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Experimental investigation into the evolution of turbulent mixing of gases by using the OSA facility

Yu.A. KUCHERENKO, O.E. SHESTACHENKO, Yu.A. PISKUNOV, E.V. SVIRIDOV, V.M. MEDVEDEV, and A.I. BAISHEV
Russian Federal Nuclear Center, Academician E.I. Zababakhin, All-Russian Research Institute of Technical Physics, Snezhinsk, Chelyabinsk, Russia

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Abstract

Experiments conducted at the OSA shock tube facility at the Russian Federal Nuclear Center–VNIITF to investigate the compressible turbulent mixing of argon and krypton gases induced by the Rayleigh–Taylor instability are described. A liquid soap film membrane of thickness ~1 micrometer embedded in an array of microconductors is used, on which specified initial perturbations can be applied. The shock is piston driven by compressed gas. The gas interface was accelerated with an acceleration g'4 3104 m0s2. The membrane is disintegrated at the beginning of the experiment by a strong electric explosion. Imaging is performed using Schlieren photography. The dimensionless growth rate of the mixing zone was determined to be 0.04.

Keywords: Different density gases; Liquid membrane; Mixing rate; Shock tube; Turbulent mixing

1. INTRODUCTION

In many problems associated with fast compression processes of matter, the situation arises when a material of less density (light material) and a more dense material (heavy material) have a contact surface and are accelerated. In case of constant acceleration, the contact surface is to be subjected to the action of the Rayleigh–Taylor instability (RTI). If the pulsed acceleration (e.g., at the passage of shock waves) takes place, then any contact surface is unstable, because the Richtmyer–Meshkov instability (RMI) arises.

The instability implies that any small perturbation has a tendency to unlimited growth, interpenetration of material occurs, shear turbulence breaks up structures into smaller-scale structures, and a turbulent mixing zone (TMZ) develops. The evolution of instabilities on the contact surface of different density media exerts an influence on the dynamics of the compression, and restricts the limiting value of compression and the dynamics of subsequent processes.

The determining parameter that takes into account the gravitational turbulent mixing influence is the turbulent mixing zone width, which depends on the density ratio of different density media, the duration of the instability, and so forth. In a number of problems, taking into account compressibility on both sides of the contact surface becomes important.

Under laboratory conditions, the investigation of RTI and arising gravitational turbulent mixing (GTM) is performed using different density liquid and gaseous media at the installations EKAP and SOM. The installation OSA makes it possible to investigate different kinds of instability (RTI, RMI) by using three replaceable drivers for these purposes. The distinctive feature of the experiments is the usage of the controlled separating membrane, making it possible to form the evolution process of GTM of different gases with preset initial conditions.

The aim of the present work is to perform experiments by using the shock tube OSA creating RTI and to apply the controlled separating membrane for these investigations.

2. SETUP OF EXPERIMENTS

For performing experiments regarding the gravitational turbulent mixing investigation the scheme presented in Figure 1 was used.

The $0 < x < x_1$ region is filled up with the compressed gas and represents a high pressure chamber. From the rest of the shock tube, part the chamber is separated by a light piston, which is found at the point $x = x_1$. The $x_1 < x < x_2$ region is filled up with a light working gas 1 of density ρ_1 and represents the low pressure chamber. The $x > x_2$ region is filled up with a heavy working gas 2 of density ρ_2 and represents

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Address correspondence and reprint requests to: Yu.A. Kucherenko, Russian Federal Nuclear Center, Academician E.I. Zababakhin, All-Russian Research Institute of Technical Physics, P.O. Box 245, 456770 Snezhinsk, Chelyabinsk, Russia. E-mail: kucherenko@five.ch70.chel.su

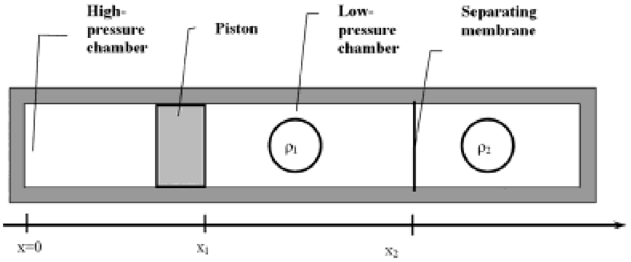

Fig. 1. Physical scheme of the experiments setup.

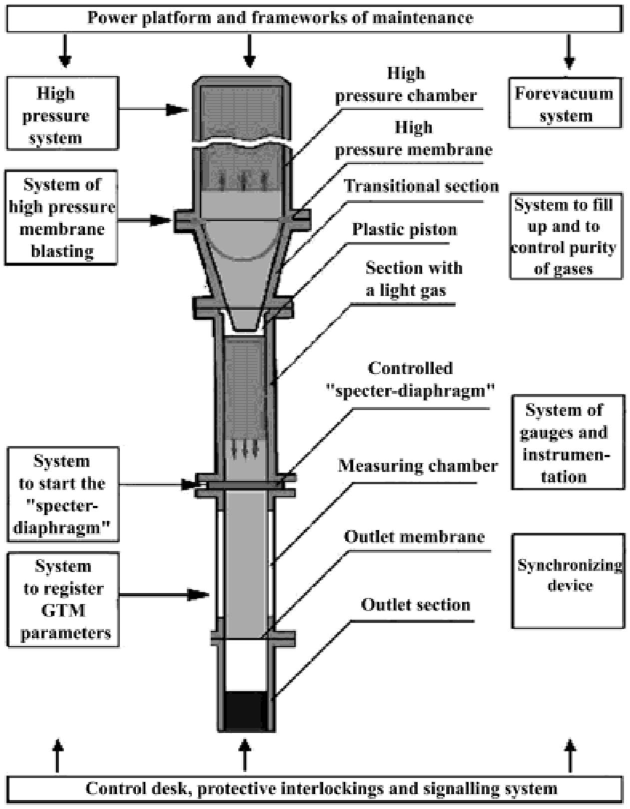

Fig. 2. Functional scheme of the installation OSA.

a measuring chamber by which the mixing process imaging is performed. In the point $x = x_2$ the separating membrane is found that prevents the mixing of working gases during the experiment preparation. At the specified instant of time, the separating membrane is destroyed into pieces of definite size by the external force. The installation operates as follows. At the instant of time $t = t_0$, the piston begins to move with constant acceleration in the positive direction of the x axis under the action of the compressed gas in the high-pressure chamber. From the piston a compression wave begins to propagate in the positive direction of the x axis with velocity C_1, where C_1 is the sound velocity in the working gas 1. At the instant of time $t = (x_2 - x_1)/C_1$ the compression wave arrives at the interface of gases $x = x_2$. At the same time, the external destructive force is applied to the separating membrane, and the contact boundary between gases begins to be accelerated. As the contact boundary, acceleration profile slightly decreases and the pressure gradient in the compression wave is directed oppositely to the density gradient at the contact boundary, and conditions are created for the RTI occurrence.

Figure 2 shows the functional scheme of the installation OSA. The total height of the installation amounts to ≈5 m. In the upper part of the installation, the high-pressure chamber is located. It is a thick-walled vessel consisting of three parts connected by flanges. The operating pressure in the chamber is up to 2 MPa. At the upper flange of the high-pressure chamber there is the emergency valve of pressure drop and pipelines for gas inlet and outlet. The high-pressure chamber is separated from the remainder of the shock tube by an aluminum membrane.

The membrane thickness is 1 mm or 0.5 mm and determines the limiting pressure of the gas in the reservoir. For the membrane destruction at the specified instant of time, a strong electric explosion is used. A sliding contact in the form of a metal needle touches the membrane in the center. The needle is connected to the positive pole of the capacitor bank by means of cables, whereas the membrane is connected to the negative pole. At the instant of time $t = t_0$, the pulse of current burns through the aluminum membrane in the center. Gas begins to flow out of the reservoir and opens the membrane completely. The gas flow passes through the conical part of the transitional section and begins to push a plastic piston. In the compression wave, the pressure profile and amplitude depend on the piston mass. Under the action of the compressed gas, the piston moves with acceleration along the section with a light gas. The section with a light gas is filled up with gas of density ρ_1. The internal cross section of the light gas section is equal to 138×138 mm^2, but the length amounts to 500 mm. The contact boundary acceleration profile depends on the light gas section. The further the contact boundary of gases is from the piston, the more the acceleration differs from the constant one and approaches a delta-shaped one.

Prior to the execution of the experiment, the section with a light gas is filled up with the working gas of density ρ_1 through the gas inlet system. Simultaneously, the measuring chamber is filled up with the working gas of density ρ_2 through the gas inlet system. The gas inlet system controls the extent of purity of working gases. Between the light gas section and the measuring chamber the controlled separating membrane is located. It is designed to prevent the mixing of working gases during the experiment preparation.

The controlled measuring membrane is an interweaved grid of microconductors, 20 μm in diameter and spaced 4 mm apart. A liquid soap film solution is applied to this grid. The film thickness amounts to ≈ 1 μm. At the specified instant of time, the electric current is passed through the grid. Microconductors are heated, and the liquid film begins to be destroyed into the pieces with the typical scale $\lambda \approx$ 4 mm in the places of contact with microconductors. Then the surface tension forces tighten the pieces of liquid film into small balls that act as initial perturbations at the contact boundary of working gases. When the compression wave reaches the boundary between gases, the contact boundary begins to be accelerated. As acceleration is directed from the light gas to the heavy one, the conditions are created for the gravitational turbulent mixing zone evolution.

Figure 3 shows the characteristic photographic images of the separating membrane destruction process at different instants of time. In this figure, microconductors are denoted by number 1, liquid film pieces by number 2, the microconductor with the liquid film around it by number 3. From this figure it is seen that after the current pulse is applied to the grid, the liquid film begins to separate from the microconductors and then, under the action of the surface tension forces, it is tightened into a drop.

The measuring section is located beyond the block with the separating membrane. It is filled with working gas of density ρ_2. The measuring chamber has two transparent walls of high-quality optical glass. This makes it possible to perform the photographic record of the turbulent mixing zone by means of a Schlieren (photograph) technique. If it is necessary to investigate the late stages of the turbulent mixing process, then an additional chamber of low pressure is mounted between the block of the controlled separating membrane and the measuring section. After the measuring chamber the low pressure chamber, 260 mm in length, is found. It is also filled up with the working gas of density ρ_2.

This chamber is necessary so that the reflected compression wave does not exert an influence on the photographic record of the turbulent mixing zone. After terminating the photographic record and passing of the piston into the low-pressure chamber, it is necessary to slow down the piston. For this purpose, the special outlet section is designed. When the piston passes into the low-pressure chamber its velocity is ≈100–150 m/s. The gas being pushed by the piston ruptures the outlet membrane, which is located between the measuring chamber and the outlet section. The gas pressure ahead of the piston becomes gradually higher than the pressure behind the piston, and the latter begins to decelerate. When the piston moves along the outlet section, the pressure of the decelerating gas increases. To decrease the acceleration of retardation and to prevent reverse motion of the piston, it is necessary to release gas from the inlet section into the atmosphere. For this purpose, in the outlet section there are exhaust windows in which the membranes of lavsan are found. When reaching the ultimate strength, the membranes are ruptured and gas gets into atmosphere. The rubber shock absorber located at the bottom of the outlet section is designed to cancel the residual speed of the piston.

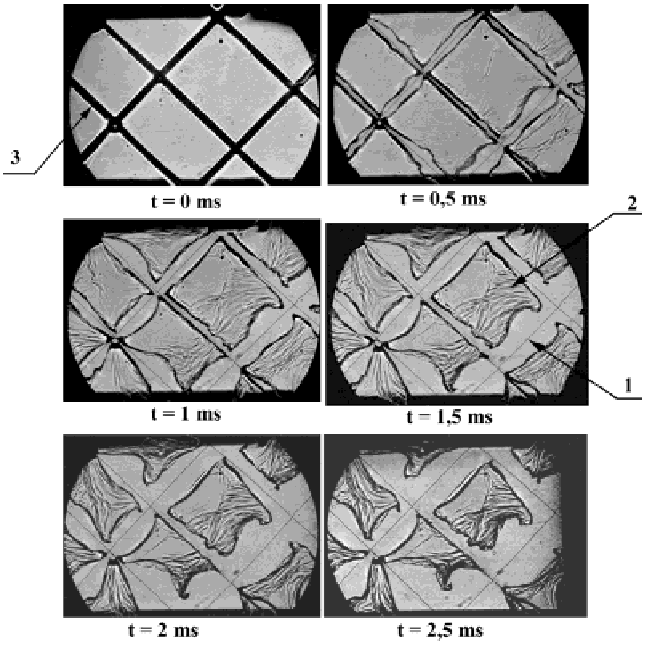

Fig. 3. Characteristic photographic images of the liquid film destruction process.

Imaging of the flow arising at the contact surface (CS) of two different density gases after its acceleration was carried out through the apertures in the measuring section by the Schlieren device IAB–451. The device is consistent with the high-speed camera VFU, operating in the mode of a time magnifier. Illumination was carried out by a flash lamp. The light pulse duration was equal to 4 ms. The flash lamp, the camera VFU-1, and the phenomenon itself were synchronized in such a way that the phenomenon registration was performed at the required stage of evolution. The optical method to image transparent inhomogeneities is based on the dependence of the refractive index of gases on density.

3. DISCUSSION OF RESULTS

In the present work Ar (density $\rho = 1.78\ \mathrm{kg/m^3}$) and Kr gas (density $\rho = 3.7\ \mathrm{kg/m^3}$) were used as working gases. The density ratio for the given pair of gases $n = 2.1$, but the Atwood number $A = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ for the given pair of gases was equal to $A = 0.35$. For these experiments, the acceleration of the contact boundary of gases amounted to $g \approx 40000\ \mathrm{m/s^2}$. The photographic record of the turbulent mixing process was carried out when changing the parameter $S = gt^2/2$ from 0.1 m to 0.5 m.

Figure 4 shows the characteristic photographic records of the gravitational turbulent mixing process. The turbulent mixing zone is seen in photos in the form of a wide dark band. It is seen that the zone width is increased with time, but the zone itself is mixing downwards. For the correct determination of the image scale, reference benchmarks are set before the measuring chamber glasses.

Figure 5 shows the dependence of the turbulent mixing zone width on the parameter S for the pair of gases Ar–Kr. The conditions of self-similarity for the given experiment are carried out at $S \geq 100$ mm.

It means that the turbulent mixing zone growth does not depend on the initial conditions on the contact boundary of

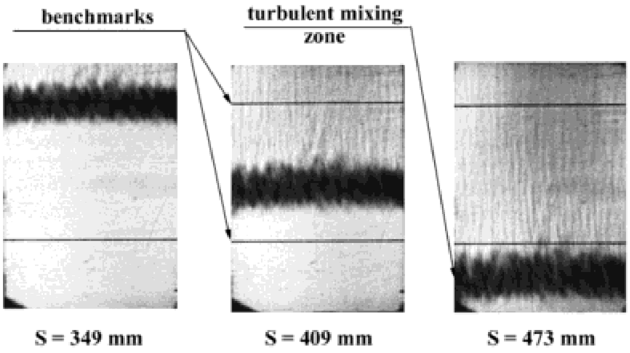

Fig. 4. Characteristic photographic records of the gravitational turbulent mixing process.

gases. All the totality of experimental points at $S \geq 100$ mm can be described by the formula $L = 4\alpha AS$, where the parameter $S = gt^2/2$ is the contact boundary displacement, $A = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ is the Atwood number, and α is the dimensionless velocity of turbulent mixing. On the basis of experimental results the constant $\alpha = 0.04$ has been determined.

4. CONCLUSION

In the present work, the Rayleigh–Taylor instability for gaseous media was studied. Ar and Kr were used as working gases. Density ratio ρ_2/ρ_1 was taken to be equal to 2.1, but the Atwood number $A = (\rho_1 - \rho_2)/(\rho_1 + \rho_2)$ was equal to 0.35.

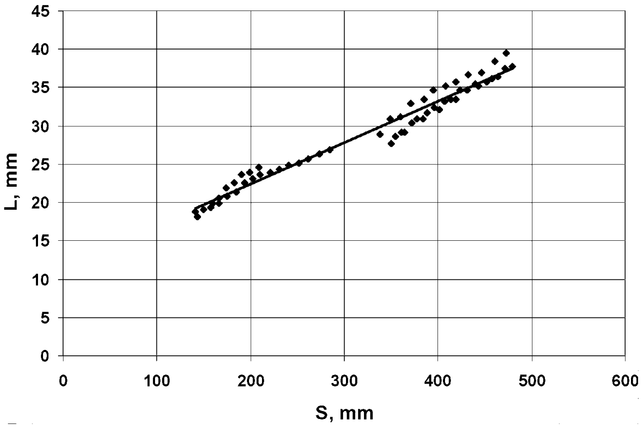

Fig. 5. Dependence of the turbulent mixing zone width on the parameter S for the pair of gases Ar–Kr.

At the initial instant of time, different density gases being investigated were located in the shock tube and were separated by the controlled separating membrane. Then the separating membrane was destroyed by the external force into small-scale fragments with a typical size $\lambda \approx 4$ mm.

The contact boundary of gases was accelerated by means of a compression wave, which was generated by an accelerating piston. The initial acceleration of the contact boundary of gases amounted to $\approx$40,000 m/s^2.

According to the results of experiments, the dependencies of the turbulent mixing zone width on the contact boundary displacement S were constructed. The parameter S was changed from 100 mm to 500 mm. At the self-similar stage of the turbulent mixing evolution, the dimensionless velocity of turbulent mixing α was determined to be equal to 0.04.