Laser Refractography: Principles and Applications in Studies of Physical Processes in Liquids

Rinkevichyus B.S., Pavlov I.N., Pudovikov D.E., Raskovskaya I.L., and Tolkachev A.V.

Abstract— This paper is devoted to the description of the method of laser refractography and the results of its application in experimental studies of physical processes in transparent liquids. Laser refractography is a novel information-measurement technique for diagnosing transparent optically inhomogeneous liquids and gases, based on the probing of fluid flows with a structured laser radiation (SLR), digital recording of the refraction images (refractograms) obtained, and their computer processing with a view to reconstructing the parameters of the flows. Block diagrams of measuring laser systems are shown, their operating principles are described, and libraries of typical refracrograms are presented. The results of numerical modeling of the temperature fields distribution around the heated and cooled bodies in liquid are presented.

Laser refractography has been used to visualize temperature gradients in thin boundary layers in the vicinity of heated of cooled bodies placed in a transparent liquid, to determine the heating or cooling time of various bodies in liquids, to establish the setting time of laminar and turbulent convection conditions, and to find out the position of local temperature changes in liquids.

Keywords — convection, diffraction optical elements, laser, refraction, optically inhomogeneous liquids.

I. Introduction

BEING extremely variegated and complex, physical processes are of considerable interest for exploration on the basis of comprehensive combination of various research approaches. However, when carrying out experiments and theoretical analyses, the investigators have to do with certain models that cannot provide adequate notions of the processes taking place under actual conditions.

In this aspect, optical methods of studies into physical processes occurring in liquids and gases offer great advantages over other techniques, for they make it possible to visualize the process under study; i.e., to perceive it with the eyes, without disturbing its characteristics [1]. Ernst Mach, an Austrian-Czech physicist and philosopher of the 19th century, who was the first to observe shock waves with the aid of a shadow instrument, was very much aware of this fact. It was his important statement that to see implies to understand. The role of optical methods in the studies of gas flows, especially supersonic ones, is tremendous. Various shadow, interference, polarization, and holographic techniques and instruments were developed for these purposes. For example, shadow instruments [2] were widely used. Because of their high cost and bulkiness, most of these instruments are no more manufactured today.

After lasers made their appearance, new methods were developed for diagnosing liquid and gas flows, namely, laser Doppler anemometry, phase Doppler anemometry, particle image velocimetry, photoluminescent techniques, and a number of others. With these methods, fine light-scattering particles are introduced into an optically homogeneous flow, and the parameters of their motion are determined from the light scattered by them. At present, instruments employing such methods are being widely used in aerohydrodynamic and thermophysical experiments.

Liquid and gas flows involved in thermophysical processes are optically inhomogeneous. The main cause of the optical inhomogeneity of a medium is the temperature dependence of its refractive index, refractive index gradients in liquid flows being substantially higher (by two orders of magnitude) than in gas flows, with the temperature gradients being the same. This restricts the use of the above-mentioned methods in the studies of liquid flows, but allows developing new laser techniques that form the basis for determining the temperature or density gradients in a liquid flow from measurements of its optical inhomogeneity. The case in point here are laser techniques based on the refraction of spatially modulated laser beams in optically inhomogeneous media.

II. Computer Modeling of a Temperature Boundary Layer

A. Description of the Numerical Model

The problem of development of a temperature boundary layer is analyzed using as an example the flow arising in the

This work was supported in part by the Russian Foundation for Basic Research under Grant 14-08-00948-a.

B. S. Rinkevichyus is with the National Research University “MPEI”, Moscow, Russia (corresponding author to provide phone: 8-495-307-86-09; e-mail: rinkevbs@mail.ru).

I. N. Pavlov is with National Research University “MPEI”, Moscow, Russia (e-mail: inpavlov@bk.ru).

D. E. Pudovikov is with the National Research University “MPEI”, Moscow, Russia (e-mail: dimonep@ciam.ru).

I. L. Raskovskaya is with National Research University “MPEI”, Moscow, Russia (e-mail: raskovskail@mail.ru).

A. V. Tolkachev is with National Research University “MPEI”, Moscow, Russia (e-mail: avtolk2008@yandex.ru).

vicinity of a stationary metal ball immersed in a liquid, the temperatures of the ball and the liquid being different. Considered are the cases of hot ball in cold liquid and cold ball in hot liquid.

To carry out numerical modeling, use was made of the program package Fluent [3], [4]. The problem was considered in a two- and a three-dimensional formulation. The analysis of the data obtained showed that the three-dimensional computation provided no additional information by comparison with its axially symmetric counterpart, demanding at the same time a much greater computational resource. For this reason, use was made in this problem of the two-dimensional approach. The stationary laminar flow obtained in the computation is of stable character.

Fig. 1 shows a fragment of the axially symmetric numerical model constructed. The domain of computation included a steel ball 50 mm in diameter placed in a 125-mm-dia. cylindrical container filled with water. The distance from the surface of the ball to the bottom of the container was 100 mm; that to the top edge of water, 50 mm.

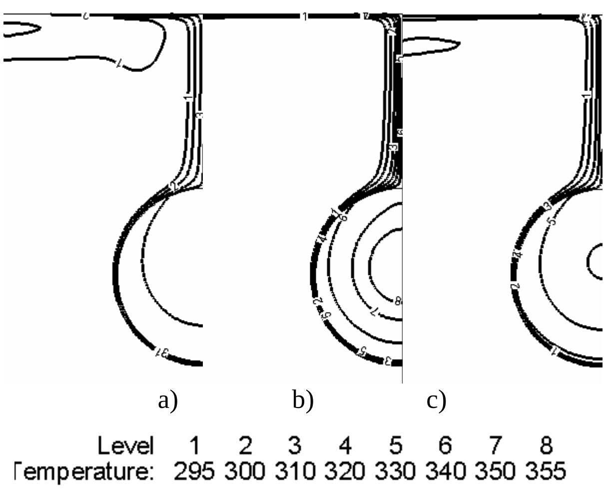


Fig. 1. Fragment of the computational model with isotherms for various instants of time: (a) 20 s, (b) 40 s, (c) 60 s.

All computations were carried out on an orthogonalized computational mesh including around 52 000 rectangular cells. Better to resolve the near-wall region and the region near the symmetry axis, the cells were made to concentrate toward the surface of the ball, both on the inside and the outside, and also toward the symmetry axis and the walls of the container. With the mesh constructed, the time it took a computer equipped with a Model AMD 2200+ processor to compute a second of real time amounted to 4.2 hours.

At the side and bottom surfaces of the container there were laid down boundary conditions the type of a "wall"; i.e., no-flow and adherence conditions, and at the top boundary of water, the no-flow condition. The dependence of the properties of water on the temperature T (in Kelvins) was introduced by means of linear interpolation. The density of water was described by the relation

$$\rho = 998.4 + (965.2 - 998.4)\,\Delta T(T),$$

its kinematic viscosity,

$$\nu = (1.0 + (0.322 - 1.0)\,\Delta T(T))\,1.0e - 006,$$

and the Prandtl number,

$$\nu = 6.94 + (1.94 - 6.94)\,\Delta T(T),$$

where $\Delta T(T) = (T - 293.0)/70$. Kelvin

B. Computation Results

B1. Hot ball

Fig. 1–3 present the results of numerical modeling of the flow arising near the walls of a ball heated to 368 K and immersed in cold water with a temperature of 293 K. Fig. 1 shows isotherms for various instants of time and Fig. 2, the results of calculation of the boundary liquid layer thickness δ as a function of the azimuthal angle α measured from the bottom point of the ball surface.

Fig. 3 shows the time dependence of the ball surface temperature at various points. The point p1 is the bottom point of the ball (180°), the point p2 is located at α = 135°, the point p3, 45°, and the point p4 is the top point of the ball (0°). As can be seen from the plot, the cooling of the ball at its top part takes its course much slower than at the bottom. This is explained by the fact that the top part of the ball is washed by liquid that has already got heated, and hence heat withdrawal at the top is weaker than at the bottom, the heat conductivity of steel being insufficient to ensure instantaneous temperature equalization throughout the bulk of the ball.

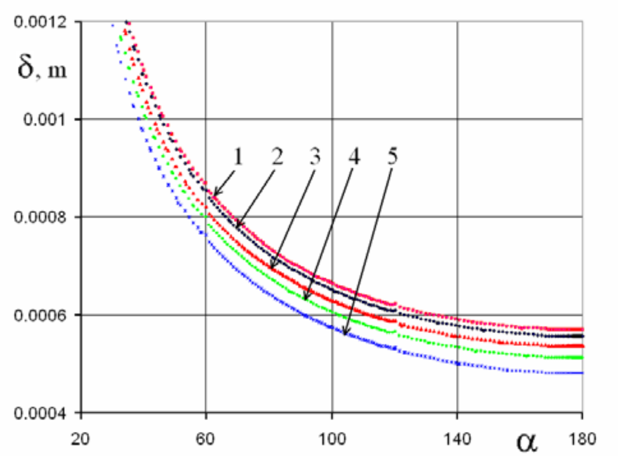


Fig. 2. Boundary layer thickness as a function of azimuthal angle α

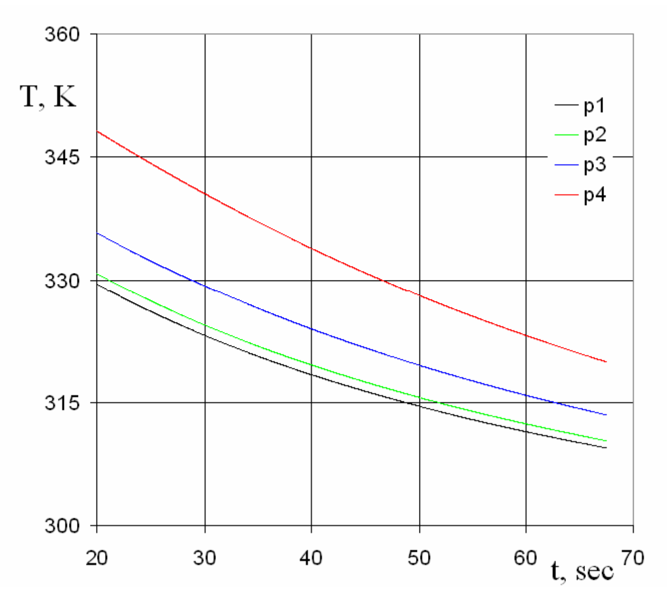


Fig. 3. Time dependence of the surface temperature of the ball at its various points

B2. Cold ball

Presented below are the data calculated for the flow arising near the walls of a cold ball (293 K) immerse in water heated to a temperature of 343 K.

Fig. 4 shows ball isotherms for various instants of time. One can see that the flow pattern here is identical to that observed in the case of hot ball, accurate to within the flow direction. Accordingly, by analogy with the preceding case, a small recirculation zone is also present here near the bottom point of the ball, whereat it warms up somewhat slower than at the top.

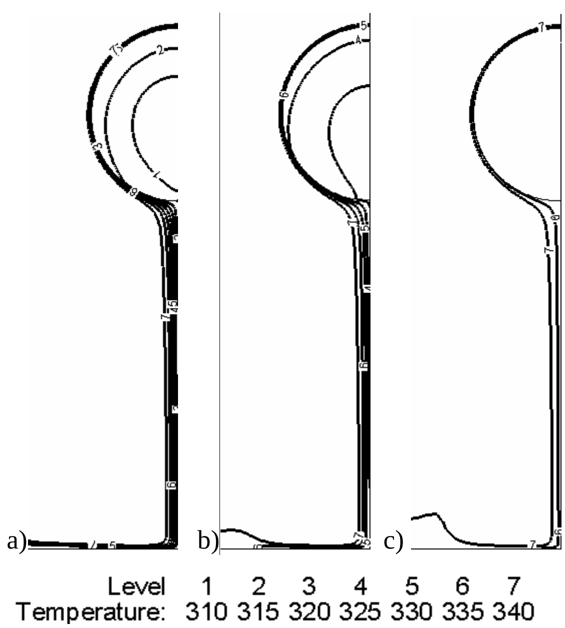


Fig. 4. Ball isotherms for various instants of time: (a) t = 30 s, (b) t = 90 s, (c) t = 120 s

Fig. 5 presents the azimuthal angle dependence of the thickness (in meters) of the boundary layer along the ball surface at various instants of time. From top to bottom, respectively, at t = 20, 40, 60, 80, 100, and 120 seconds. The border of the boundary layer is taken to be the line with T = 340 K.

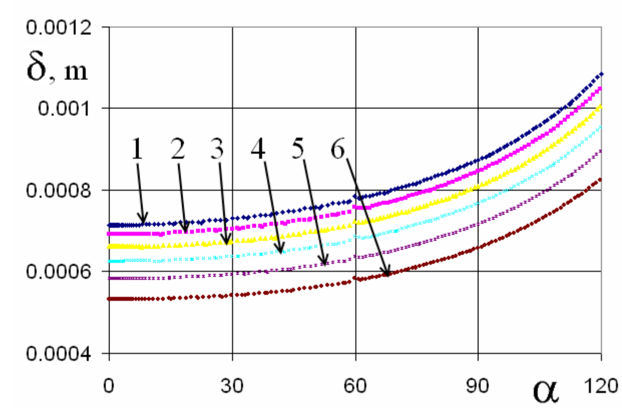


Fig. 5. Thickness of the boundary layer along the ball surface as a function of the azimuthal angle at various instants of time

Fig. 6 shows time variation plots for the surface temperature of the ball at various points. Here, as in Fig. 4 for the hot ball, the point p1 is the bottom point of the ball located at an angle of 180°, p2 is at an angle of 135°, and p3, at an angle of 45°. The curve for the top point p4 of the ball is not shown in Fig. 6, for it practically completely coincides with the curve for the point p3.

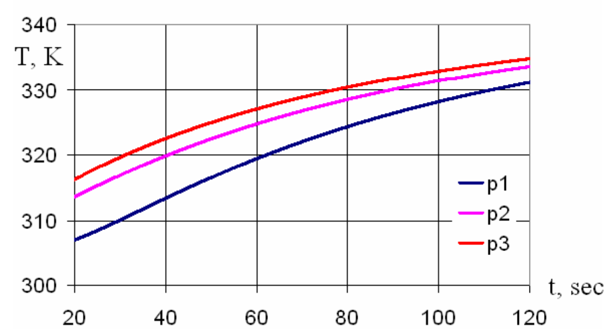


Fig. 6. Time dependence of the surface temperature at various points of the ball

Fig. 7 shows results of computer visualization of the boundary layer beneath a hot ball in water. The verticale scale is marked off in meters, and horizontal one in radians.

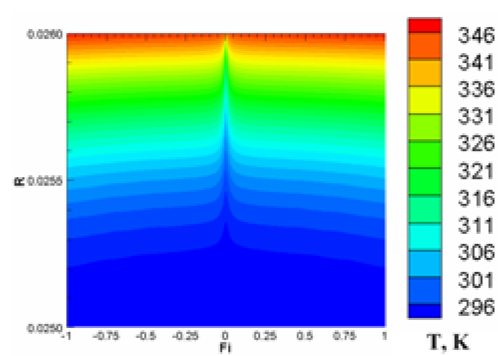


Fig. 7. Temperature distribution in water near heated ball

III. LASER REFRACTOGRAPHY PRINCIPLES

Laser refractography is based on the probing of the flow of interest with a structured laser radiation (SLR), digital recording of the refraction image (refractogram) obtained, and its computer processing with a view to determining the parameters of the flow [1]. In this measurement technique, use is made of an SLR formed by diffraction optical elements directly at the laser exit aperture [5]. Such method of forming SLR allows its high coherence to be maintained and ensures low beam divergence, thus enabling one to describe it in terms of geometrical (ray) and laser beam optics. Within the scope of this model, SLR is represented by families of rays that produce a surface in the form of a discrete set of planes, nested cylinders, cones, etc. The type of this surface forms the basis for the classification of SLR: it is either linearly-, or plane-, or else cylindrically- (conically-) structured laser radiation. The use of digital methods for the recording and processing of refractograms makes it possible to solve the inverse problem of reconstruction of the temperature or concentration inhomogeneity profile of the medium under study and quantitatively diagnose the inhomogeneous medium simultaneously with its visualization.

A. Temperature Field in Liquids

Note that all optical methods allow obtaining information only about the refractive index field n(x,y) that can subsequently be transformed by means of the appropriate calculations into the temperature field T(x, y), or into the field of some other parameter of the liquid of interest. In combined heat- and mass-transfer processes, the variation of the refractive index depends on two quantities in accordance with the relation

$$dn = (dn/dT)dT + (dn/dC)dC, \qquad (1)$$

where dn/dT is the derivative of the refractive index with respect to temperature and dn/dC, that with respect to concentration.

Even if the partial derivatives in equation (1) are known, in the general case the temperature and concentration fields are difficult to find from the measured refractive index field alone. One frequently tries to determine one of these fields by computation or non-optical measurement techniques. In addition, by selecting the appropriate working medium, one can satisfy the relation

$$(dn/dT)\Delta T >> (dn/dC)\,\Delta C, \qquad (2)$$

where ΔT and ΔC are the greatest temperature and concentration differences, respectively, for example, between the temperature and concentration values on a wall and in the external flow. In the case of nonstationary problems, use can be made of the fact that the two processes run at different rates, for in a liquid medium the heat conductivity is much higher than the diffusion coefficient.

The centigrade temperature dependence of the refractive index of water for 0.6328 μm laser radiation is given by the formula [1]

$$n(T) = 1.3328 - 0.000051T - 0.0000011T^2. \qquad (3)$$

B. SLR Refraction in Plane Inhomogeneous Media

B1. Structured Laser Radiation Sources

Structured laser radiation sources are continuous-wave semiconductor lasers equipped with diffraction optical elements (DOEs). Fig. 8 presents typical forms of laser beams produced by DOEs.

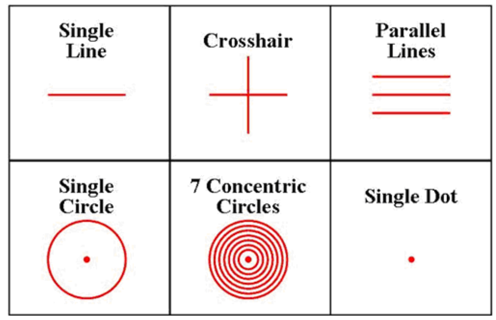


Fig. 8. Types of structured laser radiation

When the properties of the medium under study vary slowly enough as a function of coordinates, the propagation of laser beams can be described in terms of the geometrical optics approximation [1]. In that case, the beam for structured laser radiation of any type should be represented in the form of a suitable family of rays.

B2. Calculation of Refractograms for Plane Beams in the Geometrical Optics Approximation

Fig. 9 shows the trajectory of a ray propagating through an optically inhomogeneous medium whose refractive index varies only in one, vertical, direction. The ray is incident on the medium at an angle of θ1 at the point with the coordinate x_{in} and leaves the medium at the point x_{out} at an angle of θ_2. Knowing the law governing the variation of the refractive index, n(x), and the parameters of the incident ray, one can determine the parameters of the outgoing ray by the following formulas:

$$\sin\theta_2 = \sqrt{\frac{n^2(x_{\text{out}}) - n^2(x_{\text{in}}) + n_{\text{in}}^2 \sin^2\theta_1}{n_{\text{out}}^2}} \qquad (4)$$

$$l = \int_{x_{\text{out}}}^{x_{\text{in}}} \sqrt{\frac{n^2(x_{\text{in}}) - n_{\text{in}}^2 \sin^2\theta_1}{n^2(x) - n^2(x_{\text{in}}) + n_{\text{in}}^2 \sin^2\theta_1}}\,dx\,.$$

These formulas also allow one to solve the inverse problem of finding the law of variation of the refractive index of the medium from the known (measured) parameters of the incident and outgoing rays.

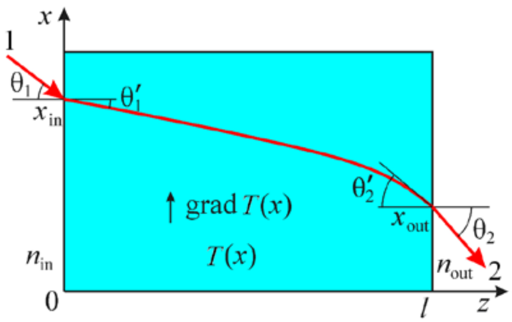


Fig. 9. Ray trajectory in a plane layered medium with a decreasing refractive index: 1 – input ray, 2 – output ray

Fig. 10 illustrates as an example the calculation of ray trajectories in an optically inhomogeneous medium. The calculation was carried out using geometrical optics formulas (4) [1].

Fig. 11 illustrates experimental laser beams trajectory below heated bal in cooled water: 1 – heated ball, 2 – laser beam, (a) – starting position, (b) – 3 sec after ball lowering in liquid, (c) – 10 sec after ball lowering in liquid.

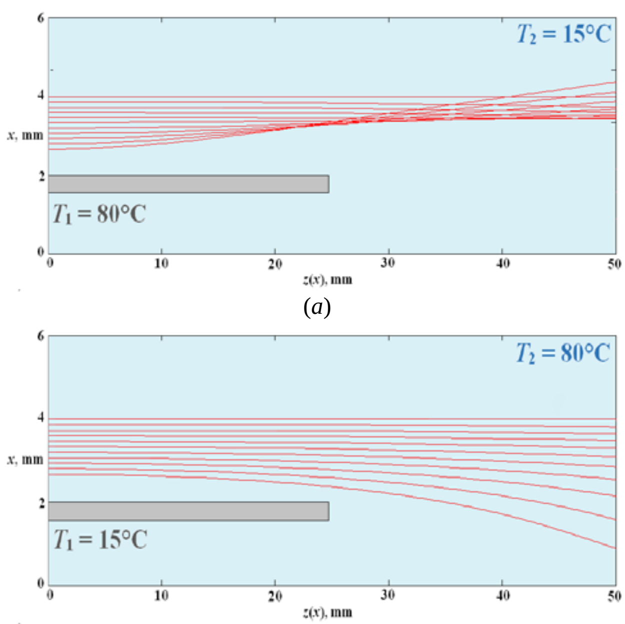
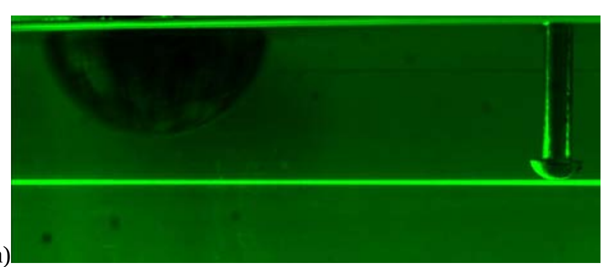


Fig. 10. Ray trajectories in a plane layered medium: (a) – heated plate, (b) – heated water



a)

b)

c)

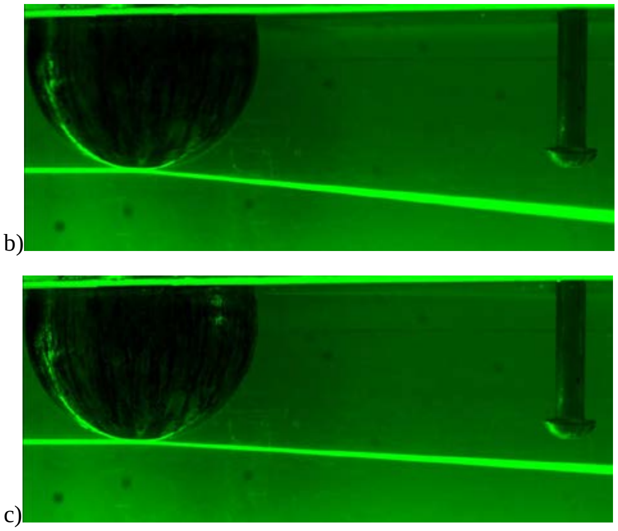


Fig. 11. Ray trajectories below heated ball: (a) – starting position, (b) – 3 sec after ball lowering in liquid, (c) – 10 sec after ball lowering in liquid

Fig. 12 shows projections of plane laser beams passing under a hot ball placed in cold water.

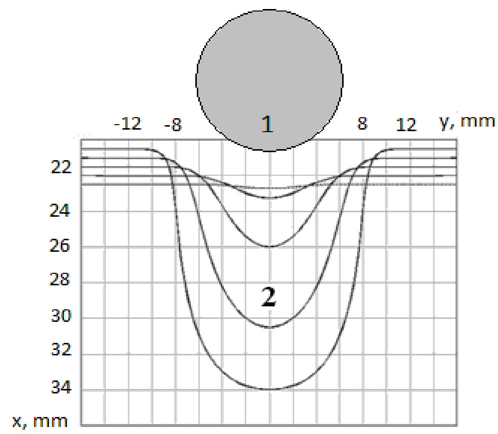


Fig. 12. Simulated 2D-refractograms of plane laser beams in a spherical inhomogeneous medium:
1 – heated ball in cooled water, 2 –refractograms

B3. Wave Model of Direct Shadowgraph Refraction Images Under Substantial Refraction Conditions

In a number of practical cases, for example, when it is necessary to measure the intensity of a field, the ray model proves invalid, and so use should be made of wave models.

The wave field of a laser beam of wavelength λ and wave number k, which have passed through an optical inhomogeneity with a specified continuous variation of the refractive index, n = n(x, y, z), can be described in terms of the Kirchhoff integral or by using the spectral approach [6], [7].

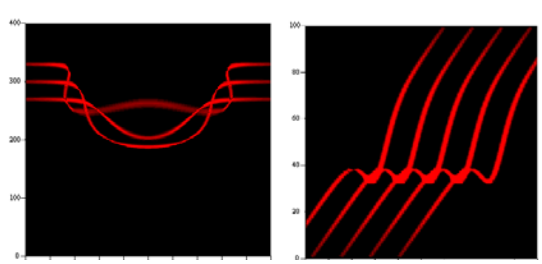
Consider a most vivid case of one-dimensional inhomogeneity where subject to probing is a layered medium with the refractive index n(x, y). In this case, the wave field A(x, y) of the beam observed in a direct shadowgraph image comprises a sum of wave fields corresponding to the transfer equations for the rays coming to the given point of observation with the coordinates (x, y):

$$A(x,y,z)=\sum_{j=1}^{J}\frac{A_0(\xi_j(x),y)}{\sqrt{1+z\frac{d^2\Psi}{d\xi^2}}}\cdot \exp\left[ik[z\sqrt{1+(\frac{d\Psi}{d\xi})^2}+\Psi(\xi_j(x))]\right], \quad (5)$$

where $\Psi = \Psi(\xi, \eta)$ is the eikonal directly at the exit from the medium, its values, as well as the values of its derivatives, being calculated in a set of stationary points ξ_j corresponding to the exit points of the rays coming to the point of observation with the coordinate x; the coordinate z specifies the distance between the plane of exit of the rays from the medium and the plane of observation (screen). The quantity $\xi_j(x)$ and these values are added together if there are several rays coming to the point of observation. Expression (5) correctly describes the wave field if the distance between the stationary points is not smaller than the characteristic size of the first Fresnel zone, $\Delta\xi=\sqrt{\lambda z}$. In that case, the relative measurement error for the field intensity of the direct shadowgraph image is no more than 10 %, except for the caustic region. The position of the caustic can be found such that

$$1+z_s\frac{d^2\Psi}{d\xi^2}=0 .$$

Fig. 13 shows theoretically calculated refractive images for plane beams. Figure 11a shows a calculated refractive image in the case of cylindrical temperature stratification that can be implemented in experiment as a boundary layer at a heated cylinder in cold water. The temperature difference at the boundary layer is 50 ^{0}C, and the characteristic dimension of the layer is 1 mm. Probing is performed with a set of three plane laser beams. Figure 11b shows a theoretically calculated refractive image in the case of planar density stratification that can be implemented experimentally as the boundary layer between two liquid layers. The probing of the horizontal layer (10 mm in thickness) is carried out with a set of five laser sheets. The density of the bottom layer is 1033 kg/m^3 and that of the top one, 1000 kg/m^3.



(*a*) (*b*)

Fig. 13. Theoretically calculated refractograms for (a) three beams passing under a hot ball in cold water and (b) five beams in the diffuse layer of a two-component liquid

IV. EXPERIMENTAL STUDIES INTO THE REFRACTION OF SLR

A. *Schematic Diagram of a Refractographic System*

Fig. 14 presents a block diagram of a laser refractographic system. The radiation of laser 1 is converted by the optical system containing diffraction optical elements (DOEs) 2 into structured laser radiation 3 passing through optically inhomogeneous medium 4 formed by a liquid containing heated or cooled bodies and produces a 2D refractogram on translucent screen 5. The refractogram image is recorded by digital photo camera 6 and inputted in computer 7, where it is processed with special software 8. The processing of 2D refractograms makes it possible to diagnose the optical inhomogeneity of interest in the given medium, which caused the laser beams to refract; i.e., to obtain information about the temperature distribution in the flow under study. The pictures in the bottom row illustrate the stages of formation of the refractogram from a narrow laser beam, along with the plot obtained for the temperature dependence in the boundary layer.

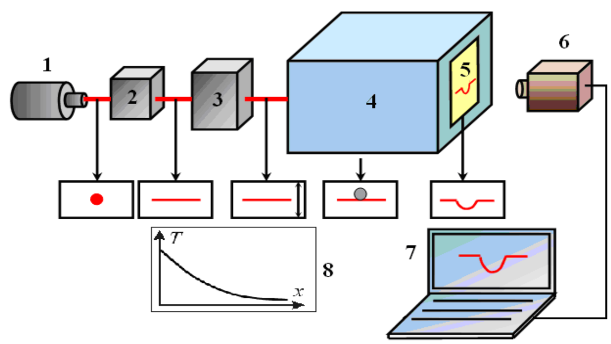


Fig. 14. Schematic diagram of a laser refractographic system: 1 – laser; 2 – DOEs; 3 – laser beam scanning block; 4 – liquid under study with a hot ball; 5 – diffuse screen; 6 – digital photo camera; 7 – personal computer with refractogram processing software; 8 – temperature plot

B. *Experimental Investigations*

The theoretical and experimental fundamentals of laser refractography are described in sufficient detail in the monograph [1]. The present-day optical techniques allow solving, in most cases, both the direct laser refractography problem, namely, to determine refraction images for an arbitrary type of structured radiation and analytically or numerically specified temperature field in the medium of interest [1], [5], and, in some cases, the inverse problem of finding the temperature field gradient in a liquid from the measured parameters of refractograms [1], [4].

Laser refractography techniques were used to investigate temperature distributions in laminar boundary liquid flows in the vicinity of cooled or heated bodies of various shapes using various types of SLR: narrow and wide laser beams, cylindrical beams, and cruciform beams [1], [5], [8].

Typical shapes of refractograms for heated bodies in cold water are presented in Table 1.

Table 1. Library of refractograms of a plane laser beam near heated bodies

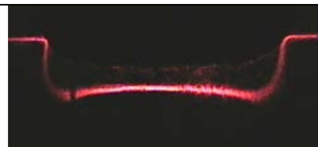
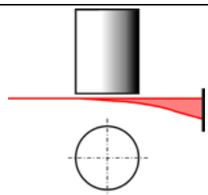
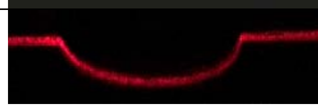
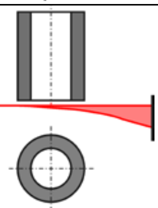
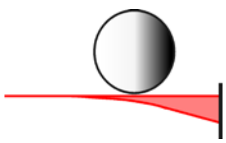
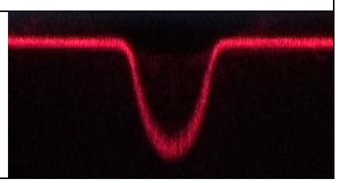
№	Shape of the object and its probing direction	Shape of refractograms for heated bodies in cold water
1		
2		
3		
4		

Fig. 15 shows the shape of a refractogram for a cold body in heated water. The laser sheet passes over the cold body.

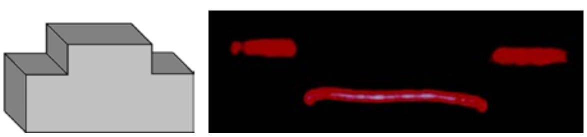


Fig. 15. Refractogram for cold body in heated water

V. Algorithm for the Reconstruction of the Temperature Distribution in a Liquid Near Heated Bodies

To determine the temperature of a liquid in the vicinity of heated bodies, a special algorithm was worked out for the processing of experimental refractograms and a method developed for comparing them with their theoretical counterparts (Fig. 16) [9].

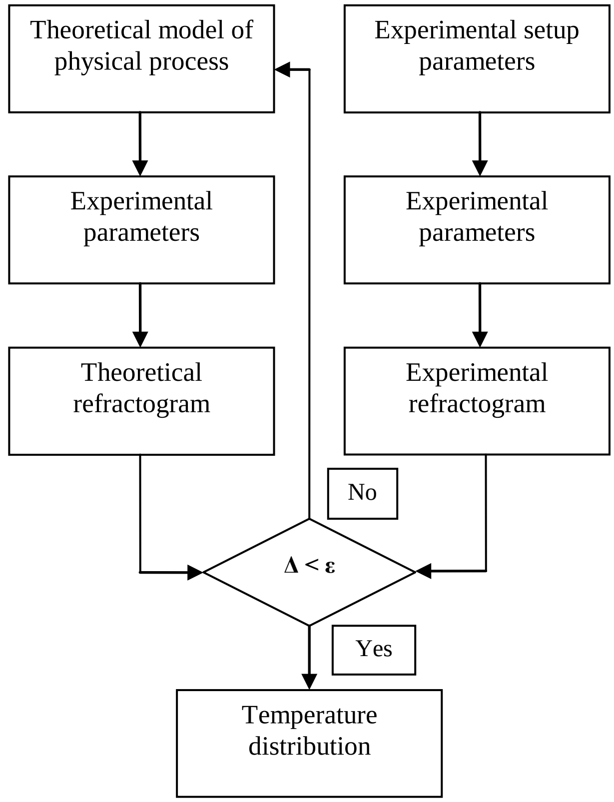
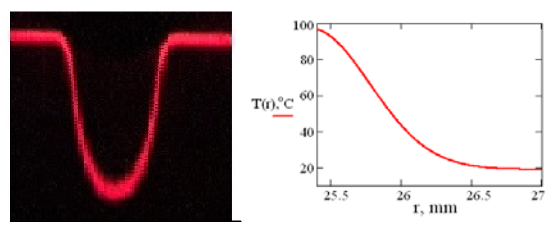


Fig. 16. Algorithm for comparing between experimental and simulated refractograms

By comparing refractograms one can determine temperature fields in boundary liquid layers; i.e., acquire quantitative information.

Fig. 17 shows an experimental refractogram for a heated ball 50 mm in diameter immersed in cold water and the reconstructed temperature profile in the boundary water layer.



(*a*) (*b*)

Fig. 17. Experimental refractogram processing: (a) – experimental refractogram, (b) – reconstructed radial temperature profile

VI. 3D Refractograms

One of the merits of laser refractography is the possibility it offers to obtain three-dimensional refractographic images [10]-[16]. Refractograms obtained with the aid of structured laser radiation are always three-dimensional. However, their images displayed on a screen are two-dimensional. Fig. 18 presents a theoretical 3D refractogram for a cold ball placed in hot water, and Fig. 19, that for a hot ball placed in cold water.

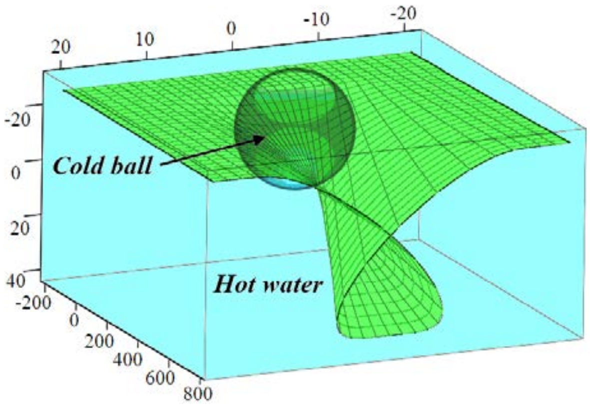


Fig. 18. 3D refractogram for a cold ball in hot water: T = 90 ºC, ΔT=80 ºC

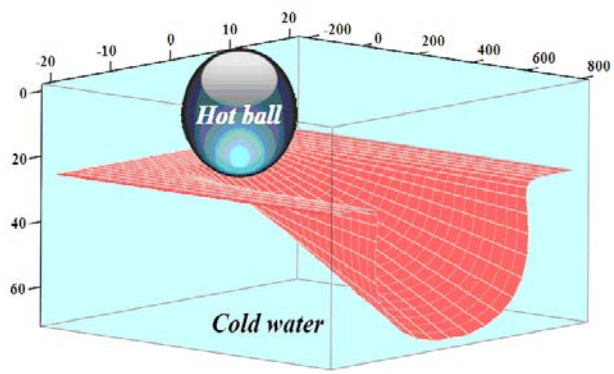


Fig. 19. 3D refractogram for a hot ball in cold water: T = 20 ºC, ΔT = 65 ºC

To obtain experimental 3D refractograms, the authors suggested using the phenomenon of scattering of structured laser radiation by fine particles specially introduced into the liquid under study (Fig. 20).

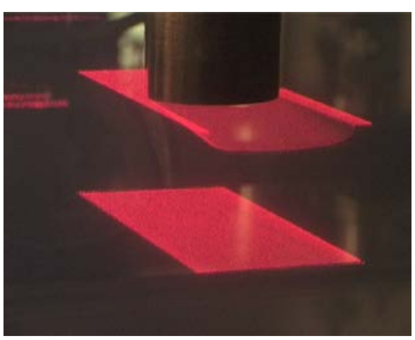


Fig. 20. Experimental 3D-refractogram for two laser sheets placed under a heated metal cylinder at different distances from its the bottom end face

VII. Visualization of Nonstationary Natural Convection Processes Taking Place Over a Hot Ball Placed in Cold Water

Numerical computations for natural convection occurring in the vicinity of a hot metal ball placed in cold water show but a single ascending current. Such a flow is observed to take place only at low temperature gradients in the boundary layer. Where the temperature gradients are high, the current over the ball becomes nonstationary and takes on the form of thermics that can readily be visualized by the laser refractography techniques. To monitor nonstationary ascending currents over a heated metal ball immersed in cold water, an experimental system was designed that implemented the method of double-viewpoint probing of the region of interest with two mutually perpendicular sheets of laser light allowing nonstationary convection currents (thermics) to be visualized by the laser radiation scattered by them [1].

Fig. 21 presents a block diagram of the experimental system implementing the double-viewpoint method for monitoring nonstationary convection currents over a hot metal ball cooling in cold water.

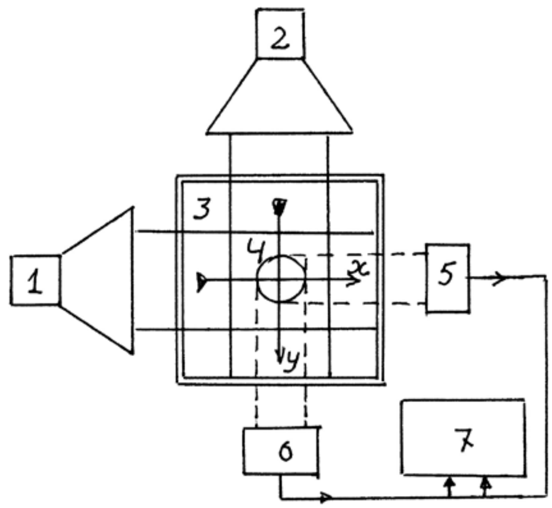


Fig. 21. Block diagram of the double-viewpoint laser refractographic system (top view): 1 – first laser module; 2 – second laser module; 3 – water-filled cell; 4 – metal ball; 5 and 6 – digital video cameras; 7 – personal computer.

The system uses two laser modules that form two plane laser beams 51 mm across propagating in orthogonal directions in a single horizontal plane in the immediate vicinity of the surface of a hot metal ball placed in the cell filled with cold water containing fine particles to scatter laser radiation. To record the images of the laser beams in scattered light, use is made of two identical digital video cameras arranged opposite to the propagation directions of their associated beams at an angle of 7.5° to their surfaces.

Subsequently to make the refractographic images produced by the two laser beams register, use is made of a needle fixed at a distance of 1.1 mm from the ball (exactly above the top point of its surface), with reference to which the probing beams can be directed as necessary.

The experimental system and the method of its employment in a thermophysical experiment allowed us to obtain refractograms of alterations of two mutually perpendicular plane laser beams probing a region with nonstationary convection currents (thermics) over a hot ball. They are presented in Fig. 22. It can be seen from the photographs that the position of the thermics is of random character.

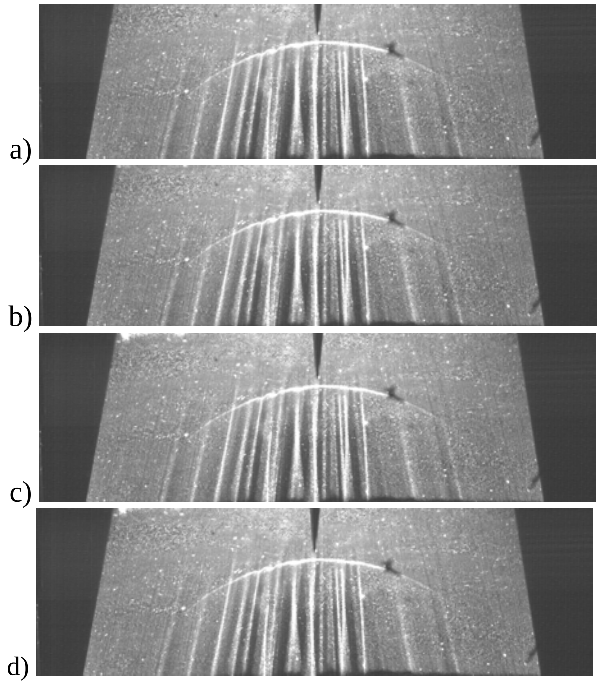


Fig. 22. Double-viewpoint refractograms of thermics for various instants of time: (a) x-axis direction, 3047 ms, 73.4 °C; (b) y-axis direction, 3047 ms, 73.4 °C; (c) x-axis direction, 4063 ms, 72.4 °C; (d) y-axis direction, 4063 ms, 72.4 °C

Note that numerical calculations for natural convection near the ball, made with the aid of professional computer programs, give only a stable convection flow picture.

The laser refractographic technique considered is inapplicable to turbid media featuring strong scattering and only limitedly applicable in cases where refraction is weak, for example, in gas media, for it requires that the distance from the object under study to the screen should be increased substantially, which is not always practicable under laboratory conditions.

VIII. Other Fields of Application of Laser Refractography

A. Visualization of the Mixing of Several Liquids and Determination of Their Mixing Time

The laser refractography measurement technique has a great many other applications.

Described in [1], [20] is a refractographic system intended for the visualization of the process of mixing of two liquids and the determination of their mixing time. It used structured laser radiation in the form of two plane-structured beams crossing at right angles from a 0.542-µm argon laser beam and a 0.6328-µm helium-neon laser. The processing of the laser refractograms obtained made it possible to determine mixing parameters and mixing time for the two liquids.

B. Determination of the Diffuse Layer Parameters in a Two-Layer Liquid

Laser rerfractography is a technique providing not only for qualitative, but also for quantitative visualization of optically inhomogeneous flows. This end can be attained if one has at one's disposal a theoretical model of the process of interest, obtained by solving the pertinent thermophysical problem. Fig. 23 shows comparison between an experimental refractogram and its theoretical countrparet and the reconstructed refractive index distribution profile and gradient solarity in the diffuse layer.

Other applications of laser refractography technique for diagnostics of boundary layers presented in the works [10], [17], [18] are 3- and 4-dimensional laser systems for the computer modeling and experimental studies of diffuse layer characteristics.

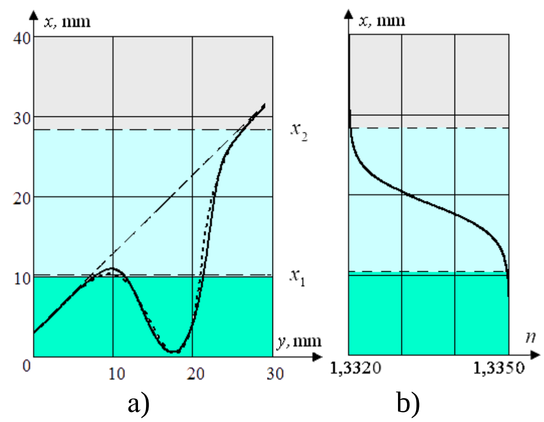


Fig. 23. Computer processing of 2D-refractograms in the diffuse layer: a) comparison between an experimental refractogram and its theoretical counterpart, b) the reconstructed refractive index distribution profile

C. Laser Beam Propagation in the Medium with Acoustical Wave

It was analyzed in [21] and a two-color refractographic system for the visualization of thermal processes taking place near a fuel element is described in [19].

IX. Conclusion

A laser-computer refraction technique is developed for qualitative and quantitative visualization of physical processes occurring in the vicinity of hot or cold bodies placed in transparent liquids. This technique is applicable to:

– verification of numerical methods for computing the parameters of physical processes in liquids

– visualization of temperature gradients in thin boundary layers near hot or cold bodies placed in transparent liquids;

– determination of the heating and cooling times of various bodies in liquids;

– determination of the setting time of laminar and turbulent convection regimes;

– note that numerical calculations for natural convection near the ball, made with the aid of professional computer programs, give only a stable convection flow picture.

The laser refractographic technique considered is inapplicable to turbid media featuring strong scattering and only limitedly applicable in cases where refraction is weak, for example, in gas media, for it requires that the distance from the object under study to the screen should be increased substantially, which is not always practicable under laboratory conditions.

References

[1] B. S. Rinkevichyus, O. A. Evtikhieva, I. L. Raskovskaya, *Laser refractography*. N-Y: Springer. 2011. 201 p.

[2] G. S. Settles, *Schlieren and shadowgraph techniques: visualizing phenomena in a transparent media*. Berlin: Springer-Verlag, 2001. pp. 376.

[3] Program package Fluent (ANSYS). http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+Fluent.

[4] Yu. F. Kashkin, A. E. Konovalov, S. Yu. Krasheninnikov, D. A. Lyubimov, D. E. Pudovikov, V. A. Stepanov, “Experimental and Numerical Investigation of Separated Flows in Subsonic Diffusers,” *Fluid Dynamics*, vol. 44, No. 4, p. 555, 2009.

[5] I. L. Raskovskaya, B. S. Rinkevichyus, A. V. Tolkachev “Structured Beams in Laser Refractography Applications,” In books: *Laser Beams Theory. Properties and Applications.* New-York: Nova Science Publishers. Inc., 2011, pp.399-414.

[6] I. L. Raskovskaya, “Refractometry of optically inhomogeneous media based on recording the position of caustics using structured laser radiation,” *Optoelectronics, Instrumentation and Data Processing*, 50 (5), pp. 505-510, 2014.

[7] I. L. Raskovskaya, B. S. Rinkevichyus, A. V. Tolkachev, “Diagnostics of convective processes in boundary layer of liquid by laser refractography,” *EPJ*, vol. 83, No. 6, pp. 1149-1156, 2010.

[8] I. L. Raskovskaya, B. S. Rinkevichyus, A. V. Tolkachev, E. S. Shirinskaya, “Refraction of cylindrical laser beam in temperature boundary layer,” *Optics and spectroscopy*, vol.106, No. 6, pp. 1016-1022, 2009.

[9] V. T. Nguen, I. L. Raskovskaya, B. S. Rinkevichyus, “Algorithms of quantitative diagnosis of optical inhomogeneities by laser refractography,” *Measurement techniques*, No.4, pp. 24-28, 2009.

[10] B. S. Rinkevichyus, I. L. Raskovskaya, A. V. Tolkachev, “Laser refractography – the new technology of the transparent heterogeneities quantitative visualization,” presented at the ISFV13 - 13th International Symposium on Flow Visualization FLUVISU12 - 12th French Congress on Visualization in Fluid Mechanics, Nice, France, July 1-4, 2008, Paper 085, P.1-4.

[11] B. S. Rinkevichyus, O. A. Evtikhieva, M. V. Yesin, I. L. Raskovskaya, A. V. Tolkachev, “3D-laser refractography – new chapter of information optics,” *Journal of Physics: Conference Series,* 206 (2010) 012010.

[12] M. V. Yesin, I. L. Raskovskaya, B. S. Rinkevichyus, A. V. Tolkachev, “Three-dimensional refractograms and its applications for diagnosis of gradient inhomogeneities,” *Radiotechnics and electronics*, vol. 57, No. 4, pp. 485-491, 2012.

[13] I. L. Raskovskaya, “Laser refractive tomography of phase objects,” *Quantum Electronics*, vol. 43, No.6, pp.554-562, 2013.

[14] B. S. Rinkevichyus, I. L. Raskovskaya, A. V. Tolkachev, “3D-laser refractography,” In Book of abstracts. "*18th International Conference on Advanced Laser Technologies*". 11 – 16 September 2010. Radboud University Nijmegen. The Nederlands. P.135.

[15] M. V. Yesin, B. S. Rinkevichyus and A. V. Tolkachev, “3D Images Reconstruction of the Objects with Indistinct Boundaries,” *Proc. SPIE 4900 Part Two* 1140-1146. 6/2009.

[16] M. V. Yesin, I. L. Raskovskaya, B. S. Rinkevichyus, and A. V. Tolkachev, “3D-Laser Refractograms in measuring technique,” *Optoelectronics, Instrumentation and Date Processing*, vol.48, No.3, pp.219-226, 2012.

[17] I. L. Raskovskaya, B. S. Rinkevichyus and A. V. Tolkachev, “Laser refractography of optically inhomogeneous media,” *Quantum electronics*, vol 37, No. 12, pp. 1176-1180, 2007.

[18] A. V. Krikunov, I. L. Raskovskaya, B. S. Rinkevichyus, “Refraction of an astigmatic laser beam in a transition layer of a stratified liquid,” *Optics and Spectroscopy*, vol.111, No.6, pp.956-961, 2011.

[19] B. S. Rinkevichyus, M. V. Yesin, I. L. Raskovskaya, A. V. Tolkachev, “Laser refractographic system for visualization of physical processes in liquid,” Patent No. 105433 from 10.06.2011. БИ-10-2011. МПК-601F 1/00.

[20] M. V. Yesin, O. A. Evtikhieva, S. V. Orlov, B. S. Rinkevichius, A.V. Tolkachev, “Laser refractometral method for visualization of liquid mixing in twisted flows,” *CD Rom Proceedings of 10-th International Symposium on Flow Visualization*, Kyoto, August 26-29, 2002, Paper No. F037.

[21] I. L. Raskovskaya, “Laser beam propagation in the medium with acoustical wave,” *Radiotekhnika i elektronika*, vol.49, No.11, pp.1382-1389, 2004.