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MULTIINFORMATIVE METHODS OF EXPERIMENTAL STUDY OF THE STRUCTURE AND EVOLUTION OF TWO-PHASE FLOWS

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New experimental techniques based on fixation of gas-liquid interface image to control and describe 2D and 3D effects of two-phase flows are described. The developed signal processing algorithm enables to obtain extensive information about the behavior of a bubble and a liquid droplet in two-phase flows: its three-dimensional trajectory, the three component velocity fluctuations, the contour and size of the dispersed phase. Examples of using the developed technique for the study of two-phase bubble flows are provided.

Keywords: gas-liquid interface image, two-phase flow, three-dimensional trajectory, velocity fluctuations, liquid droplet.

INTRODUCTION

Over recent years, two-phase bubble flows have been actively studied due to the expansion of their applications in heat power industry, metallurgy, pharmaceutics and chemical industry. Several new methods [1,2], based on the use of optical methods have been proposed in the experimental study of bubble flows lately. However, these methods having broader options are expensive. With a digital high-speed camera and performing appropriate digital processing of the image, one can successfully receive different information on the movement of dispersive media. So, to define the trajectory and velocity of the gaseous phase in the liquid the authors of [3,4] has successfully applied a high-speed camera with a subsequent image processing. But unfortunately, the applied processing algorithms do not provide information about the size of the bubble, its form and evolution, and to make quantitative two- and three-dimensional measurement.

In cases where the application of non-contact methods is difficult, studies of the evolution of two-phase media involve the use of probe techniques. Probe methods are contact and require the placement of measuring sensors directly in the investigated medium, or on its boundary. The advantages of contact sensors is the ease of interpretation of the information obtained, their downside is the disturbance of the flow under study. The disturbances are induced both by sensors and auxiliary (construction) devices that are used to, place sensors in the flow and to connect to systems of data collection. Examples of such gauges are temperature-sensing elements, optical probes, conductivity probes [5, 6]. Foreign researchers in their work [6] suggested to develop a grid sensor on the basis of conductivity probe. This sensor is based on a system of wire electrodes disposed perpendicular to and at a short distance from each other which combine two functions: measuring the spatial distribution of electrical characteristics of the fluid flow under study and input of obtained information in a data collection system [6,7]. When placing the probe in conductive fluid the measured parameters are specific conductivity or dielectric permittivity of the flow at the cross-section of the grid probe. The study of thermal-hydraulic processes using grid probe is based on tracking the dynamics of transference and tailing of electrically contrast marker.

I. DESCRIPTION OF METHODS BASICS

Two-phase bubble flow is characterized by the presence of gas or vapor inclusions in the fluid and moving at relatively low speeds. These objects include floating up bubbles in a stationary liquid, gas- and vapor-liquid flow in pipes and channels of different geometry, boiling liquid, destruction of gas or vapor structures, etc. Liquid and bubbles have different optical transparency, so at fixation of an image one can always visually determine the contour of bubbles. Having a time sequence of frames of the same object it is possible to determine the dynamics of its shape changes and to obtain quantitative data on its velocity. The developed technique of experimental study of bubble flow in two-phase media is based on the method of fixation of the medium movement with a digital high-speed camera, followed by the identification of image objects and their digital processing. The speed of the object fixation depends on the object motion speed and the picture quality and can reach 2000 frames per second. Moreover, the technique makes it possible not only to obtain simple information about the linear speed of the object, but also to build a two- and three-dimensional trajectory of the motion defining averaged values of velocity and fluctuating 2D and 3D components of the velocity vector, as well as to find out the velocity vector and the rotation vector of the object. These data are extremely important in the study of two-phase flows, at measurement of turbulent characteristics, determining the characteristic oscillation frequencies of the shape and volume of bubbles. Conceptually, the developed technique of the experimental study is an analogue of the well-known tomography. As in the computed tomography it is possible to isolate any section with further detailed its expansion and obtaining the quantitative characteristics of velocities and gas content.

Matrix diagnostics method is based on the simultaneous detection of spatial distributions of parameters of the complex conductivity and dielectric permittivity of a liquid in the flow of one and two-phase fluids of electrically conductive liquids. The grid probe of a matrix sensor can detect the spatial distribution of the electrical parameters of a medium, such as specific conductivity and specific electrical capacity. The probe consists of two groups of wire electrodes spaced apart and separated from each other. The first group of electrodes is exciters (reference signal generators) and the second group is the receivers. The spatial intersection of the two groups of electrodes forms a measuring area consisting of a set of nodes, each of which is formed by a pair of electrodes: a generator and a receiver. The measurement of parameters is carried out in the gap between two electrodes, one of which is used as a voltage source and the second as a current receiver. The effective electrical impedance of the medium in the space between the electrodes is determined on the basis of the measured current.

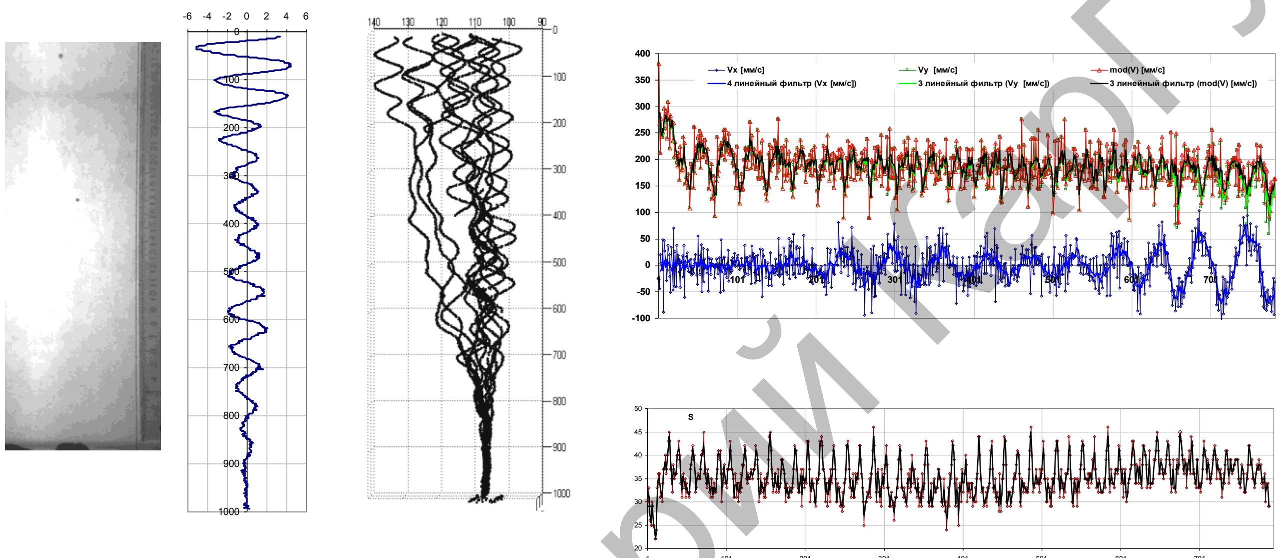
The method of investigation of heat transfer processes using a field recording of electrical impedance properties of flows is based on the registration of dynamics of marker transfer. This method is similar to the methods of optical visualization of hydrodynamic flow fields. When visualizing the processes of heat transfer a contrast marker (tracer) is used. The marker can be either natural (gas or steam inclusions in a liquid flow) or additionally introduced into the fluid. A gas phase has a highly contrast dielectric permittivity as compared to a liquid. Dielectric permittivity of liquids is usually two or more times greater than that of gases. In this case, the spatial distribution and time variation of the apparent dielectric permittivity can be used to obtain the characteristics of the flow under study.

II. SOME EXAMPLES OF TECHNIQUES APPLICATION

This section provides examples of the application of techniques to the case of air bubbles floating-up in liquids, liquid droplet diffusion. Examples are given without discussing the physical results, because the scope of this report does not allow doing it.

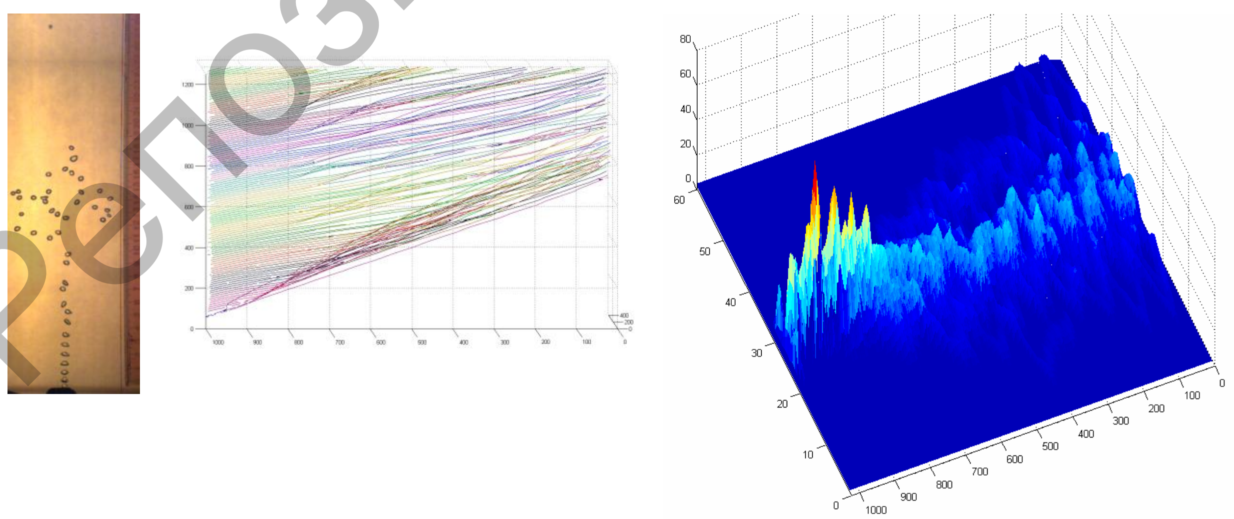
The simplest example of the use of high-speed photography technique is related to the determination of the laws of motion of a gas bubble in a flat gap of a liquid. Figure 1 shows a randomly selected frame of the original image of a floating up bubble and the trajectory of its center of mass. Here are all the trajectories of bubbles in the case of a linear chain of bubbles. Figure 1d shows the vertical and horizontal component of fluctuations of velocity vector and its module for the center of mass of a single bubble floating up in a quiescent fluid. Spectral analysis of the fluctuations indicates the existence of two prominent peaks in the spectrum of velocity fluctuations at low frequencies that correlate with the area of the bubble oscillation and pulsation of the angle of rotation of the bubble around its main axis.

Figure 2 shows the image of the beginning of the formation of bubbles floating up in a fluid from one source, the time base sweep of the process. Each curve corresponds to each new bubbles appearing on the cut of the source. The vertical axis represents time, and the horizontal one represents height of floating up. The slope of the curves is the speed of floating up of each bubble. The time-integrated distribution of the gas content along the height and width of the channel for a extended chain of bubbles is shown in Figure 2 c. Note that the phenomenon of vertical stratification of gas content near the source of generation of bubbles is experimentally recorded for the first time.



a) b) c) d)

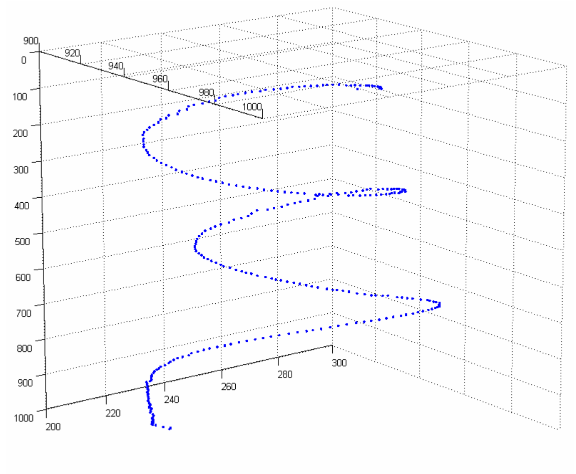
Fig.1. a – floating up of a single bubble with a diameter of 3 mm and a chain of bubbles in a flat channel; b – a trajectory of a single bubble; c – trajectories of bubbles in a jet; d – fluctuations of components and the velocity module of a single floating up bubble



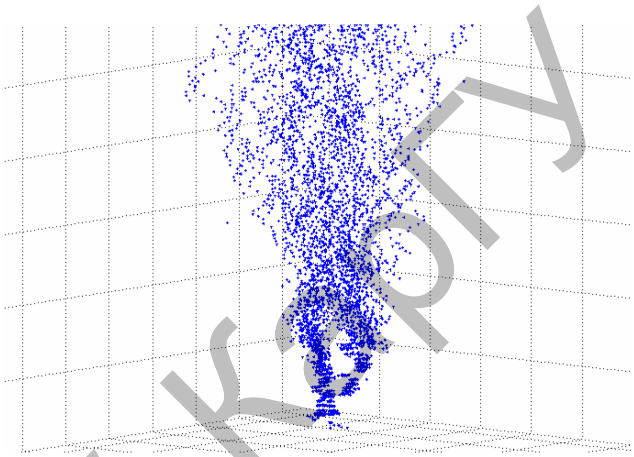
a) b) c)

Fig.2. a – the formation of a "bubble" jet, b – trajectories of all the bubbles in the jet; c – the distribution of gas content along the height and width of the bubble jet

Figures 3a and b show the trajectory of the bubble floating up in a free volume of a liquid, and Figures 3 c, d present trajectories of a "bubble" jet in the free volume of the liquid. Each curve corresponds to a single bubble moving in the generated jet of bubbles. Here is a top view of the trajectory of a single bubble (on the left) and the trajectories of all bubbles in the case of generating a jet of bubbles (on the right). The corresponding diagrams for the three velocity components for a randomly selected bubble from the bubble chain are shown in Figure 4.



a)



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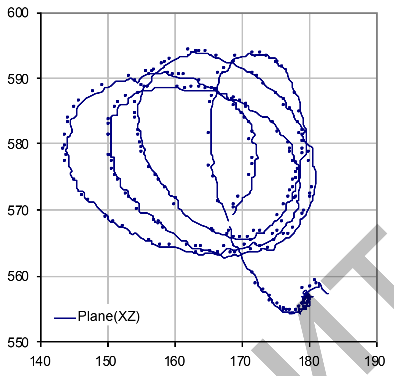
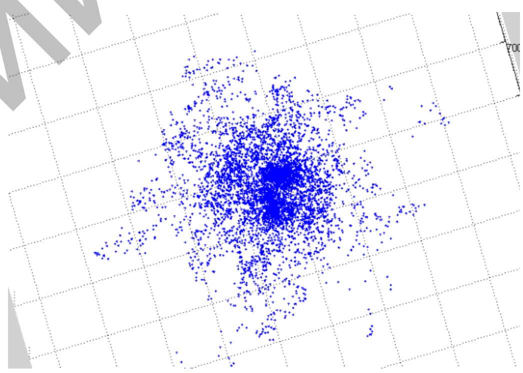


b)



d)

Fig. 3. a – a volume trajectory of a bubble floating up in a free volume of the liquid; b – top view of the trajectory of a single floating up bubble; c – 3D trajectories of free gas bubbles floating up from a single source in the liquid; d – a top view of the trajectory of all floating up bubbles in a jet

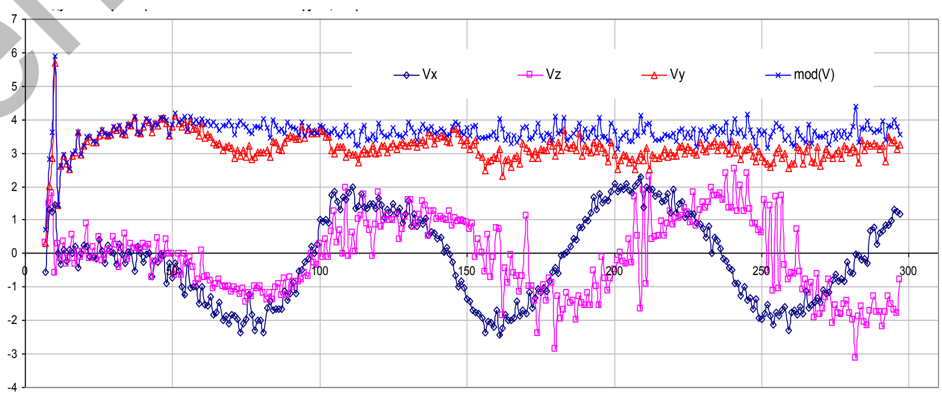


Fig.4. Three components of the velocity vector for the bubble floating up in the volume of fluid

Figure 5 shows the 3D trajectory of a single bubble floating up in the tube. In the case of a developed bubble jet in the pipe, one can determine the distribution of the gas content and compute the fluctuations of the three components of velocity establishing velocity vector for any pipe section of selected height. Figure 6 shows an example of determining the three components of the velocity fluctuations of a single bubble, separated from a set of bubbles, floating up in the pipe with the liquid. Possibilities to make measurements in two-phase media by means of matrix grid sensor are shown in the following two examples. The investigated mass transfer process at the free movement of a drop of NaCl solution in pure water is shown in Figure 7a. Register time distributions of salinity in the track section dissolving a drop. As a result of the measurements a three-dimensional image of the evolution process of a single drop of salty liquid in pure water was restored.

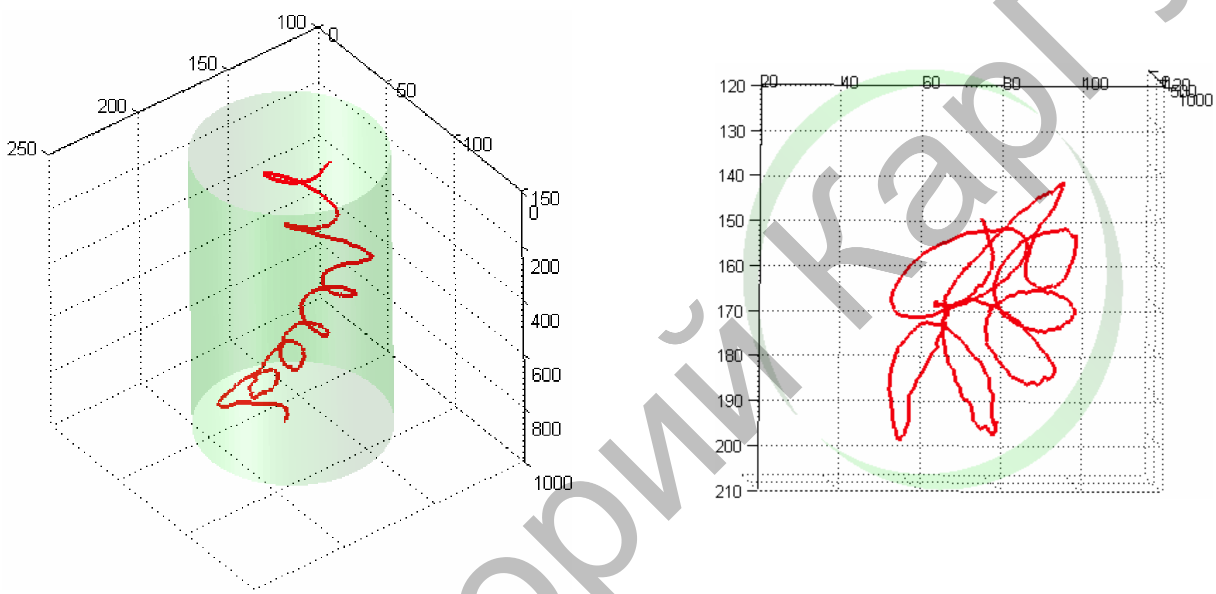


Fig. 5. A 3D trajectory of a single bubble floating up in the pipe with water. The right-hand image is a top view.

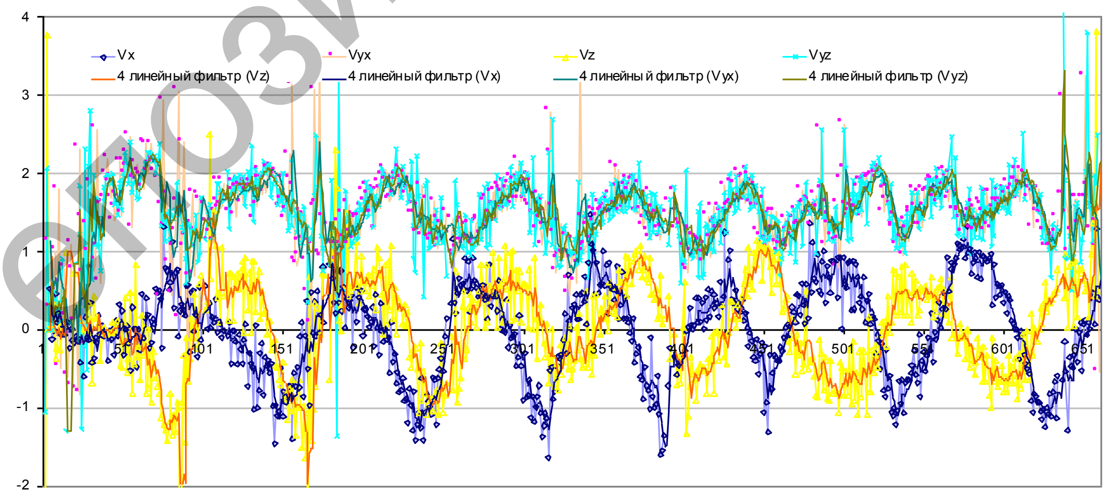


Fig.6. Fluctuations of three components of the velocity vector and the velocity module
for a bubble in the tube

In addition, an optical visualization of the process using an optically contrast tracer was carried out shown in Figure 7b. The results of measurements of salinity are consistent with the optical visualization and the data of experimental works of other researchers.

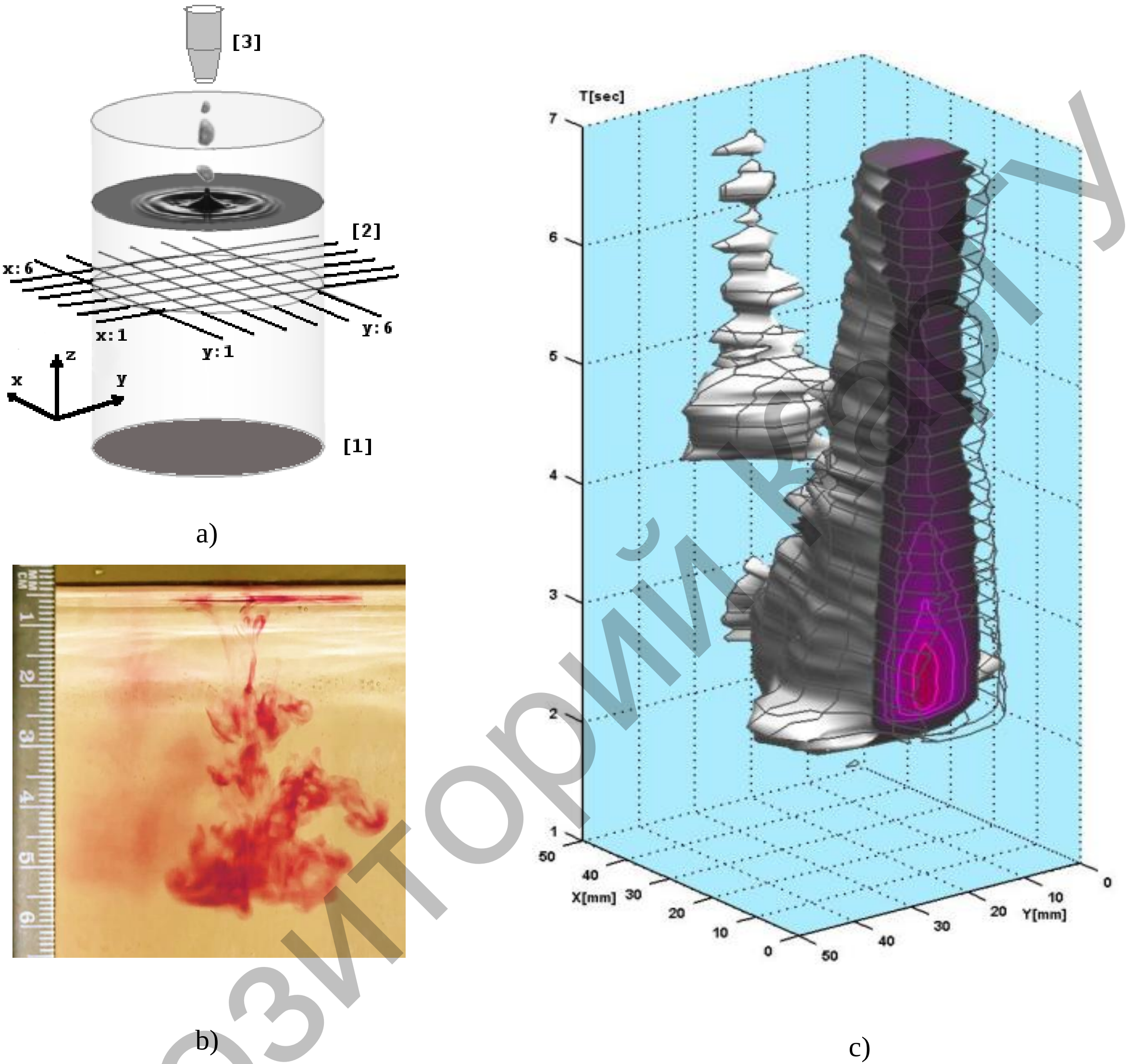
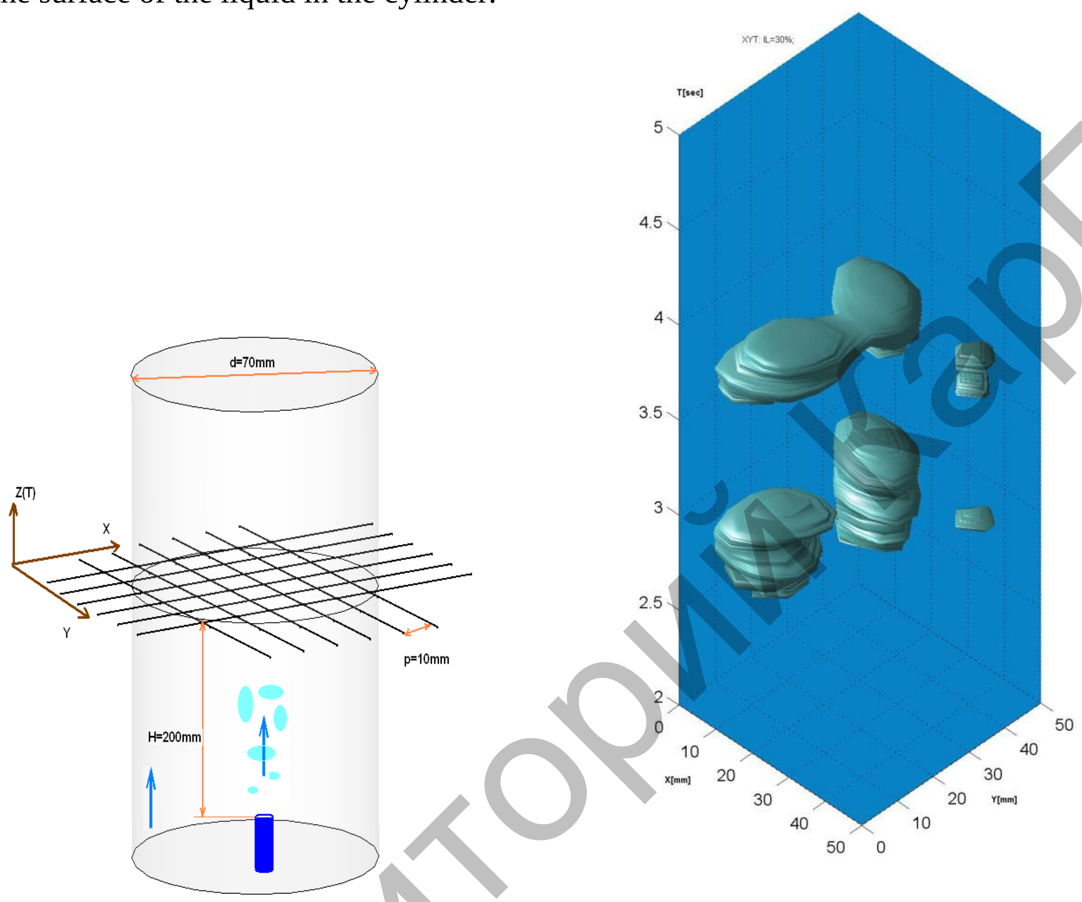


Fig.7. a - diagrammatic view of the laboratory setup to study possibilities for registration of the process of liquid-liquid mass transfer using matrix sensor; 1- cylinder with liquid, 2 - matrix grid sensor 3- marker supply nozzle; b - visual image of diffusion of a salty liquid droplet; c –a three-dimensional isosurface of a liquid droplet on the level of salinity of 0.025 in the space XYT. Additional cut in the plane X = 10 mm.

Recording of matrix grid sensor readings was made at a rate of 25 frames per second. After the recording, all measurement results were converted to the nodal values of the effective salinity. On the basis of the measured data, we restored the concentration distribution of NaCl occurring when a droplet of soluble liquid moves the other. The three-dimensional concentration distribution plotted at a coordinate system XYT, where the third coordinate is the observation time is shown in Figure 7c. Spatial axes are formed by the guiding electrodes of the grid sensor. The time axis is related to the moments of recording of the grid sensor readings. The point of intersection of the electrodes x:1 and y:1 is selected as a zero point on the coordinate axes X and Y. The recording time of the first data frame is taken as zero on the time axis. The reconstructed three-dimensional field of concentration along the cross section XYT is shown in Figure 7c.

The scale ratio of the time axis to the coordinate axes is 1:20, which corresponds to the uniform movement of the studied medium at a rate of 20 mm/sec. The droplet surface at salinity levels of 0.02, 0.1 and 0.05 has a complicated shape which was formed at the free fall of the droplet on the surface of the liquid in the cylinder.



a) b)

Fig.8. a - the scheme of the experiment on investigation of gas bubbles floating up in the liquid;
b – a three dimensional isosurface of gas bubbles in a liquid

We also studied the process of motion of bubbles in the liquid. The experimental stand consisted of a vertical channel of 1,500 mm length circular section and an inner diameter of 90 mm. The grid sensor of 36 nodes (6x6) with a grid spacing of 10 mm (diameter of the electrodes is 0.3 mm) is installed in the cross section of the channel. For the air supply, a circular nozzle with the diameter of 4 mm is installed at the distance of 200 mm from the sensor. An outline drawing of the experimental section is shown in Figure 8a. At the course of the experiment, a gas mixture was supplied to the working fluid flow through the nozzle. The volumetric rate of the gas mixture was equal to 30-40 ml/sec. The working fluid inside the loop was motionless. The three-dimensional model of the motion of the gas phase reconstructed on the basis of the measurement results is shown in figure 8b. The model is based on the assumption of aconstant movement velocity of the gas inclusions related to the cross-section of the grid sensor.

CONCLUSION

The above examples show only the potentialities of methods and do not claim to be a complete physical description of the process. Even for these examples, the use of the developed methods allowed not only to see a number of interesting phenomena, including the new ones, but also to obtain a quantitative description of the ongoing processes. A detailed description of these phenomena is the purpose of subsequent studies and publications.

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