Diagnostics of Boundary Effects in Fluids using Structured Laser Radiation

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Abstract. Considered in this paper is the principle of a novel measurement technique – laser refractography – used to diagnose near-wall and boundary layers developing in liquids as a result of temperature or concentration gradients occurring therein. This technique is based on the probing of the transparent liquid of interest with a structured laser radiation produced with the aid of diffraction optical elements and the digital recording and processing of the refraction patterns obtained. The propagation of laser rays in a flat near-wall layer of a liquid with a negative refractive index gradient corresponding to the case of heated water moving along a cold wall is numerically modeled in the geometrical optics approximation, and the propagation of an inclined laser sheet of light in a diffusion layer of a two-layer liquid comprising a bottom layer of saline water and a top layer of fresh water is analyzed. Refractograms are obtained while varying the refractive index of the bottom layer and while varying the inclination angle of the laser sheet of light. 2D cylindrical laser beam refractograms are for the first time obtained for a diffusion liquid layer while varying the position of the beam and while varying the position of the diffusion layer center. These refractograms demonstrate the possibility of solving the inverse problem. A description is presented of an experimental laser refractography setup intended for investigations into boundary liquid layers near heated or cooled bodies. The setup uses visible semiconductor lasers up to 25 mW in power, an assembly of optical elements to produce plane (sheet) and cylindrically structured laser radiation, a test cell for the liquid of interest, a digital photo camera to record the refraction patterns observed on a ground glass screen, and a personal computer to record and process the digitally recorded refraction patterns. Also presented are exemplary experimental 2D- and 3D-refractograms confirming the results of the calculations performed. An experimental investigation is conducted into the diffusion layer arising at the boundary between saline and fresh water. A special program is used to determine salinity distribution in the diffusion layer. The background oriented schlieren (BOS) technique is used to study the evaporation of various liquid droplets from a horizontal surface. A 3D image of a water droplet is obtained.

1. Introduction

Laser measuring techniques are widely use in our time for flows diagnostics [Albrecht, 2003, Karasik, 1995, Rinkevichyus, 1998, Settles, 2001]. The purpose of work is developing experimental methods of diagnostics fluids flows through a structured laser radiation, obtained by means of diffractive optical elements and structured screens. Created experimental setups are used to study the effects in stratified fluids, and the near-wall effects in micro scale. Presented a new information measurement technology – laser refractography (LR) (Rinkevichyus,2011) based on the refraction of a structured laser radiation (SLR), obtained by means of diffractive optical elements (DOE) [Raskovskaya, 2011, Kuzmicheva, 2012]. Applying modern laser technology and computer technology can be used to visualize the flow through refraction effects on qualitatively new level and to realize their diagnostics in quantity. A new step in the development of LR has been made in connection with the development of techniques of visualization and processing of 3D-refractogram. 3D-refractogram is a picture of three-
dimensional surface formed by the refraction of the SLR rays in media. Digital methods of refractogram recording and processing allows to solve the inverse problem of reconstructing the profile of stratification in the fluids and carry out a quantitative diagnostics with visualization simultaneously.

Background Oriented Schlieren (BOS) visualization system consists of a specially designed background screen, on which a video camera is focused. Investigated flow is between the screen and the video camera. Randomly structured background of natural origin is used as the screen, what is important for the study of gas flows. The resulting images of the screen which are distorted under the influence of flow transmitted in real-time to the computer, where with the help of a special software the stratification profile flow is recovering. BOS allows to receive a two-dimensional and a three-dimensional fields of stratification flow.

Used methods are complementary, and the LR method best suited for the study of processes in the fluids in which refraction is strong, and the BOS is most often used in full-scale experiment, including the study of gas flows. Moreover, both methods are suitable for visualization and near-wall micro flows.

2. Laser Refractography Principles

Consider the propagation of a laser ray in a single-layer plane-structured medium (Fig. 1). The incident ray falls onto the interface between two media: the external, optically homogeneous medium characterized by the refractive index $n_{\text{in}}$ and an inhomogeneous medium with a refractive index of $n(x)$. The angle of incidence is $\theta_1$, and the entrance point is at $x_1$. The ray emerges from the inhomogeneous medium at the point $x_\text{out}$ at an angle of $\theta_2$ into a medium with a refractive index of $n_{\text{out}}$. The propagation of rays in such media has been considered in the monograph [Rinkevichyus, 2011] and is described by the relations

$$ l = \int_{x_\text{in}}^{x_\text{out}} \sqrt{\frac{n_\text{out}^2(x_\text{in}) - n_{\text{in}}^2 \sin^2 \theta_1}{n(x) - n_\text{in}^2 + n_{\text{in}}^2 \sin^2 \theta_1}} \, dx, \quad (1) $$

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

![Fig. 1. Propagation of a laser ray in a single-layer inhomogeneous medium.](image)
Equation (1) makes it possible to find the exit point of the ray, given the entrance point, the entrance angle, the length $l$, and the law governing the variation of the refractive index of the inhomogeneous medium. Equation (2) allows one to find the exit angle. Figure 2 illustrates the propagation of rays in a boundary layer of a medium with an exponential refractive index variation of form $n(x) = n_0(1 + \exp(-x/a))$ at $x > 0$ and at various ray incidence angles at the point $x = 0.025$ m; the layer parameter $a = 0.03$ mm, $n_0 = 1.330$. The analysis of the graphs allows one to conclude that, given the length and width of the medium, some rays fail to leave it through the rear vertical wall, which is necessary for staging the experiment.

The propagation of a ray in a diffusion liquid layer depends on the refractive index distribution therein (Fig. 3a). At present, there are several expressions describing this distribution. In [Raskovskaya, 2009], use is made of the tangential distribution described by the expression

$$n(x,y) = 0.5 \times (n_1 + n_2) + 0.5 \times (n_1 - n_2) \times \tanh[(x-x_s+a \times y)/h(x)],$$  \hspace{1cm} (3)

where $n_1$ is the refractive index of the bottom layer, $n_2$ is the refractive index of the top layer, $x_s$ is the center coordinate of the layer, $a$ is a coefficient accounting for the ray entrance point in the $x$-$y$ plane, and $h(x)$ is the layer parameter that in the general case depends on the coordinate $x$, which makes it possible to describe the asymmetric diffusion layer. The diffusion layer boundaries are determined such that $n(x_1) - n_1 = 10^{-5}$, $n_2 - n(x_2) = 10^{-5}$. The character of the refractive index distribution described by formula (3) is shown in Fig 3a.

Figure 3b shows the propagation of three laser rays in the diffusion layer of a two-layer liquid. The first ray propagates in straight lines in the optically homogeneous top layer, the second ray propagates in out-of-straight lines in the optically inhomogeneous diffusion layer, and the third ray propagates in straight lines in the optically homogeneous bottom layer.
Fig. 3. Propagation of laser rays in the diffusion layer of a two-layer liquid: (a) vertical refractive index distribution; (b) ray trajectories.

Figure 4 shows the trajectories of laser rays in the diffusion liquid layer for various entrance points. The diffusion layer parameters: length $L = 300$ mm, refractive indices $n_1 = 1.3460$ and $n_2 = 1.3320$; the refractive index distribution parameters: $h = 1$ mm, the center coordinate of the layer is $x_s = 50$ mm.

The analysis of the graphs shows that in the second case there occurs the formation of a caustic and no unique correspondence is observed between the exit and entrance coordinates of the rays.

Figure 5 presents theoretical 2D-refractograms for various refractive indices of the bottom liquid layer. The refractograms were calculated for conditions close to the experimental ones: the laser beam...
inclination angle $\alpha = 45^\circ$, the refractive index $n_1$ of the bottom liquid layer varying over the range 1.335–1.356, the refractive index of the top liquid layer $n_2 = 1.332$, refractograms observed on the inner wall of the cell at a distance of $L = 300$ mm, the diffusion layer center is at $x_s = 50$ mm, and the layer parameter $h = 1$ mm.

Figure 6 presents 2D-refractograms of a plane laser beam (laser sheet of light) at various inclination angles $\alpha$ and the following diffusion layer parameters: length $L = 300$ mm, refractive indices $n_1 = 1.3460$ and $n_2 = 1.3320$; the refractive index distribution parameters: $h = 1$ mm, the center coordinate of the layer is $x_s = 50$ mm.

![Fig. 5. Theoretical 2D refractograms for various refractive indices of the bottom liquid layer: 1 - $n_1=1.335$, 8 - $n_1=1.356$.](image)

![Fig. 6. 2D refractograms for the diffusion layer: 1 - $\alpha = 15^\circ$, 2 - $\alpha = 30^\circ$, 3 - $\alpha = 45^\circ$, 4 - $\alpha = 60^\circ$.](image)

Figure 7 presents theoretical cylindrical laser beam refractograms calculated under the following conditions: $n_1 = 1.3371, n_2 = 1.3310$, cell length $L = 150$ mm, distance from the cell to the screen $= 180$ mm, layer parameter $h = 1$ mm, layer center coordinate $x_s = 50$ mm, beam positions: first position $x = 58$ mm, second position $x = 50$ mm, third position $x = 40$ mm.

![Fig. 7. Theoretical cylindrical laser beam refractograms.](image)
The analysis of these graphs shows that the 2D refractograms of a cylindrical laser beam are very sensitive to the position of its center relative to the center of the layer, which allows the variation dynamics of the layer to be determined. By virtue of the fact that the rays constituting the cylindrical beam can concurrently pass through all the sections of the diffusion layer, 2D refractograms contain the entire information on the parameters of the layer.

3. Experimental Setup

To investigate near-wall temperature layers in liquids and diffusion layers of stratified liquids, use is made of the experimental setup whose schematic diagram is presented in Fig. 8.

Fig. 8. Schematic diagram of the experimental setup: 1 – laser, 2 – optical system, 3 – scanning system, 4 – medium under study, 5– diffuse screen, 6 – CCD camera, 7 – PC, 8 – refractogram processing.

The setup uses semiconductor laser 1 emitting radiation in the red or the green wavelength region. The radiation power amounts to 5–25 mW. The laser beam passes through diffraction element 2 that transforms the initial narrow laser beam into a structured laser radiation differing in shape, for example, plane, conical, or cross-shaped laser beams. To position these beams with respect to the object under study, use is made of scanning system 3 that allows these beams to be moved in two orthogonal planes. Temperature and concentration boundary layers in the vicinity of heated or cooled bodies, as well as diffusion layers, are investigated in glass cell 4 150 by 200 by 300 mm (WHL) in size. Two-dimensional refractograms are observed on diffuse screen 5 placed at a distance of 100–250 mm from the cell and recorded with digital camera 6 whose output is entered into personal computer 7. The computer processing of the refractograms by means of a special program yields information 8 about the parameters of the near-wall and boundary layers. The bottom row of images in the above figure illustrates the stages of transformation of the narrow laser beam into structured radiation and then into a 2D refractogram.

The experimental technique for studying various boundary temperature layers near heated or cooled bodies was described in detail in the monograph [Rinkevichyus, 2011]. Here we will dwell on the method of investigation of a diffusion layer in a stratified liquid comprising a bottom saline water layer and a top fresh water layer. The refractive indices of these layers were measured with an Abbe refractometer accurate to within 10^{-4}. The refraction of a plane beam in such a layer was studied earlier in [Krikunov, 2010].

4. Experimental Results

Figure 9 presents experimental 2D cylindrical beam refractograms obtained under the following experimental conditions: laser wavelength 0.652 µm, cell length \( L = 250 \) mm, \( n_1 = 1.3346 \), and \( n_2 = 1.3320 \). The distance between the exit wall of the cell and the screen was 150 mm.
Fig. 9 Experimental 2D refractograms of a cylindrical laser beam in a two-layer liquid for various positions of the center of the layer.

Fig. 10 Experimental 2D refractograms of a cylindrical laser beam in a two-layer liquid for various positions of the center of the beam.

The top three photographs correspond to a gradual lowering of the beam relative to the center of the layer, while the bottom ones, to a variation of the layer with the beam position remaining unchanged. The top refractograms show the invariability of the width of the diffusion layer, and the bottom ones, the possibility of measuring the amount of displacement of the layer.

5. 3D-Refractogram Recording

3D-refractograms were recorded by diffuse light with a digital photo camera [Rinkevichyus, 2010]. To this end, an additional 445 mm long water-filled cell with a refractive index of 1.3320 was placed at a distance of 73 mm after the cell containing the medium of interest. The pattern obtained (see Fig. 11a) is the refractogram image visible owing to the radiation scattered by the particles present in water. Figure 11b presents a theoretical 3D-refractogram obtained under the same conditions.
Fig. 11 – 3D-refractograms for boundary layer of salt stratified fluid: experimental (a) and simulated (b).

Experimental setup is designed and a detailed study of evaporation of various fluids by BOS is carried out [Skornyakova, 2004, Mikhalev, 2010]. Experimental setup consists of a structured screen, light source, a digital camera. Digital BOS image of droplet is processed by computer with help of special software. Figure 12 shows two images of the water droplet surface with volume of 0.1 ml. The droplet is evaporated from a glass surface in the time \( t = 34.93 \text{ sec} \). Figure 12a shows the result of cross-correlation processing of BOS images of the water droplet surface with the levels of correlation coefficient values. Figure 12b shows 3D-reconstructed image of the surface with approximation. On Figure 12b the center of the droplet surface has a gap.

Fig. 12 – Profile of a water droplet during evaporation at time \( t = 34.93 \text{ sec} \):
  a – the image of the droplet after processing BOS image, b – the three-dimensional view of droplet.

6. Computer Processing of 2D-Refractograms for Two Layer Liquids

Laser refractography 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.
Figure 13 presents the width of the diffusion layer ($\Delta h = x_2 - x_1$) as a function of its formation time. It can be seen that the layer becomes twice as wide in three hours. This relationship was obtained by comparing between experimental and theoretical refractograms and determining the top and bottom boundaries of the diffusion layer.

![Graph showing diffusion layer width as a function of time.](image)

**Fig. 13.** Diffusion layer width as a function of time.

Figure 14 shows comparison between an experimental refractogram and its theoretical counterpart and the reconstructed refractive index distribution profile and gradient solality in the diffuse layer.

![Comparison between experimental and theoretical refractograms and reconstructed refractive index distribution profile and gradient solality.](image)

**Fig. 14.** 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) gradient solality.

7. Conclusion

✓ The present-day stage of development of the refractive techniques for the diagnostics of optically inhomogeneous flows is characterized by the use of coherent light sources, novel optical elements, including DOE, and computer processing of refractive images.
✓ Laser refractography is the next step in the development of the refractive techniques that allows obtaining not only 2D, but also 3D refractograms that are more vivid and informative.
✓ Laser refractography is orientated not only towards visualizing inhomogeneities, but also towards getting quantitative information about optically inhomogeneous flows.
✓ Laser refractography can be used to diagnose two-layer liquids.
✓ Laser refractography can find application not only to the diagnostics of stationary processes, but also to that of fast nonstationary processes, including thermal processes in liquids, gases, and plasmas, free convection in liquids near heated or cooled bodies, and the mixing of different liquids in chemical process vessels.

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9. References


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