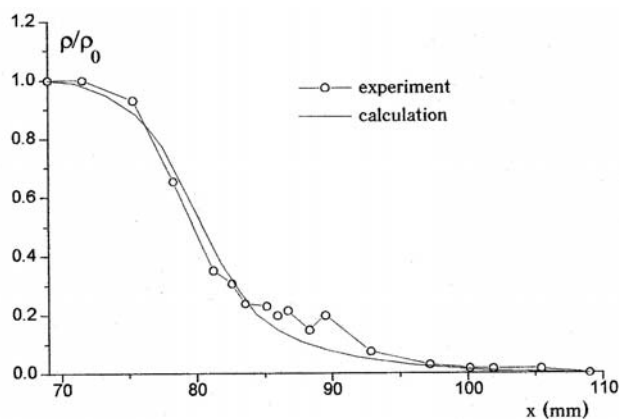


Fig. 6 Averaged distribution of air concentration in the turbulent mixing zone at the air-helium interface. Comparison with calculation [13].

In connection with these results the question comes up: are the observed in these experiments specific features as heavy gas concentration jump at the interface with the mixing zone random and inherent only in this experiment or are they inherent in the mixing zone structure at the gas-gas interface in general? Apparently, this specific feature is of general character, otherwise, the absence of concentration jump at the heavy gas - mixing zone interface will result in dying of the gas mixing process.

2. Turbulent mixing zone development at the interface accelerated by non-stationary shock wave.

Peculiarities of turbulent mixing zone development at the interface accelerated by non-stationary shock wave are illustrated by results of shock tube experiments (fig. 7) [14-16]. A strong non-stationary decaying shock wave was generated by detonation relatively a thin layer of acetylene-oxygen mix. The mix layer is detonated simultaneously in 36 points uniformly located on rigid wall 1 by electric explosion of a set of short (~ 1 mm) wires. Detonation initiation timing is very good to get practically plane detonation and then a shock wave front. These experiments were performed on the acetylene shock tube with the channel cross section 8×8 cm², the length 25 cm (the extent of the chamber filled with gas mix is 1.95 cm).

Visualization of flow in a shock tube was carried out by defocused gratings [12]. The lattice of filaments with a diameter of 0.16 mm in steps of 1 mm was installed inside the observation pipes of the shadow installation IAB-451 in its wall (the value of defocus $\Delta = 125$ mm). Registration of the flow was produced by the camera SENSICAM, optically jointed with the IAB-451.

The complexity of the registration zone of turbulent mixing in this case are determined, on the one hand, by self-illumination of the detonation products, heated to high temperatures (over 4000°C), and, on the other hand, the fact that the window channel of the shock tube was made of plexiglas sheet plates with a low quality of the surfaces (smooth surface of the plates, but with the deviation from flatness). This can be seen on the curvature of the shadow image of the grid lines at the top and bottom walls in the undisturbed air before the shock wave front in fig. 9,a. Using on experiments method of defocused gratings failed to get enough high-quality image of shock waves and turbulent mixing zone at the contact interface.

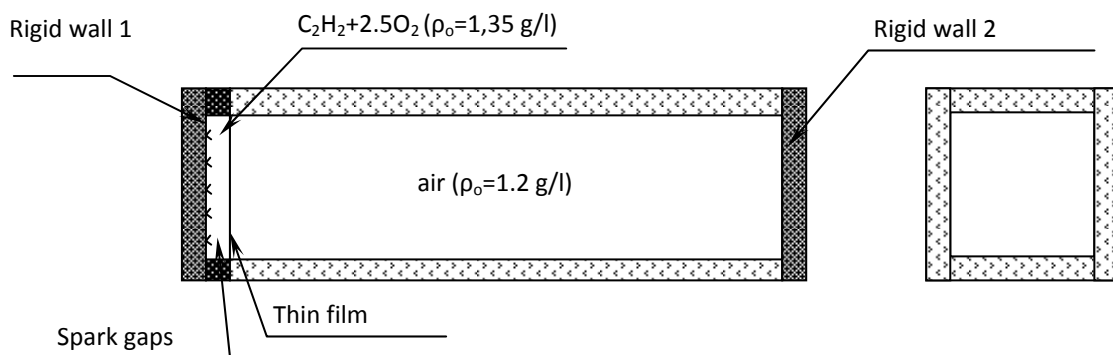


Fig. 7. Diagram of shock tube with a shock driver as a relatively thin layer of detonating stoichiometric acetylene-oxygen mix.

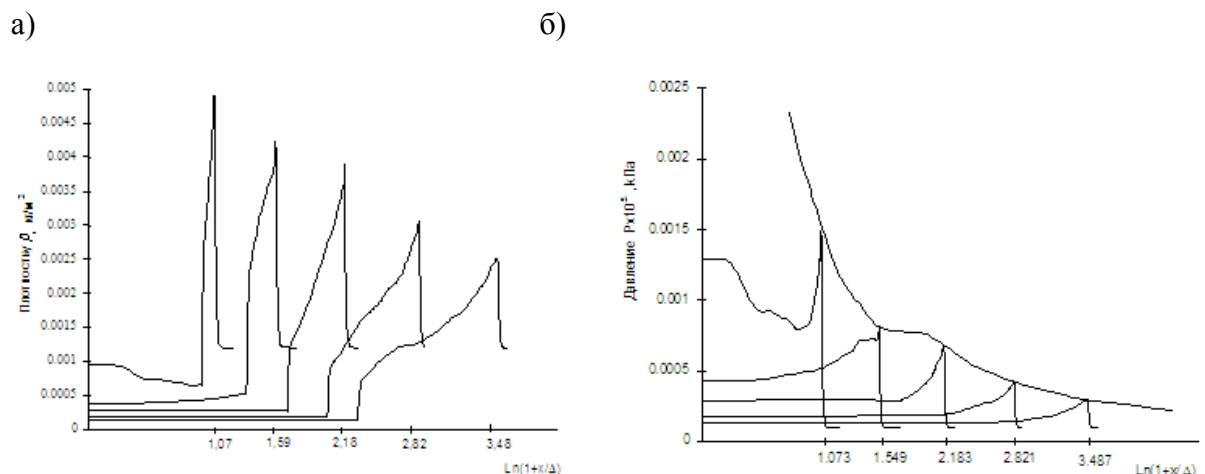


Fig. 8. Results of one-D calculation for shock tube operation: a) density profiles; b) pressure profiles behind shock wave front for various times (x is coordinate, Δ is initial thickness of gas mix layer) [15]

Fig. 8 presents the results of one-D flow calculation in the shock tube performed in the assumption of instant detonation of acetylene-oxygen mix [15].

Figures 9,a and 9,b show flow patterns for various times in the shock wave obtained by the method of out-of-focus grids [12]. Fig. 9,a illustrates the flow pattern before the shock wave comes up to rigid wall 2. Fig. 9,b shows the flow pattern, after the reflected from rigid wall 2 shock wave passes through to the interface.

Fig. 10 gives the $x-t$ flow diagram in the shock tube. The flow shadow pattern was recorded by a camera SFR in a multi-frame mode and by camera SENSI CAM in a single-frame mode. Before the shock wave, reflected from rigid wall 2 ($\tau=500\mu\text{s}$), reaches the interface (detonation products-air), the initial interface perturbation practically does not grow. After the reflected wave comes up to the interface, the turbulent mixing zone begins its fast development at it.

Fig. 9,a illustrates a complicated and regular flow structure behind the shock wave front at the initial times in the shock tube. The observed pattern represents the flow behind the shock wave front with *three-dimensional* periodic perturbation. When the detonation wave, propagating over the acetylene-oxygen mix, comes up to the interface with air, the film separating gases, is subjected to fast heating up to very high temperatures at which the film decomposes. According to estimates from [15] the film with the thickness lower than $0.5\ \mu\text{m}$ is heated for fractions of a microsecond. The temperature of acetylene-oxygen mix detonation products according to estimates reaches $4000 - 4800\ \text{K}$. The film heated quickly up to these temperatures is to be turned into a thin layer of destruction products in the form of smoke thereby not affecting the development of the turbulent mixing zone.

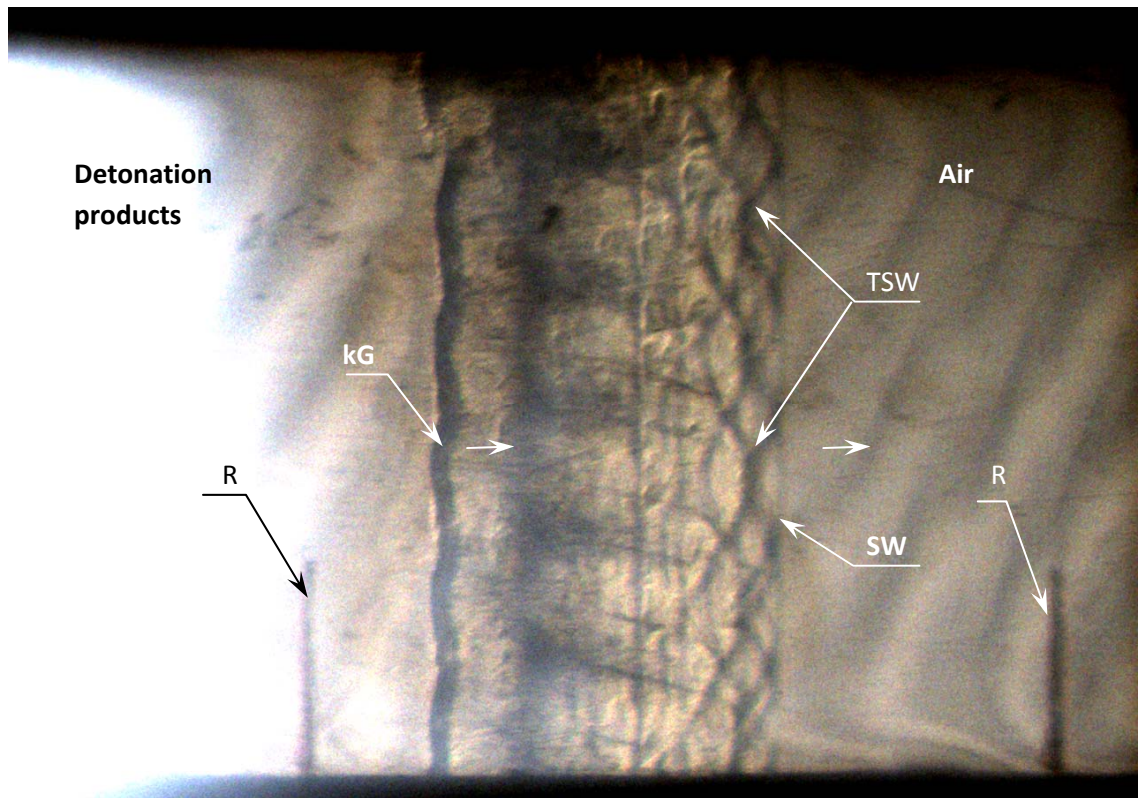
Of interest is unusual behavior of perturbation at the detonation products-air interface. Despite the fact that the initial perturbation of the interface that is generated after the perturbed detonation wave comes up to this interface is large in amplitude, there is no further growth of perturbation at the first stage of this interface motion up to the point of coming out of the shock wave reflected from rigid wall 2 (Fig. 9,a and 10).

Such interface behavior can be explained by the following way. After the detonation wave comes up to the gas interface, the latter is accelerated by a jump up to a rate of about $1000\ \text{m/s}$, but right after that its rate begins decreasing, and up to the time when the reflected from wall 2 shock wave comes up, the interface rate drops down to $\sim 250\ \text{m/s}$. Respectively, the interface deceleration is associated with fast expansion and drop of pressure in the thin layer of gaseous mix of detonation products. The initial density of acetylene-oxygen mix ($\rho_0=1,35\text{g/l}$) is approximately equal to the air density ($\rho_0=1.205\text{g/l}$), but in the process of expansion of detonation products their density drops down, and the air density, compressed by the shock wave, increases. Thus, at the initial stage of movement the detonation products – air interface moves with deceleration, and acceleration appears to be directed from heavier gas (compressed air) to lighter gas (expanding detonation products), i.e., this corresponds to the case of stability [1,2], when the interface perturbation oscillates and dies down.

In such a way, when two-gases interface is accelerated by the non-stationary (decaying) shock wave in the direction from light to heavy gas, a contradictory situation is emerging. On the one hand exactly after the shock wave crosses the interface, the conditions for development of initial perturbation are emerging, almost immediately after that the acceleration, directed from heavy to light gas, arises that makes a stabilizing effect on perturbation development. The following perturbation behavior in various cases will depend on the interface acceleration rate. Thus the rate and nature of perturbation development will be determined by the pressure decrease behind the shock wave front. The pressure weak change and, consequently, low

acceleration scale practically does not affect the perturbation growth, which will be determined by the first acceleration pulse of the shock wave interface

a)



b)

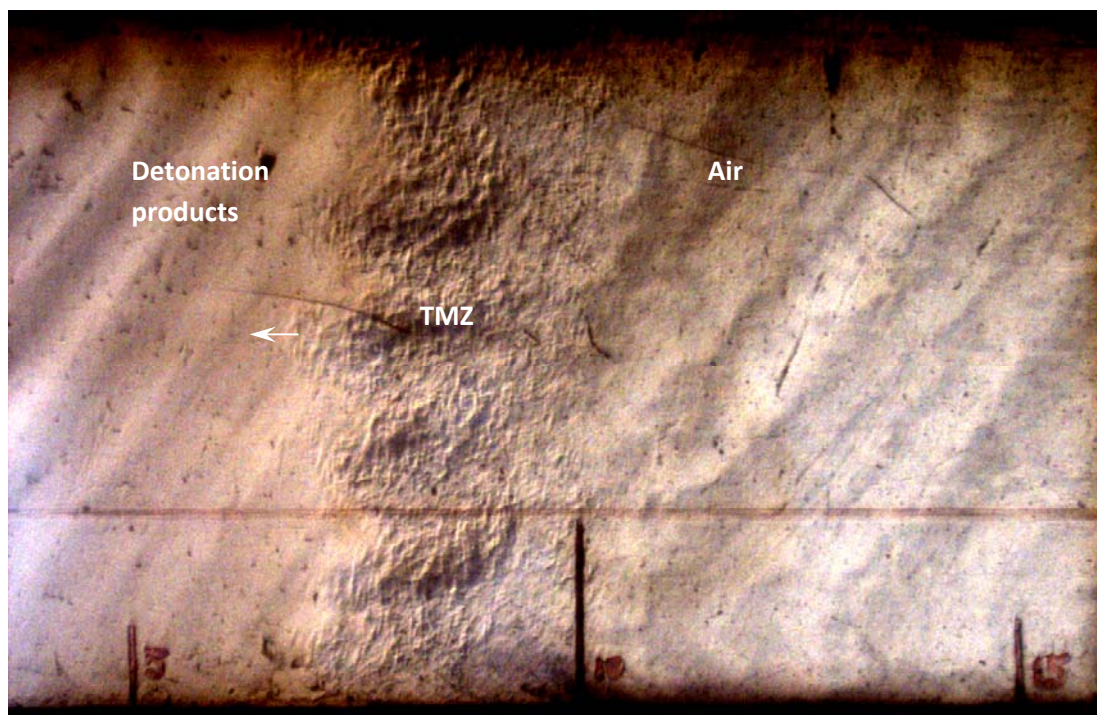


Fig.9. The flow pattern in shock tube for various times τ : a) $\tau_1 = 100\mu\text{s}$; b) $\tau_2 = 700\mu\text{s}$. The time is counted from the moment of initiation of acetylene-oxygen mix layer. Designations: SW is shock wave; TSW is transverse shock wave system; KG – is detonation products – air interface; TMZ – is turbulent mixing zones; R-reference. Arrows show flow direction.

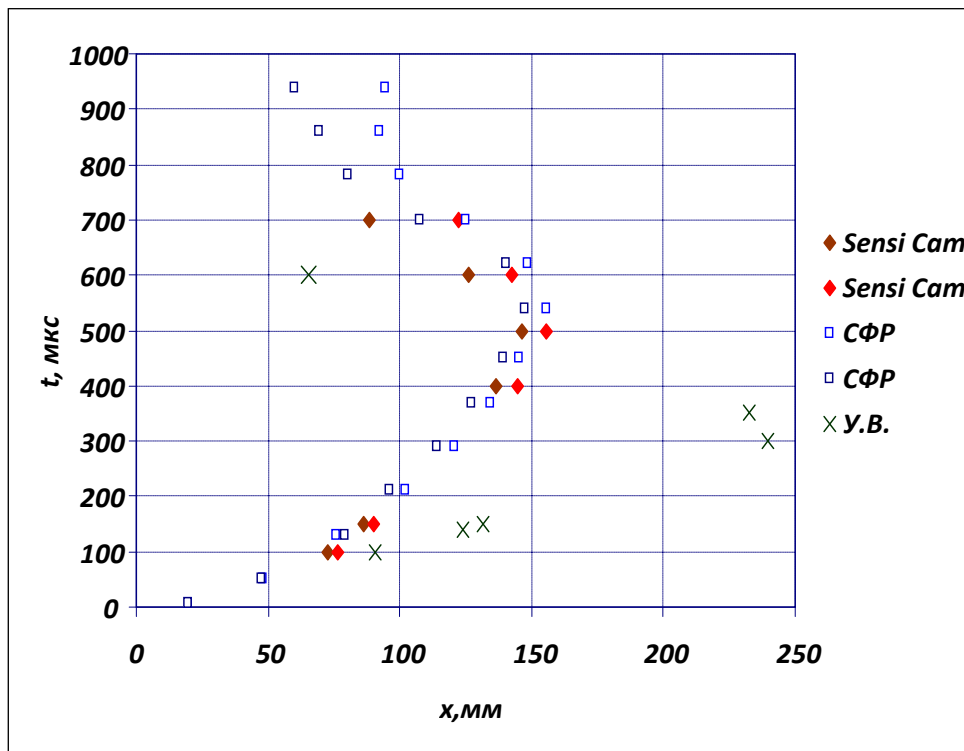


Fig. 12 $x-t$ flow diagram in shock tube.
Designations: \times - is shock wave front

All the above refers to the flow in the acetylene shock tube before the shock wave, reflected from wall 2, comes up to the interface. In case of the shock tube that is built according to the scheme of Fig. 7 with the channel end plugged by rigid wall 2, the shock wave reflects from this wall and comes into the interface. By this time the initial perturbation almost decays. However, after the reflected wave comes up to the interface, the turbulent mixing zone begins developing very fast at it (Fig. 9,b and 10). In this case the initial perturbation is the residual perturbation of the interface. In spite the relatively low scale of this perturbation, it develops reasonably fast, since there is simultaneous effect of both RM- and RT- instabilities.

Similar peculiarities of instability development at the interface between gas mix detonation products and air are observed in cylindrical geometry [16]. In this case the symmetry axis of the gaseous mix-air system is used as rigid wall 1. At this axis there is a thin wire exploded by high-volt electric pulse.

Thus from these examples it follows that with the accelerated by non-stationary wave interface there are cases when RT-instability may reduce development of RM-instability.

Note also the acetylene shock tube advantages over conventional shock tube (in particular, with the tube , as described in Section 1). In such a shock tube channel length can be several times shorter than the channel of normal shock tubes. In particular, it can be established laboratory shock tube with a large cross section (eg $0.5 \times 0.5 \text{ m}^2$) and the short length (less than 1 meter) of the channel.

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References

1. Lord Rayleigh. Proc. London Math. Soc., v.14, 1883, p.170.
2. G.I.Taylor. The instability of liquid surfaces when accelerated in a direction perpendicular to their planes. I. Proc. Roy. Soc., v.A201, 1950, p.192.
3. R.D.Richtmyer. Taylor instability in shock acceleration of compressible fluids. Commun.Pure Appl.Math. V.13, 1960, 297.
4. E.E.Meshkov. Instability of shock-accelerated interface between two gases. // Izv.RAS USSR, MZG. N 5, 1969, 151-158. (in Russian)
5. E.E.Meshkov. Instability of shock-accelerated interface between two media. // Proc. of the First Intl Workshop on the Physics of Turbulent Compressible Mixing (Princeton, USA, 1988), 1992, pp.473-503.
6. V.Andronov, I.Zhidov, E.Meshkov, N.Nevmerzhitsky, V.Nikiforov, A.Razin, V.Rogachov, A.Tolshmyakov, Yu.Yanilkin. Computational and Experimental Studies of Hydrodynamic Instabilities and Turbulent Mixing. // (Review of VNIIEF Efforts). Los Alamos National Laboratory. N LA-12896, 1995г.
7. E.E.Meshkov. The study into hydrodynamic instabilities in laboratory experiments. // Sarov, 2006, 138 p. (in Russian).
8. V.A.Andronov, S.M.Bakhrakh, E.E.Meshkov, V.N.Mokhov, V.V.Nikiforov, A.V.Pevnitskiy, A.I.Tolshmyakov. Turbulent mixing at the shock accelerated interface // ZETF, v,71, vyp. 2(8), 1976, p. 806-811. (in Russian)
9. V.A.Andronov, S.M.Bakhrakh, E.E.Meshkov, V.V.Nikiforov, A.V.Pevnitskiy, A.I.Tolshmyakov. Experimental study and numerical simulation of turbulent mixing in one-D flows. // DAN, v. 264, N 1, 1982, p. 76-82. (in Russian)
- 10.E.E.Meshkov, V.V.Nikiforov, A.I.Tolshmyakov. Turbulent mixing zone at shock accelerated two-gas interface. // FGV, N 3, 1990, p. 71-77. (in Russian)
- 11.A.I.Abakumov, V.Yu.Fadeev, S.I.Kholkin, E.E.Meshkov, V.V.Nikiforov, P.N.Nizovtsev, A.A.Nikulin, N.N.Sadilov, S.K.Sobolev, A.I.Til'kunov, V.O.Tochilin, A.I.Tolshmyakov, N.V.Zhidkov. (1995) Studies of Film Effects on the Turbulent Mixing Zone Evolution in Shock Tube Experiments. // The Proc of the 5th IWPCTM, Stony Brook, USA, 1995, p.118-123.
- 12.Y.B.Bazarov, A.E. Levushov, A.A. Logvinov, E.E.Meshkov, V.V.Popov Application of the method of defocused grids for flow visualization in shock experiments.// Transaction of RFNC VNIIEF, v.11 2007, pp.294-297. (in Russian)
- 13.V.V.Nikiforov. Turbulent mixing at the interface between media of various density // VANT, ser. Theor. and Applied Physics. Vyp.1, 1985, 3. (in Russian)
- 14.E.E.Meshkov. One Approach to the Experimental Study of Hydrodynamic Instabilities: Creation of a Gas-Gas Interface Using the Dynamic Technique. // The Proc of the 5th IWPCTM, Stony Brook, USA, Editors R.Young, J.Glimm & B.Boston, 1995, P.237.
- 15.Yu.A.Vlasov, S.I.Gerasimov, E.V.Gubkov, V.I.Dudin, V.P.Kopyshev, E.E.Meshkov, A.A.Nikulin, V.P.Ryabov, V.A.Tilkunov. Shock tube with GEM-driver. // Preprint 47-96. RFNC-VNIIEF, 1996.
- 16.Yu.V.Alekhanov, A.E.Levushov, A.I.Logvinov, S.A.Lomtev, E.E.Meshkov, A.A.Polovnikov, E.A.Polovnikov, First Mix Experiments on the Cylindrical Acetylene Shock Tube. // Proc. of the 10th IWPCTM, Paris, France July 17-21, 2006, p.p. 244-248.