Experimental study into Rayleigh-Taylor turbulent mixing zone heterogeneous structure

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Abstract: The heterogeneous structure study has been performed by means of a "light-sheet" technique at the SOM gas-dynamic accelerator. The investigated system consisted of three layers of different density liquids. For leading out the information from the mixing zone inner region illuminated by the "light-sheet", visualizing particles were seeded into one of the liquids. The visualizing particles, which got into the "light-sheet", diffused light, and at the same time photo images of the liquid fragments, contained the visualizing particles, were formed by a light-sensitive receiver. For the error reduction, refractive indexes of all the three liquids were equalized. A special test has been conducted for determining of measurements inaccuracy. Experiments have been performed for two values of acceleration of artificial field of gravity. Distributions of liquid fragments sizes are showed in the form of bar charts for different moments of time.

1 Introduction

Up to the present, the gravitational turbulent mixing heterogeneous structure is insufficiently known though it has been made considerable efforts for solution of this problem. There had been made an attempt to value fragments scales of different density miscible liquids at their gravitational mixing by an electro contact technique in experimental work [1]. In this work, a qualitative result had been obtained. According to this result, mixing at the unstable stage occurred by large fragments but at the turbulent mixing stage fragment sizes amounted ~ 1 mm. In work [2] structure of the Richtmyer-Meshkov turbulent mixing of different density gases had been studied by a "laser knife" technique. In this work, there had been obtained photo images of non-uniformities in inner sections -of the mixing zone that gave an idea of the gases mixing character. In experimental & numerical works [3,4] the structure of gravitational turbulent mixing of miscible liquids with educing of molecular component had been studied for low Atwood numbers. Molecular part evaluations of mixing and density fluctuations were obtained in these works. In experimental & numerical work [5] fractal dimension evaluations of constant concentration contours had been obtained for the Rayleigh-Taylor turbulent mixing of liquids for low Atwood numbers. In work [6] density profiles of mixing liquids had been obtained from photo images of mixing zone sections by a "laser sheet" technique.

In the present work, an attempt of direct determination of immiscible liquids fragments sizes at their Rayleigh-Taylor turbulent mixing has been made. A "light sheet" technique has been employed for this study. It is known that for immiscible liquids the smallest size of fluid elements, which are in result of fragmentation, depends on relation between inertial forces determining by acceleration of a system and resistant forces determining by surface tension of given couple of liquids (Kolmogorov's criterion). A. V. Polionov offered the following relation for evaluation of the minimum size of fluid elements:

$$d \approx 4{,}3\left(\frac{s/r}{A g_1}\right)^{4/7}\frac{1}{L^{1/7}}. \qquad (1)$$

Here **s** is surface tension value, ρ is density, $A=\frac{r_2-r_1}{r_2+r_1}$ is Atwood number, g_1 is acceleration of artificial field of gravity, ***L***- is turbulent mixing zone size. So the minimum size of fluid elements for chosen experimental system containing immiscible liquids depends on acceleration value g_1. Therefore experiments have been performed for two essentially different accelerations.

2 Experimental technique

Experiments were performed at the SOM installation described in work [7]. The measuring module of the installation represents a vertical channel, in upper part of which an ampoule containing studied liquids is placed at initial moment of time. The ampoule is accelerated by a gas flow, and a liquid system placed inside of the ampoule becomes unstable because of the acceleration is directed from a heavy liquid to a light one in the coordinate system connected with the ampoule. Owing to unstable a 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 with a step of 56 mm. Each channel contained the "light sheet»-forming block. The sketch of a horizontal section of the light channel is shown in Fig. 1.

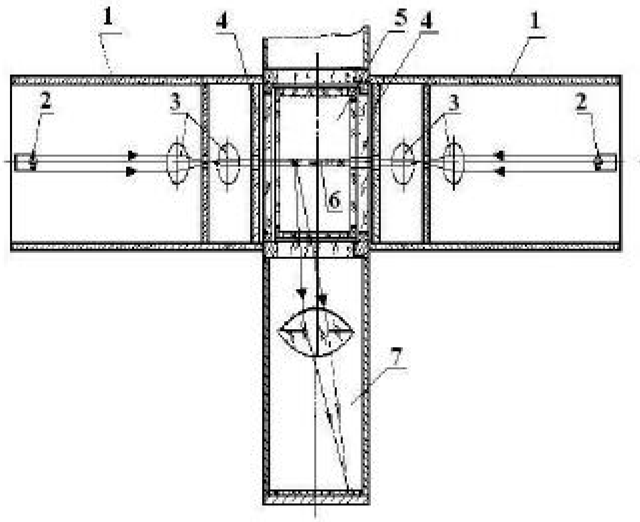

Fig. 1. Sketch of a horizontal section of the light channel

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 a form of "light sheet" of thickness ~ 1.5 mm. The "light sheet" comes into the ampoule (5) from two sides and illuminates chosen section of the mixing zone. Scheme with two-side coming of the "light sheet" is chosen from consideration of uniform illumination of chosen section along the ampoule length.

Visualizing particles inserts 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 which contains visualizing particles.

3 Sensitivity of the technique

The light channel sensitivity, i. e. the least registered size of non-uniformities, depends on a set of factors, so that it was determined by the most direct method – with using some models. There used jets specified size and form as models of non-uniformities. The jets formed by special formers two of which is shown in Fig. 2.

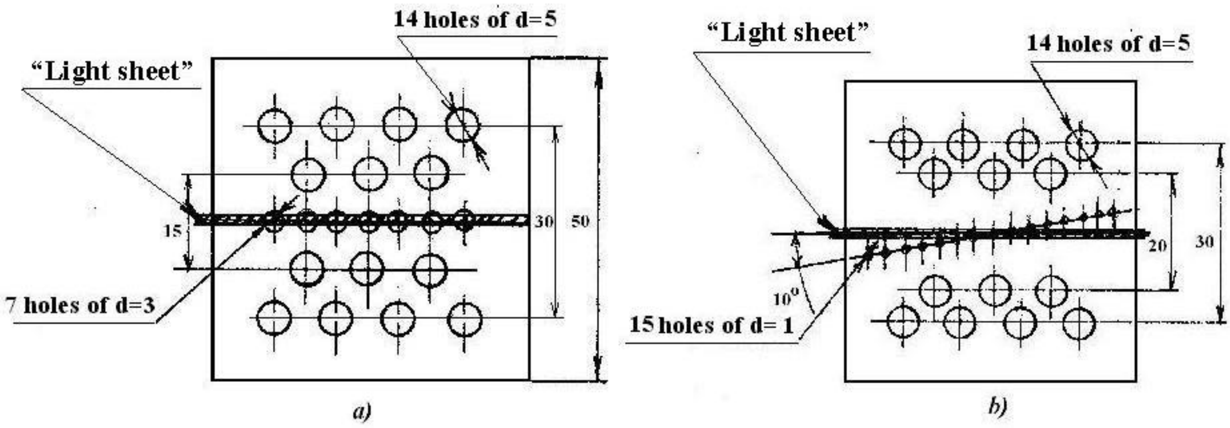

Fig.2. Formers for jets forming

The formers were located inside the ampoule at the contact boundary of the liquids which were aqueous solution of glycerin and benzine with the density ratio ***n*** = 1.6. Visualizing particles were in the aqueous solution of glycerin. At moving a former down, the heavy liquid containing visualizing particles passes through the holes producing jets, form and diameter of which corresponds to the 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 Fig. 3. In Fig. 3*a*, there are distinctly seen four jets of diameter 5 mm found themselves in the “light sheet” section and not seen other jets not found themselves there. In Fig.3*b*, there are distinctly seen seven jets of diameter 3 mm formed with applying the former shown in Fig. 2*a*. In Fig. 3*c* and Fig. 3*d*, there are seen by four jets of diameter correspondingly 2 mm and 1 mm. These jets were formed with the former shown in Fig. 2*b*. Holes of that former were placed on an angle to the “light sheet”. It is seen that the images only correspond to those jets which found themselves in the “light sheet” section. Jets of diameter less than 1 mm do not practically have images. Obtained results give a possibility to assert that:

1. Concentration of visualizing substance is enough for sharp image acquisition of non-uniformities of sizes not less than 1 mm;
2. Those non-uniformities, which do not find themselves in the “light sheet” section, do not have photo images.

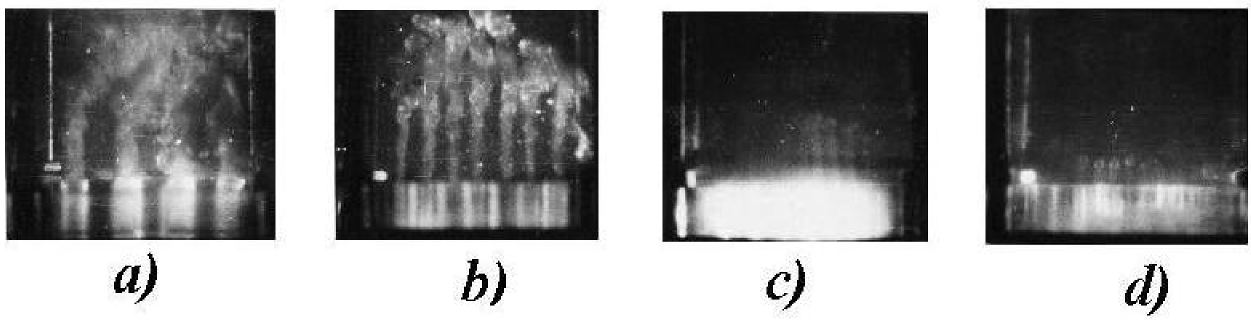

Fig. 3. Photo images of jets taken with special formers

4 Set up of experiments

Scheme of set up of experiments is shown in Fig. 4.

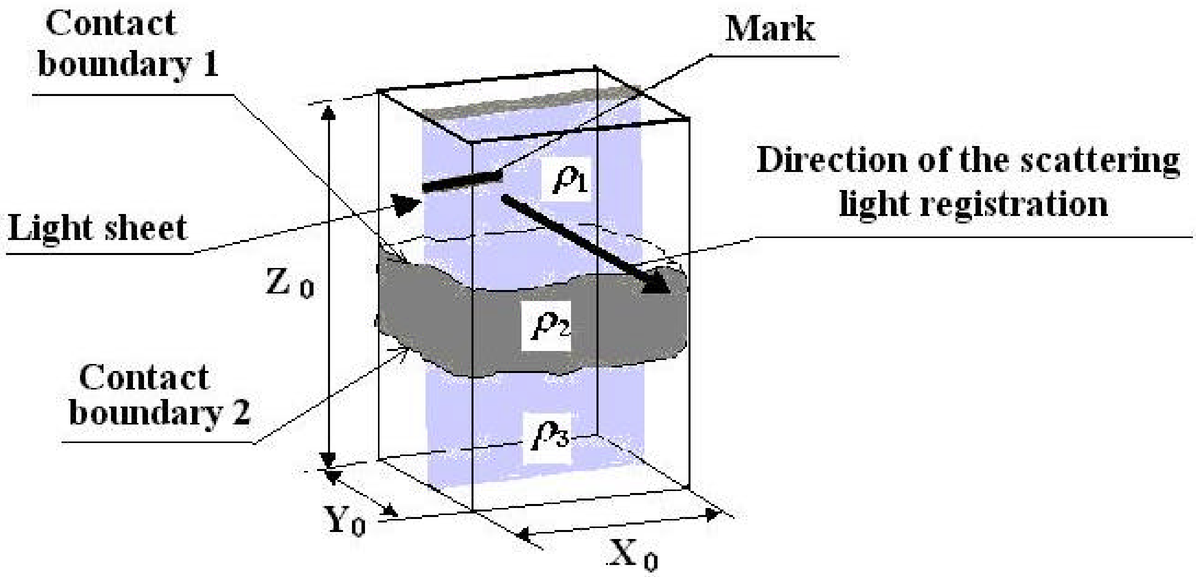

Fig.4. Scheme of set up of experiments

Experiments were performed with the system consisted of three layers of different density liquids placed inside of a hermetically ampoule. The lower layer was an aqueous solution of sodium hyposulfite (Na_2SO_3) with adding of glycerin of density ρ_3 = 1.24 g/cm^3 and viscosity n_3 = 1.95 CSt. The middle layer of thickness 15 mm was a mixture of water and glycerin of density ρ_2 = 1.10 g/cm^3 and viscosity n_2 = 4.5 CSt. The upper layer was benzine of density ρ_1 = 069 g/cm^3 and viscosity n_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 visualizing substance was determined by a photoelectric pickup having recorded intensity of transmitted and scattered laser light. Surface tension at the contact boundaries between 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 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 "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 fronts coordinates. A scale grid was placed inside the ampoule in the light sheet plane for preliminary determining the light channels enlargement. Initial perturbations at the contact boundaries of the liquids were created by blow with a special striker made of fluoroplastic of mass 40 g upon the ampoule cover. Specific mass of the equipped ampoule was $\boldsymbol{m}$ = 23.9 g/cm^2.

There were performed two groups of experiments differed by initial acceleration g_1. In the first group of experiments acceleration was g_1 = 350 g, in the second one - g_1 = 100 g, where g – acceleration of the Earth's gravity. When the ampoule has passed distance 784 mm, in the first group of experiments acceleration becomes 230 g and in the second group – 66 g. In its turn every group consisted of two series of experiments differed by the range of recording. The reason was connected with availability of CB2 formed by miscible liquids with not great Atwood number *À* = 0.11. Because of that turbulent mixing at that contact boundary started after some delay and was developing not enough intensive for heterogeneous structure measuring in that range. It had to enlarge the ampoule displacement along the measuring channel by 500 mm to measure the heterogeneous structure. So that the ampoule displacement was S = 784 mm in the first series of experiments and S = 1284 mm – in the second one.

5 Experimental results

Each group consisted of 20 experiments. Characteristic photo images captured in the 1st group of experiments are shown in Fig. 5. Photo images for the 2nd group are presented in Fig. 6.

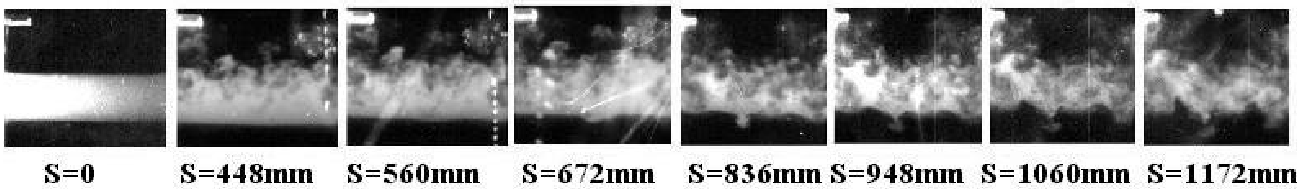

Fig. 5. Characteristic photo images of the mixing zone structure for the 1st group of experiments

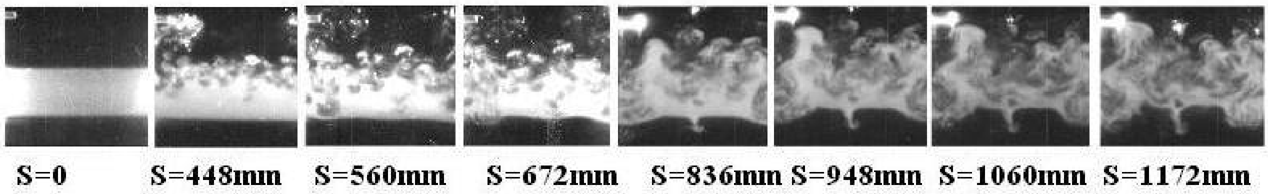

Fig. 6. Characteristic photo images of the mixing zone structure for the 2nd group of experiments

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 processing the following manner. Two-dimensional (X – Z) matrix of the film blackening intensities was produced at scanning each photo image. For arbitrary section $Z = Z_0$ the dependence of the film blackening density on coordinate X was built. Next this dependence was processing according to a special developed algorithm, which gave a possibility to obtain sizes of liquid fragments having found themselves in the light sheet section by computer. The 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 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 liquid fragments distribution at their sizes were built as the result of 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 $Z = \pm$ 4mm, $Z = \pm$ 8mm. Inaccuracy of measurements of liquid fragments sizes was obtained with using of photo images of the jets, produced in model experiments. Transversal sizes of the jets were determined in ten sections along Z-coordinate by both a handle method and machine one. As a result of this measuring the maximum inaccuracy is $\boldsymbol{h}$ = 15%.

Bar charts of sizes $\boldsymbol{d}$ distributions of both light liquid fragments (of density ρ_1 =0.69 g/cm^3) and heavy ones (of density ρ_2 =1.23 g/cm^3) built at considering all fragment sizes of each liquid obtained for all displacements $\boldsymbol{S}$ and all sections $\boldsymbol{Z}$ as the same statistical population in each group of experiments are shown in Fig. 7.

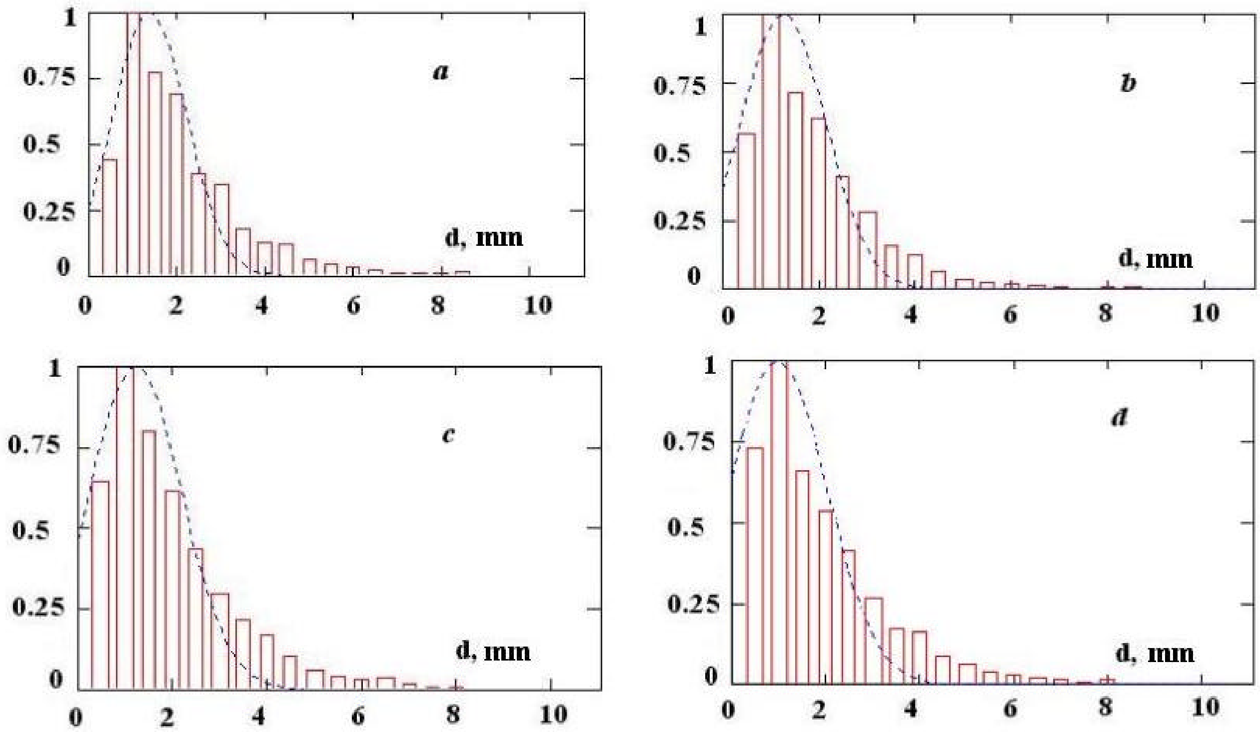

Fig. 7. Bar charts of distributions of liquids fragments sizes in the mixing zone
a – light liquid of density $\boldsymbol{r}_1$, the 1st group of experiments; ***b*** – heavy liquid of density $\boldsymbol{r}_2$, the 1st group of experiments; ***c*** - light liquid of density $\boldsymbol{r}_1$, the 2nd group of experiments; ***d*** - heavy liquid of density $\boldsymbol{r}_2$, the 2nd group of experiments

It is seen from the bar charts that in the 1st group of experiments the maximum of the distribution is $\grave{a}_1$ = 1.39 mm for the liquid of density $\boldsymbol{r}_1$, and $\grave{a}_2$ = 1.26 mm for the liquid of density ρ_2. In the 2nd group of experiments the maximums of the distributions are $\grave{a}_1$ = 1.23 mm and $\grave{a}_2$ = 0.98 mm for the light and heavy liquids correspondingly.

6 Conclusion

Performed experiments showed that in developed turbulent flow produced by the Rayleigh-Taylor instability sizes of most part 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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