Investigation of partially transparent and high-density two-phase liquids using laser interference method

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Abstract The purpose of the present work was to investigate partially transparent and high-density two-phase liquids using the laser interference method to establish the limits of applicability of this method. The results of the work include the interference fringe patterns of drops when using various kinds of liquids, the calculated drop sizes. The calculation of inaccuracies was also carried out to further establishing the limits of applicability of this method.

1. Introduction
Currently, there is vast amount of methods for investigating flows based on various physical phenomena, but non-contact research methods attract growing interest. Such methods allow to investigate flows without disturbances, which excludes insertion of additional distortions into the researched environment. These methods include, in particular, the laser interference method.

The Interferometric Particle Imaging method (IPI), was suggested in 1993 and based on the registration of images of particles in scattered radiation using a CCD camera, which allows to determine the speed and size of particles simultaneously [1]. The IPI principle is based on the interference of scattered and refracted light on a single particle situated in specially structured laser radiation. To obtain an interference fringe pattern of liquid drops or air bubbles, data registering should be performed with a defocused image using a digital CCD camera [2]. The obtained interference fringe patterns represent circles with a set of alternating dark and light stripes. By the number of interference fringes, it is possible to determine the diameter of the bubble, and using the cross-correlation method - and its speed.

The applicable scope of the Interferometric Particle Imaging method is quite extensive. IPI allows to determine the size of liquid particles and air bubbles from tens of micrometers to several millimeters. The requirements to resolving power for the IPI method are significantly lower than for other methods, and the speed measurement capabilities are limited only by the parameters of recording equipment. The quality of the interference fringe pattern depends on several setup parameters, for example, the focusing plane, the angle of observation and the camera angle. When considering particles, one should not forget about the properties of liquid and gas, which will also affect the quality of the interference fringe pattern [3]. This work presents the results of experimental investigations for liquids with different parameters, which allows to determine the limits of the method’s applicability.
2. Experimental setup
Represented in the figure 1 configuration of experimental setup using laser interference method included semiconducting laser module with wavelength \( \lambda = 0.655 \) micrometer and power 25 milliwatt, the object under investigation, recording equipment and computer.

![Figure 1. Configuration of experimental setup](image)

1 – laser, 2 – glass plate, 3 – gas bubble under investigation, 4 – digital video camera, 5 – computer.

The radiation of the semiconducting laser module (1) passes through the medium (2) with the investigated spherical particles (3). The radiation scattered by them is collected using a digital video camera (4) and transmitted to a computer (5). At the output of the laser, the radiation has the form of divergent beam. The ideal beam should be symmetrical with a round spot in cross section, but in reality its shape is asymmetric due to the instability of the laser. The use of a semiconducting laser module allows to reduce the dimensions of the setup, as well as the presence of a higher output power, in comparison with He-Ne, simplifies the investigation of partially transparent liquids.

The JAI RM-2040GE camera with a resolution of 1392x1040 was used in the experiment. The shooting speed at full resolution reaches 34 frames per second. The camera uses a 1/2" CCD matrix. The connection interface is Gigabit Ethernet.

3. Experimental data processing
During determining the size of spherical gas particles in partially transparent liquids, various liquid solutions of chemical elements and dyes were applied. Bubbles were produced in a cuvette with water using a piezo generator, and then 5 g or 5 ml of the substance matter was added (depending on aggregative state). The following test liquids were selected for experimental researches:

- Copper (II) sulfate (aqueous solution – green);
- Potassium permanganate (raspberry-red);
- Gouache (blue);
- Water color (yellow);
- Stamp ink (purple);
- Food dye (light-blue);
- Gas-cut water (dark green);
- Vegetable oil (yellow; higher optical density compared to water).
The first stage of testing liquids demonstrated the following features of the obtained solutions. Copper (II) sulfate, being soluble in water, as a result of a chemical reaction should have formed a residuum in the form of a heavy salt – blue copperas (CuSO₄·5H₂O), and color the water in a green-bluish color. In practice, however, the residuum fell out only partially and partially sedimented on the walls of the cuvette. Based on the experiment, it was concluded that copper sulfate is inapplicable as a material for investigation using IPI.

A similar situation occurred with potassium permanganate. Potassium salt of permanganic acid did not lyse in cold water.

Paints, inks and food dye have been successfully dissolved in water to give the necessary result. There was prepared 200 ml of an aqueous solution of each of the substances and mixed with 5 liters of water in a cuvette to maintain the same concentration of substances in the entire volume of the liquid.

Gouache, ink and water color almost completely absorbed laser radiation, preventing the formation of a laser plane inside the cuvette to illuminate the bubbles. The usage of an industrial setup also did not give results, even taking into account the use of a laser with a higher output power. Obviously, this is due to the molecular structure and, consequently, the chemical properties of the received solutions. Of the samples presented, only food dye was suitable for IPI investigations. The resulting interference fringe patterns are represented in the figure 2.

![Figure 2. Interference fringe patterns of air bubbles moving in the blue food dye solution.](image)

The averaged values of the diameters of air bubbles in tinted water, as well as the relative measurement inaccuracy, are shown in the table 1.
Table 1. Results of measuring the parameters of bubbles in water.

| №  | Averaged diameter (dpac, millimeter) | Relative measurement inaccuracy (%) | Averaged flow speed (v, centimeters/second) |
|----|-------------------------------------|------------------------------------|-------------------------------------------|
| 1  | 0.284                               | 2.7                                |                                           |
| 2  | 0.273                               | 2.6                                |                                           |
| 3  | 0.275                               | 2.6                                |                                           |
| 4  | 0.283                               | 2.7                                |                                           |
| 5  | 0.285                               | 2.8                                |                                           |

Also, green gas-cut water was used as a test liquid to consider the possibility of tracking a spherical air particle formed as a result of artificial gassing of water and measuring the bubbles created by the generator. The received interference fringe patterns are demonstrated in the figure 3.

Figure 3. Interference fringe patterns of air bubbles moving in gas-cut water.

The averaged values of the results of measurements of the parameters of air bubbles created by the piezo generator in green gas-cut water are represented in the table 2.

Table 2. Measurements of the parameters of the generated particles in the gas-cut water.

| №  | Averaged diameter (dpac, millimeter) | Relative measurement inaccuracy (%) | Averaged flow speed (v, centimeters/second) |
|----|-------------------------------------|------------------------------------|-------------------------------------------|
| 1  | 0.500                               | 5.1                                |                                           |
| 2  | 0.511                               | 5.2                                |                                           |
| 3  | 0.504                               | 5.3                                |                                           |
| 4  | 0.525                               | 5.3                                |                                           |
| 5  | 0.489                               | 5.3                                |                                           |
The table 3 shows the parameters of the particles that were formed in the liquid due to artificial gassing (CO\textsubscript{2} gas). The density of CO\textsubscript{2} gas under normal conditions is 1.5 times greater than that of air (1.9769 kg/m\textsuperscript{3} versus 1.2928 kg/m\textsuperscript{3} for air).

| №  | Averaged diameter (dpac, millimeter) | Relative measurement inaccuracy (%) | Averaged flow speed (v, centimeters/second) |
|----|-----------------------------------|------------------------------------|--------------------------------------------|
| 1  | 0.300                             | 8.5                                |                                            |
| 2  | 0.312                             | 8.9                                |                                            |
| 3  | 0.288                             | 8.8                                |                                            |
| 4  | 0.295                             | 8.8                                | 3.1                                        |
| 5  | 0.293                             | 8.7                                |                                            |

In further researches, vegetable oil was used as a test liquid, which has a higher optical density than all other solutions and a refractive index different from water (at a temperature of 20° C, the refractive index is $n = 1.476$). At a higher refractive index, the bubble diameters will have significantly different sizes than in aqueous solutions.

The oil has more heavy-bodied consistency than other considered liquids, which is caused by the chemical structure of the substances included in it. The viscosity of oil is $64.5 \cdot 10^{-5}$ kg/(m s), water is $1.05 \cdot 10^{-5}$ kg/(m s). During the filling of the investigated volume, air bubbles formed in the laser plane, which created additional inconveniences, because directly influenced the investigated parameters of the generated flow.

It is possible to make an assumption that the air bubble moves uniformly and its speed does not actually depend on the viscosity, but is proportional only to the ratio of the densities of the liquid and gas inside the bubble.

The figure 4 demonstrates the interference fringe pattern of air bubbles in oil. It should be noted that the interference fringe pattern of the bubbles created by the generator is hardly distinguishable against the background of passive particles already present in the oil.

![Figure 4. Interference fringe patterns of air bubbles moving in oil.](image_url)
Based on the experimental data obtained, it was only possible to determine the flow rate as a whole. It amounted to 3 cm/s with an approximate particle diameter varying from 0.03 to 0.07 mm. The data received is inaccurate and is caused by the impossibility of obtaining full-fledged interference patterns.

4. Conclusion
Experimental investigations have been performed using the developed modifications of the laser interference method. Substances have been selected which make it possible to color the liquid. As a result of experiments, it was found that IPI allows one to diagnose diameters of air bubbles in a colored (partially transparent) liquid with an inaccuracy of no more than 3%.

Additionally, the performed experiments demonstrated that the method is not applicable for liquids with initial artificial gassing (measurement inaccuracies of particle diameters from 5 to 9%) and for liquids with high optical density. The resulting interference fringe patterns are blurred, and it is almost impossible to determine the diameters of air bubbles from them.

References
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