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Experimental study into the Rayleigh–Taylor turbulent mixing zone heterogeneous structure

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Abstract

Experiments conducted on the SOM facility at the Russian Federal Nuclear Center–VNIITF, concerning the turbulent mixing induced by the Rayleigh–Taylor instability in a three-layer system of immiscible liquids are described. The fluids are contained in a small tank 6.4 cm × 5.4 cm × 12 cm, which is accelerated vertically downward by a gas gun. The mixing layer evolution was imaged by seeding one of the fluids with particles and using a bidirectional light sheet method (refractive index matching was used to minimize measurement errors). Experiments were performed for two different accelerations ($g = 350\, g_0$ and $g = 100\, g_0$, where $g_0 = 980$ cm/s^2, and the acceleration decreases with distance traveled), and with aqueous solutions of glycerin and benzene (with density ratio 1.6). The lower, middle, and upper layers were a sodium hyposulfite–glycerin solution, a water–glycerin solution, and benzene, respectively. The glycerin solution was seeded with particles. The principal objective of the experiments was to obtain the distribution of fluid particle sizes arising from the mixing of the immiscible fluids.

Keywords: Heterogeneous structure; SOM facility; Turbulent mixing

1. INTRODUCTION

Up to the present, the heterogeneous structure of gravitational turbulent mixing is insufficiently understood, although considerable effort to study this problem has been made. An attempt has been made to measure the distribution of fragment scale sizes in different density miscible liquids undergoing gravitational mixing using an electro contact technique in the experimental work of Kikoin *et al.* (1953). In this work, a qualitative result was obtained. According to this result, unstable mixing occurred by large fragments but at the turbulent mixing stage, the fragment sizes were ~1 mm. In work by Meshkov *et al.* (1982), the structure of the Richtmyer–Meshkov turbulent mixing of different density gases was studied by a "laser knife" technique. In this work, photo images of nonuniformities in inner sections of the mixing zone that provided information on the character of gas mixing were obtained. In experimental and numerical works by Linden *et al.* (1991, 1994) the structure of gravitational turbulent mixing of miscible liquids with educing of a molecular component was studied for low Atwood numbers. Molecular part evaluations of mixing and density fluctuations were obtained in these works. In experimental and numerical work by Dalziel *et al.* (1997) fractal dimension evaluations of constant concentration contours were obtained for the Rayleigh–Taylor turbulent mixing of liquids for low Atwood numbers. In work by Schneider *et al.* (1997) density profiles of mixing liquids were obtained from photo images of mixing zone sections by a "laser sheet" technique.

A direct determination of the fragment sizes in immiscible liquids undergoing Rayleigh–Taylor mixing was attempted in the present work. A "light sheet" technique was employed for this study. It is known that, for immiscible liquids, the smallest fluid particle sizes resulting from fragmentation depend on the relation between the inertial forces determined by acceleration and resistive forces determined by the surface tension (Kolmogorov's criterion). A.V. Polionov offered the following relation for evaluation of the minimum size of fluid elements:

$$d \approx 4.3\left(\frac{\sigma/\rho}{Ag_1}\right)^{4/7}\frac{1}{L^{1/7}}. \tag{1}$$

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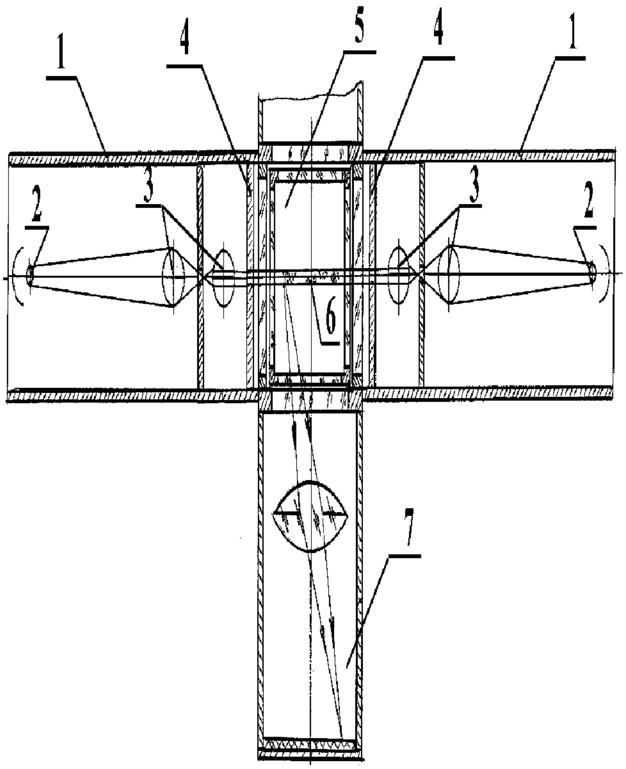

Fig. 1. Sketch of a horizontal section of the light channel.

Here σ is surface tension value, ρ is density, $A = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ is the Atwood number, g_1 is acceleration of the artificial field of gravity, and L is the turbulent mixing zone size. Therefore, the minimum size of the fluid elements for the chosen experimental system containing immiscible liquids depends on acceleration value g_1. Therefore experiments were performed for two essentially different accelerations.

2. EXPERIMENTAL TECHNIQUES

Experiments were performed at the SOM installation described in the work of Kucherenko *et al.* (1995). The measuring module of the installation represents a vertical channel, in the upper part of which an ampoule containing the studied liquids is placed at the initial moment of time. The ampoule is accelerated by a gas flow, and a liquid system placed inside of the ampoule becomes unstable because acceleration is directed from a heavy liquid to a light one in the coordinate system associated with the ampoule. Turbulent mixing arises at the contact boundary of the liquids. In the present work, the measuring module was equipped with 14 horizontal light channels located 56 mm apart. Each channel contained the light-sheet-forming block. The sketch of a horizontal section of the light channel is shown in Figure 1.

Light radiated by a pair of impulse sources (2), which is located in case (1), transforms by means of cylindrical optics (3) and diaphragms (4) to a luminous flux having the form of a light sheet ~1.5 mm thick. The light sheet comes into the ampoule (5) from two sides and illuminates the chosen section of the mixing zone. The scheme with two-side illumination is chosen after consideration of the uniform illumination of the chosen section along the ampoule length.

Visualizing particles are seeded into one of the liquids. Light scattered by the visualizing particles, which are in the light sheet section, finds itself in the photo recorder (7), where a photo image of the mixing zone section forms. This photo image is some set of fragments of that liquid that contains visualizing particles.

3. SENSITIVITY OF THE TECHNIQUE

The light channel sensitivity, that is, the least registered size of nonuniformities, depends on a set of factors, so that it was determined by using some models. There, jets of specified size and shape were used as models of nonuniformities. Special formers, two of which is shown in Figure 2, formed the jets.

The formers were located inside the ampoule at the contact boundary of the liquids, which were an aqueous solution of glycerin and benzene with a density ratio $n = 1.6$. Visualizing particles were in the aqueous solution of glycerin. As the former moves down, the heavy liquid containing the visualizing particles passes through the holes producing the jets, the form and diameter of which correspond to the

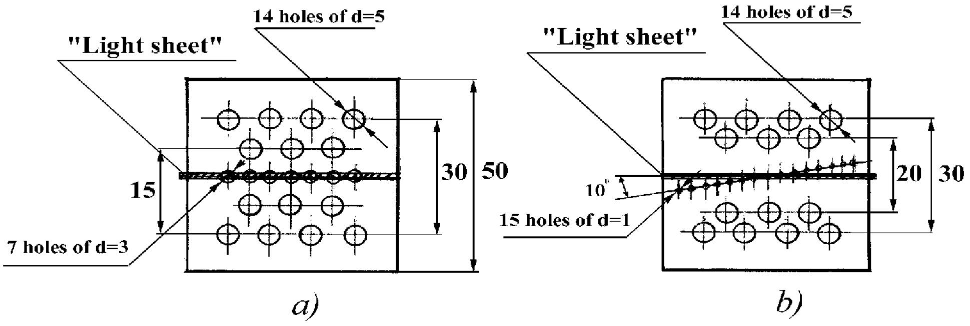

Fig. 2. Formers for jets forming.

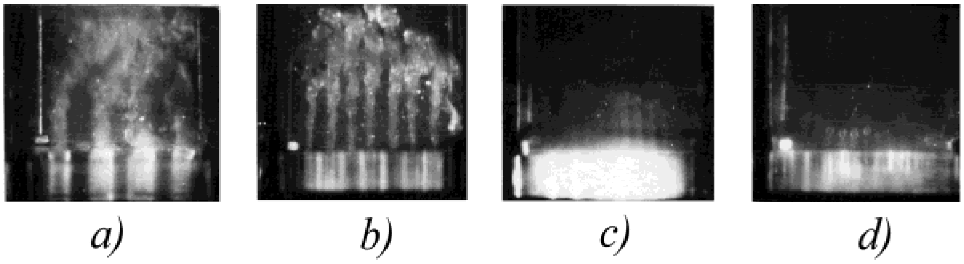

Fig. 3. Photo images of jets taken with special formers.

form and diameter of the holes in the former. The photo recorder only takes those images for which jets find themselves in the light sheet section. Photo images of the jets are shown in Figure 3. In Figure 3a, four jets 5 mm in diameter are distinctly seen in the light sheet section and other jets are not observed that are not in that section. In Figure 3b, there are distinctly seen seven jets 3 mm in diameter formed with applying the former shown in Figure 2a. In Figure 3c,d, there are seen four jets 2 mm and 1 mm in diameter. These jets were formed with the former shown in Figure 2b. Holes of that former were placed on an angle to the light sheet. It is seen that the images only correspond to those jets that found themselves in the light sheet section. Jets of a diameter less than 1 mm do not practically have images. The obtained results allow us to assert that:

1. concentration of the visualizing substance is enough for sharp image acquisition of nonuniformities of sizes not less than 1 mm;
2. those nonuniformities that do not find themselves in the light sheet section do not have photo images.

4. SETUP OF EXPERIMENTS

A scheme of the setup of experiments is shown in Figure 4. Experiments were performed with a system consisting of three layers of different density liquids placed inside a hermetically sealed ampoule. The lower layer was an aqueous solution of sodium hyposulfite (Na_2SO_3) with adding of glycerin of density $\rho_3 = 1.24$ g/cm^3 and viscosity $\nu_3 = 1.95$ CSt. The middle layer of thickness 15 mm was a mixture of water and glycerin of density $\rho_2 = 1.10$ g/cm^3 and viscosity $\nu_2 = 4.5$ CSt. The upper layer was benzine of density $\rho_1 = 0.69$ g/cm^3 and viscosity $\nu_1 = 0.77$ CSt. Gelatin as a visualizing substance was added in the mixture of water and glycerin. Mass concentration of gelatin was 2%. Glycerin was only used for matching of indexes of refraction of all three layers. Optimum concentration of the visualizing substance was determined by a photoelectric pickup having recorded intensity of transmitted and scattered laser light. Surface tension at the contact boundaries between the aqueous solution of sodium hyposulfite and benzine, and between the glycerin and water mixture and benzine amount to 20–30 dyne/cm.

The inner sizes of the working volume of the ampoule were $X_0 = 64$ mm, $Y_0 = 54$ mm, $Z_0 = 120$ mm. Impulse luminous flux in the form of a sheet illuminated the central section of the ampoule (the light sheet coordinate is $y = 27$ mm). There was a fixed mark inside the ampoule in the light sheet plane for determining of the contact boundaries' initial positions and mixing front coordinates. A scale grid was placed inside the ampoule in the light sheet plane for

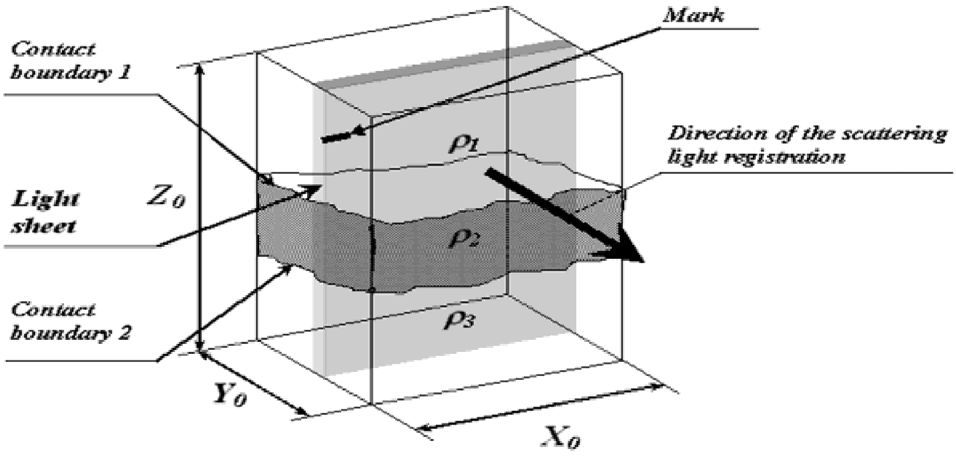

Fig. 4. Scheme of setup of experiments.

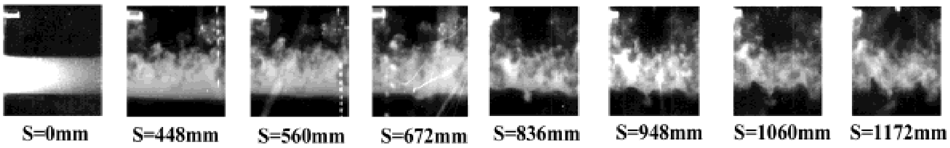

Fig. 5. Characteristic photo images of the mixing zone structure for the first group of experiments.

preliminary determination of the light channel enlargement. Initial perturbations at the contact boundaries of the liquids were created by impact with a special striker made of fluoroplastic of mass 40 g upon the ampoule cover. Specific mass of the equipped ampoule was $m = 23.9\ \mathrm{g/cm^2}$.

Two groups of experiments differing by the initial acceleration g_1 were performed. In the first group of experiments, the acceleration was $g_1 = 350\ g$; in the second one the acceleration was $g_1 = 100\ g$, where g is the acceleration of Earth's gravity. When the ampoule has traversed a distance of 784 mm, the acceleration becomes 230 g and 66 g in the first and second group of experiments, respectively. Every group consisted of two series of experiments differing by the range of recording associated with the availability of contact boundary 2 formed by the miscible liquids with small Atwood number $A = 0.11$. As a result, turbulent mixing at that contact boundary starts after some delay and develops too slowly for heterogeneous structure measurements in that range. The ampoule displacement had to be extended along the measuring channel by 500 mm to measure the heterogeneous structure. Thus, the ampoule displacement was $S = 784$ mm and $S = 1284$ mm in the first and second series of experiments, respectively.

5. EXPERIMENTAL RESULTS

Each group consisted of 20 experiments. Characteristic photo images captured in the first group of experiments are shown in Figure 5. Photo images for the second group are presented in Figure 6. It is seen from the photo images that the turbulent mixing first develops at the contact boundary CB1 and some time later at the contact boundary CB2.

Photo images were processed in the following manner. A two-dimensional $(X\text{–}Z)$ matrix of the film blackening intensities was produced upon scanning each photo image. For arbitrary section $Z = Z_0$, the dependence of the film blackening density on coordinate X was constructed. Next this dependence was processed according to a specially developed algorithm, which allowed us to obtain sizes of the liquid fragments having found themselves in the light sheet section by computer. A program was developed so that it determined fragments sizes of one of the liquids, namely that liquid whose fragments at positive image were light. For determining fragments sizes of another liquid (not containing visualizing substance) it was the processing negative image of the frame at which fragments images of that liquid were light. All the data obtained for the same moment of time were referred to the same statistical population. Bar charts of the distribution of liquid fragment sizes were constructed from the processing.

At each photo image, determination of liquid fragments sizes in the mixing zone was produced at the following sections (along Z-coordinate): at the section where the initial contact boundary CB1 was placed $(Z = 0)$, and at the sections $Z = \pm 4$ mm, $Z = \pm 8$ mm. Inaccuracy of measurements of liquid fragments sizes was obtained with the use of photo images of the jets, produced in model experiments. Transversal sizes of the jets were determined in 10 sections along the Z-coordinate by both a handle method and machine one. As a result of this measuring, the maximum inaccuracy is $\eta = 15\%$.

Bar charts of sizes d distributions of both light liquid fragments (of density $\rho_1 = 0.69\ \mathrm{g/cm^3}$) and heavy ones (of density $\rho_2 = 1.23\ \mathrm{g/cm^3}$) built after considering all fragment sizes of each liquid obtained for all displacements S and all sections Z as the same statistical population in each group of experiments are shown in Figure 7. It is seen from the bar charts that in the first group of experiments, the maximum of the distribution is $a_1 = 1.39$ mm for the liquid of density ρ_1, and $a_2 = 1.26$ mm for the liquid of density ρ_2. In the second group of experiments, the maximums of the distributions are $a_1 = 1.23$ mm and $a_2 = 0.98$ mm for the light and heavy liquids, correspondingly.

6. CONCLUSION

The experiments performed showed that in developed turbulent flow produced by the Rayleigh–Taylor instability

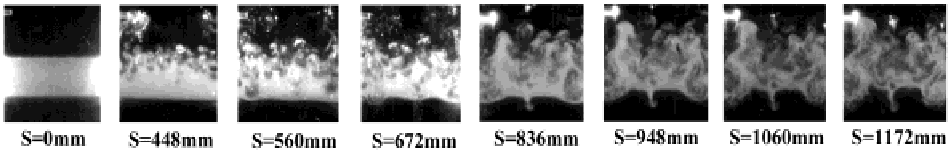

Fig. 6. Characteristic photo images of the mixing zone structure for the second group of experiments.

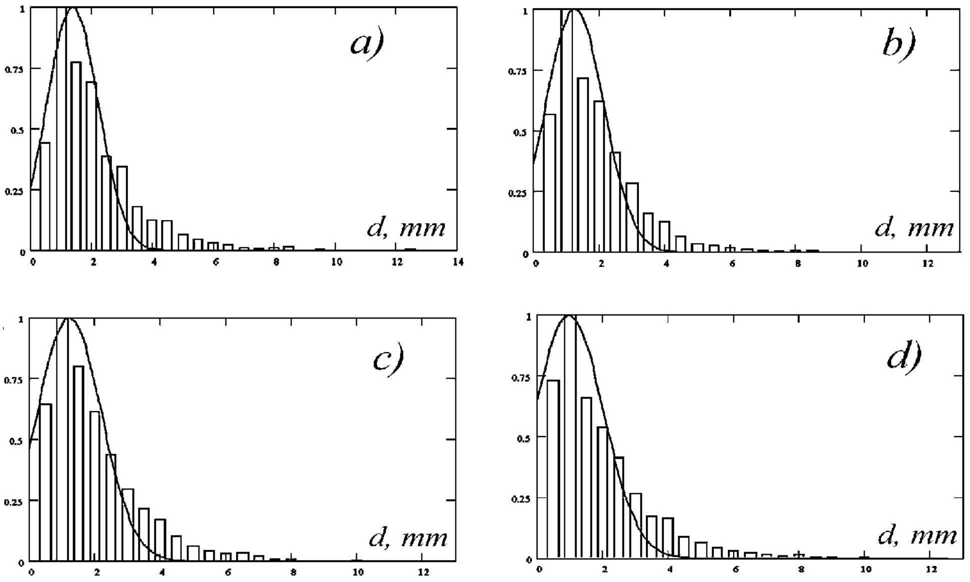

Fig. 7. Bar charts of distributions of liquids fragments sizes in the mixing zone. a: light liquid of density ρ_1, the first group of experiments; b: heavy liquid of density ρ_2, the first group of experiments; c: light liquid of density ρ_1, the second group of experiments; d: heavy liquid of density ρ_2, the second group of experiments.

sizes of most parts of fragments of immiscible liquids are in the range from 1 mm to 1.5 mm. Evaluations of minimum sizes of liquid fragments by the Polionov's relation (1) show that they are in the range from 0.5 mm to 1.1 mm for the light liquid and from 0.36 mm to 0.8 mm for the heavy one. These evaluations are in qualitative agreement with the experiment.

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