Some peculiar features of hydrodynamic instability development

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We discuss the results of experiments that illustrate some features of a turbulent mixing zone (TMZ) structure at a gas–liquid interface (Rayleigh–Taylor instability) and at a gas–gas interface accelerated by shock waves (Richtmyer–Meshkov instability). The important feature is the existence of a heavier substance concentration (density) jump at the interface between the heavy medium and the TMZ. It is found that the existence of this jump is a generic feature of any developed TMZ and is the necessary condition for its continuous development. In the case of a gas–liquid interface, the stable existence of this jump is connected with the stability of the cupola of gas bubbles penetrating into the liquid in a TMZ. The important feature of the development of interface instability accelerated by an unsteady shock is the decaying ability (up to full suppression) of the interface instability in the case when a decaying wave passes through the interface in the direction from light gas to heavy gas.

1. Introduction

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

In the first case, when acceleration is constant or changes slowly in time and is directed from light medium to heavy one, the interface turns out to be unstable. Such a type of instability is usually called Rayleigh–Taylor (RT) instability [1,2]. The interface is stable if acceleration is directed from heavy medium to light.
In the second case, when acceleration has a pulsed nature, or when the interface is accelerated by a stationary shock wave, instability develops irrespective of acceleration direction. This type of instability is usually called Richtmyer–Meshkov (RM) instability [3,4].

For more than 40 years, the author has worked on the development of both RM and RT instabilities. The results are described in earlier studies [5–8] and the proceedings of many international conferences. This paper includes a discussion of some essential features of the development of hydrodynamic instabilities observed in earlier experiments and describes some works performed by the author and with his participation [9–22].

2. Taylor bubble cupola stability

Figure 1 presents streak photographs of the turbulent mixing zone (TMZ) development process at the unstable interface of a gel layer, accelerated by acetylene–oxygen mixture detonation products [9]. In this case, the typical pressure of detonation products is about 1 MPa; at these pressures gel behaves as liquid, and in this case one can actually observe the development of the TMZ at the gas–liquid interface with its typical attributes. In particular, figure 1 shows that gaseous detonation products penetrate into the gel layer in the form of bubbles extending in time.

Figure 2 presents frames from a video of another experiment, in which an air bubble rises in a water channel of square cross section [10]. The bubble has a large volume and occupies practically the entire channel cross section. This is nothing but a simple air block that we can observe in everyday life. In the scientific literature, such a type of bubble is called a Taylor bubble, and the flow mode appearing in this case is sometimes called gas piston flow. The bubble is formed after a thin rubber shell filled with air is destroyed by a needle in the pole. In the process of rapid shrinking of the remaining shell portions (in a time of approx. 2 ms), the initial small-scale perturbations are formed at the bubble surface. The growth of these perturbations at the bubble cupola as a result of RT-instability development dies down at the very beginning, and so they are said to ‘slide’ down the bubble surface.

In terms of RT-instability development in both cases (figures 1 and 2), the principal distinction is only in the shape of the gas–liquid interface. In gel experiments, the interface is initially flat; and in experiments with the bubble, it is approximately spherical. But the results of these experiments turn out to be extremely different: in the first case, the RT instability and the TMZ develop; and in the second case, the development of the TMZ is not observed. This brings up the question: why does the cupola of the emerging Taylor bubble turn out to be stable? This phenomenon cannot be explained only by the surface tension effect. Estimates show that in a similar case a typical scale for the critical length of an initial perturbation wave is about 1 cm [11]. At the same time, the size of the channel, where the bubble emerges, is much larger. Apparently, this relates to the effect of shear flow on the bubble cupola surface occurring when the bubble is in water.

This effect is manifested most clearly in the experiments presented in figure 3 [12]. A circular perturbation was generated on the bubble cupola surface emerging in a cylindrical channel by a metal ring located on the surface of an inflated rubber shell. Here, the flow including the perturbation development stage is two-dimensional. At the same time as the perturbation grows due to RT instability, it also expands fast, and finally this circular perturbation slides down from the bubble surface, and the bubble cupola remains smooth and unperturbed. Thus, the cupola of the emerging bubble turns out to be stable relative to perturbations of various types, including circular-type perturbations.

In experiments [11], we observed the development of RT instability on the air bubble cupola emerging in water in a circular gap formed by the walls of two coaxial cylinders. In this case, RT instability develops without restrictions, and the circular bubble cupola disintegrates into a number of round bubbles.

Earlier we found that the front of a TMZ at a gas–liquid interface consists of bubbles that are analogues of Taylor bubbles. As the TMZ grows, these bubbles also expand due to suppression of

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1 A gel of gelatin water solution (solution concentration is \( C \sim 4\% \)).
Figure 1. Development of a TMZ on a gel layer interface accelerated by detonation products (DPs) in a channel of square cross section [9].

Figure 2. Stills from a video (approx. 25 frames s⁻¹) of an air bubble emerging in water in a channel with square cross section (11 × 11 cm²) from a state of rest [10]. (Online version in colour.)

Figure 3. Development of a circular perturbation (2) on the surface of a bubble emerging in a cylindrical channel filled with water. Perturbation was generated by the ring (1), located on the cupola of the rubber shell before its destruction [12].

adjacent bubbles or integration with them. As the bubbles grow, the radius of curvature on their cupola surface also increases. Ultimately, they tend to a flat shape. This raises the question: how will this effect influence the stability of bubble cupolas? In the study of Meshkov et al. [13], there is an assumption that sooner or later the bubble cupola may lose its stability, and the law of TMZ development should be changed.

Further investigation of the described phenomenon, aiming to find out the mechanisms that determine the stability of Taylor bubble cupola and the mechanism’s limits, has been our interest here.

3. Specific features of turbulent mixing zone structure at gas–gas interface

The effect of shock-accelerated turbulent mixing at the interface between two gases of different density was discovered by the author experimentally in 1968 and published in previous studies [14–16].
Experiments \cite{14-16} were performed in a shock wave in the following geometry: air \((\rho_0 = 1.2 \text{ g/cm}^3)\), helium \((\rho_0 = 0.178 \text{ g/cm}^3)\), rigid wall (figure 4). The shock tube channel cross section is \(4 \times 12 \text{ cm}^2\) and the helium portion length is 16.6 cm. The Mach number of the initial stationary shock wave in the air is \(M = 1.3\).

In experiments using this configuration, the flow optical recording was performed by the following techniques: (i) shadow method with recording by an SFR high-speed camera \cite{14,16} and (ii) TMZ visualization using a laser sheet with flow recording in a single-frame mode \cite{16}.

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 then moves further with constant speed by inertia. As helium is much lighter than air, after discontinuity decay a rarefaction wave goes into air, and a shock wave with amplitude much lower than that of the incident wave goes into helium. This wave is reflected from the rigid wall at the end of the channel as a shock wave, which in turn is reflected from the helium–air interface also as a shock wave and so on. As a result, the interface is decelerated by a series of shock waves with sequentially decreasing amplitude. The flow pattern is illustrated by shadow streak photographs of the experiment (figure 5).

In experiments, the role of initial perturbation was played by the natural thickness variation (hence, mass variation) of the film; the thickness distribution had a random nature and could reach about \(\pm 50\%\) of the average value. After the first shock acceleration of the interface, it moves for some time by inertia at constant speed. However, in the experiment, the gases are separated by a thin film with a low, but finite, mass, so the interface accelerates up to the predicted flow rate over a short, but finite, distance. During this time, there is a pressure difference between the sides of the film. The film portions with different mass accelerate differently, which results in the boundary shape distortion. If deformation exceeds the elastic strain limit of the film, it tears into fragments and micro-jets of compressed air flow in the gaps between these fragments \cite{17}. As a result of these processes, the seed perturbation is formed (frame 2 of figure 5), and one can

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**Figure 4.** Diagram of a shock tube test section in experiments on the development of the TMZ at an air–helium flat interface accelerated by shock waves.

**Figure 5.** TMZ development at an air–helium interface \cite{14}. SW, shock wave; RW, rigid wall. The shadow method was used.
Figure 6. Photo of the TMZ obtained by a laser sheet method at the interface between air (with smoke impurity) and helium at time \( t \approx 890 \mu s \) [16].

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.

Figure 6 presents the picture of the TMZ at an air–helium interface obtained with the help of a laser sheet. The experiments were performed in 1982 [16]. The experimental set-up with a shock tube is similar to the one provided in figure 4, with the exception that cigarette smoke is added to the air bordering with helium. At the set time, a flat thin laser beam (approx. 1 mm) was passed through the TMZ along the shock tube channel axis (the beam was passed through a transparent window at the end of the channel). The laser sheet light was scattered on smoke particles in the air, including the air in the mixing zone. Thus, an image of the distributed air in the TMZ in the laser sheet plane was formed at a particular instant.

The TMZ pattern in diffused light (figure 6) differs significantly from the pattern obtained using the shadowed display (figure 5). A typical feature of this pattern is the presence of a pronounced boundary between the air (‘heavy’ gas) and the TMZ. At the same time, the boundary between the TMZ and the helium (‘light’ gas) is not observed. Thus, between the heavy gas and the TMZ there is a heavy gas concentration (and density) discontinuity, i.e. a concentration jump between the heavy gas and the TMZ. There is no discontinuity (jump) between the TMZ and the light gas.

In the TMZ, the air concentration gradually falls to zero. The photo in figure 6 discloses the mechanism of TMZ development at a later stage, when the film fragments that initially separate the gases basically shift to the zone edge, and their effect on the zone development can be ignored practically. At this stage, the TMZ development is determined by the effects occurring at the interface between the heavy gas and the TMZ. As mentioned earlier, a density jump continuously exists at this interface. The heavy gas penetrates into the TMZ 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 positions (beyond jets) remains reasonably smooth and non-perturbed. Thus, at the stage of the developed flow, one can observe in the TMZ the combination of ordered flow components at the interface with the heavy gas (the interface between the heavy gas and the TMZ 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 a time of 800 µs was photometrically measured over 25 lines in the direction of the channel axis in the shock tube (negative processing procedure and photo measurement results were described in detail in [16]). As a result, the air concentration distribution over each line was obtained. Figure 7a provides the photo fragment with the lines. Figure 7b provides the air concentration plot in the TMZ after processing over line no. 5. Based on these photo measurements, the air concentration at the air–mixing zone interface drops with a jump by an order of magnitude from 1 to approximately 0.15. At the same time, the averaged (over every line) distribution of air concentration has a smooth nature and agrees with the results of mixing zone calculations according to the Nikiforov model [23] (figure 8).

In connection with these results, the question comes up: are the specific features observed in these experiments, such 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 a concentration jump at the heavy gas–mixing zone interface will result in the decay of the gas mixing process.
Figure 8. Averaged distribution of air concentration in the TMZ at an air–helium interface. Comparison of experiment (open circles joined by lines) with calculation (full curve).

Figure 9. Diagram of the acetylene shock tube; the shock driver is a relatively thin layer of detonating stoichiometric acetylene–oxygen mixture.

It should be noted that the existence of a concentration jump at the boundary with the TMZ is generic for both gas–gas and gas–liquid interfaces. However, the mechanism for jump implementation in the two cases is different. In the gas–liquid case, gas penetrates into liquid as an ensemble of bubbles. Their growth requires a continuous feed. Thus, these bubbles apparently must be connected with the pure gas region by channels. The channels of adjacent bubbles are separated from each other by liquid layers. In the gas–gas case, the light gas does not penetrate into the TMZ in a pure form and exists there only mixed with heavy gas. In this case, the TMZ development carries on because of the continuous penetration of heavy gas jets into the TMZ. The presence of a concentration (density) jump in experiments with two types of interface makes it possible to assume that such a characteristic feature can be realized with any interface. The presence of the density jump guarantees the continuous development of instability.

4. Experiments in acetylene shock tube: turbulent mixing zone development at the interface accelerated by a non-stationary shock wave

Features of TMZ development at an interface accelerated by a non-stationary shock wave are illustrated by the results of acetylene shock tube experiments (figure 9) [18–21]. A strong non-stationary decaying shock wave was generated by detonation of a relatively thin layer of acetylene–oxygen mixture. The mixed layer is detonated simultaneously at $6 \times 6 = 36$ points
uniformly located on rigid wall 1 by electrical explosion of a set of short wires. Detonation initiation timing is very good to get practically planar detonation, and then a shock wave front. These experiments were performed on a shock tube with a channel cross section of $8 \times 8$ cm$^2$ and a length of 25 cm (the extent of the chamber filled with gas mixture is 1.95 cm).

Figure 10 presents the results of one-dimensional flow calculation in the acetylene shock tube performed under the assumption of instant detonation of the acetylene–oxygen mixed layer [19].

Figure 11a,b shows flow patterns for various times in the acetylene shock wave obtained by the method of out-of-focus grids [20]. Figure 11a illustrates the flow pattern before the shock wave comes up to rigid wall 2. Figure 11b shows the flow pattern after the shock wave reflected from rigid wall 2 comes up to the interface.

Figure 12 gives the $x$–$t$ flow diagram in the shock wave. The flow-shadowed pattern was recorded by an SFR streak camera in a multi-frame mode and by SENSI CAM in a single-frame mode. Before the shock wave that is reflected from rigid wall 2 ($\tau = 500$ µs) reaches the interface between the detonation products and air, the initial interface perturbation practically does not grow. After the reflected wave comes up to the interface, the TMZ begins its fast development there.

Figure 11a 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 through the acetylene–oxygen mixture, comes up to the interface with air, the film separating the gases is subjected to fast heating up to very high temperatures at which the film decomposes. According to estimates from [19], a film with a thickness lower than 0.5 µm is heated for fractions of a microsecond. The temperature of the acetylene–oxygen mixture detonation products according to estimates reaches 4000–4800 K. The film heated quickly up to these temperatures is turned into a thin layer of destruction products in the form of smoke, thereby not affecting the development of the TMZ.

Of interest here is the unusual behaviour of the 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 the 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 (figures 11a and 12).

Such interface behaviour can be explained in 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 m s$^{-1}$. Immediately after that, its rate begins to decrease, and up to the time when the shock wave reflected from wall 2 comes up, the interface rate drops to approximately 250 m s$^{-1}$. Respectively, the interface acceleration–deceleration is associated with fast expansion and drop of pressure in the thin layer of gaseous mixture of detonation products. The initial density of the acetylene–oxygen mixture ($\rho_0 = 135$ g l$^{-1}$) is approximately equal to the density of air ($\rho_0 = 1.205$ g l$^{-1}$). In the process of expansion of detonation products, their density decreases, and
Figure 11. The flow pattern in the acetylene shock tube for various times: (a) $\tau_1 = 100 \, \mu s$; (b) $\tau_2 = 700 \, \mu s$. The time is counted from the time of initiation of the acetylene–oxygen mix layer. SW, shock wave; TSW, transverse shock wave system; kG, detonation products–air interface; TMZ, turbulent mixing zone; R, reference. Arrows show flow direction [20]. (Online version in colour.)

Figure 12. The $x-t$ flow diagram in the shock tube. Cross symbols denote shock wave front. (Online version in colour.)

the air density, compressed by the shock wave, increases (figure 10a). Thus, at the initial stage of movement, the detonation products–air interface moves with deceleration. The acceleration of the interface 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 the interface between two gases is accelerated by a 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 the development of an initial perturbation are emerging. Almost immediately after that, the acceleration, directed from heavy to light gas, has a stabilizing effect on perturbation development. The following perturbation behaviour 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 slow change in pressure and, consequently, low acceleration scale practically do not affect the perturbation growth, which will be determined by the first acceleration pulse of the shock wave interface.

All the above refers to the flow in the acetylene shock tube before the shock wave that is reflected from wall 2 comes up to the interface. In the case of a shock tube that is built according to the scheme of figure 9, 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 at the interface has almost decayed. However, after the reflected wave comes up to the interface, the TMZ begins to develop quickly there (as shown in figures 11b and 12). In this case, the initial perturbation is the residual perturbation of the interface. In spite of the relatively low scale of this perturbation, it develops reasonably quickly, as there is a simultaneous effect of both RM and RT instabilities.

Similar features of instability development at the interface between gas mixture detonation products and air are observed in cylindrical geometry [22]. In this case, the symmetry axis of the gaseous mixture–air system is used as rigid wall 1. At this axis, there is a thin wire exploded by a high-voltage electrical pulse that initiates detonation of the gaseous mixture.

From these experiments, it follows that with the interface accelerated by a non-stationary wave there are cases when development of RM instability is suppressed by the RT instability effect. It should be noted that destruction of the film separating the gases at the investigated interface will make it possible to use the acetylene shock tube for investigation of the TMZ structure at a gas–gas interface.

5. Conclusion

The experimental observations suggest that there are essential characteristic features in the structure of the developed TMZ at an unstable interface moving with acceleration. These features refer to the permanent existence of a concentration jump at the edge of the TMZ bordering with the heavier medium. A similar concentration jump of the heavier medium exists in the case of both gas–liquid and gas–gas interfaces. Constant (and accelerated) development of the TMZ in both cases is determined by instability development of the interface between the heavy medium and the TMZ. In the case of gas–liquid, the development of instabilities of this interface goes through penetration of gas bubbles into liquid (these bubbles actually being Taylor bubbles); the stability of their cupola guarantees TMZ development. In the case of gas–gas, the heavy gas penetrates into the TMZ in the form of jets. Kelvin–Helmholtz instability at the lateral surface of these jets results in mixing of the heavy gas with the light one. The permanent existence of a concentration jump at the heavy gas–TMZ interface provides the constancy of the TMZ development.

In the case of a joint effect of RT and RM instabilities emerging when the interface is accelerated by a non-stationary shock wave, there are some situations when these instabilities suppress each other.

Thus, in the issue of hydrodynamic instabilities (RT and RM instabilities) and the development of the TMZ, there are features that present obvious interest for future investigation.

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