The investigation of heat transfer by Background Oriented Shlieren Method

by

N.M. Skornyakova [(1)], E. M. Popova, B.S. Rinkevichyus [(2)], and A.V.Tolkachev

Moscow Power Engineering Institute (Technical University),

V.A. Fabrikant Physics Department,

Krasnokazarmennaya str., 14, 111250 Moscow, Russia

[(1)] E-mail: SkorniakovaNM@mpei.ru

[(2)] E-mail: RinkevichiusBS@mpei.ru

ABSTRACT

The purpose of this work is to investigate natural convection in the fluid and to find the 2D distribution of the refractive index gradient and the 2D distribution of the temperature gradient with the help of the Background Oriented Schlieren (BOS) method. The process of natural convection in the water near the heated bodies of different shapes is the investigated object. The initiation of the natural convection when the body is heated and its decrease while cooling down is investigated.

Designed experimental setup for recording of visualization pictures of BOS method consists of a light source, background screen, video camera, computer and software. The calibration methodic with optical wedge is considered.

The filtration methodic, algorithms of correlation processing and postfiltration of images and their program realization in Mathcad developed early are used. Also the algorithms and program realization for field directions methods of BOS images processing are used.

The example of BOS image correlation processing of natural convection process near heated sphere in water is shown in figure 1. The level surface represent depending on normalizing either the distribution of the correlation index or the distribution of the gradient of the refractive index or the temperature in the space. The correlation index is equal to 1 (red) where the refractive index is not changing and the biggest change of refractive index is equal to the least (blue) correlation index.

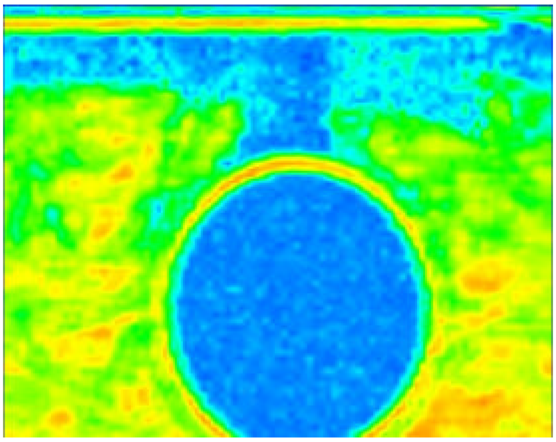


Fig. 1. Surface representing the distribution of correlation index

Common using of Background Oriented Shlieren and Laser Sheet Refractometry methods is proposed for natural convection from heat and freeze bodies' investigation.

1. INTRODUCTION

Optical methods for aerohydrodynamic flows investigations are one of the oldest methods (Vasilyev, 1968; Settles, 2001) without which modern progress in the science and technics would not be possible. Classic schlieren methods of flow diagnostics are based on the refraction of light beams on the large-scale optical imperfections. In these devices different space filters placed in the focal plane of the output objective which makes analog processing of optical image are used. The Fuco knife is most widely used as such filter. Expensive high-quality optical instruments and devices and photographic recording of schlieren image are used in schlieren devices. These devices are bulky, difficult in adjustment and exploitation. That is why they are commonly used only in aerodynamic investigations of supersonic flows in industrial wind tunnels (Raffel, 1998; Rinkevichius, 1990). In termophysic liquid investigations schlieren devices are rarely used (Hauf, 1970; Zimin, 1988).

Optical methods of flow diagnostics based on light beam refraction in optically inhomogeneous mediums nowadays experience rebirth. That circumstance is connected with three reasons: high metrological characteristics of lasers, creation of digital video cameras with the number of pixels higher than 10^6; appearance of fourth generation computers with frequency higher than 2 GHz and memory volume bigger than 20 Gb.

Application of lasers, matrix photoreceivers and personal computers in refraction methods allows getting qualitative new results. Good quality laser beams are achieved with simple optical systems. High space coherence of laser beams allowed creating new schemes of gradient refractometers: scanning (Gumennik, 1987), multichannel (Evtikhieva, 1980), speckl-refractometer (Shatokhina, 1997; Fomin, 1998).

Matrix photoreceivers and personal computers allow to appreciably simplifying processing of the refraction images. Although modern CCD matrices are appreciably inferior to photographic plates in information capacity (more than 10^3 times), however they have doubtless advantages when we speak about storage and information processing. Information from CCD matrix is written directly into computer where it can be then stored and processed with the help of the already developed computer methods of optical image processing (Metods …, 2003). Modern computers allow to process large data files typical for refraction methods.

Background oriented schlieren (BOS) method was introduced by Meier (Meier, 2002) as the further simplification of the optical schlieren system and transfer to the computer processing of refraction images. In this method flow characteristics are determined by the distortion of the image of the screen fixed behind the flow. Distortions are determined by means of computer processing of data recorded by digital camera. Nowadays the present method is successfully applied in aerodynamic investigations (Klinge, 2003).

The aim of this work is to widen the area of BOS method application to the investigation of natural convection in liquids near heated bodies which placed in box.

2. THE BASES OF BACKGROUND ORIENTED SCHLIEREN METHOD

Background oriented schlieren method is based on the computer evaluation of image changes of a screen caused by the changes of refractive index in investigated flow. Toward this end the background screen is fixed behind investigated flow and two frames are recorded by means of the digital video camera. One frame is without investigated flow, another is with investigated flow. Then distorted and undistorted images of the screen are digitally compared. The structure of the screen can be different: accidental or regular, dots or lines. The type of the screen is chosen taking into account the characteristics of the investigated flow. The method has become usable in practice owing to the immense progress in computing power and to newly developed fast-correlation algorithms (Raffel 1998). The main advantages of this method are:

– simplicity of the technical realization: only the background screen, one digital camera, computer and processing program are necessary for the experimental setup;

– the possibility of using existent algorithms of digital processing of optical images, especially, developed for PIV.

The BOS method can be used for the visualization of any processes during which the changes of the medium refractive index in the field observation take place, for example, during the investigation of flows near the helicopter blade (Raffel, 1998).

The optical scheme of the BOS method is represented in figure 2. It consists of the background screen, the investigated flow, the camera objective and the CCD matrix. Let the screen contain white field and black dots. If there is no flow the camera objective will form undistorted image of the screen. On placing the optically inhomogeneous flow between the screen and the camera, the distortions of the screen image appear. There are two types of the distortions as a first approximation: expansion of dot images and their displacement. Defocusing of dot images will be cause by additional curvature of wave-front caused by small-scale optical inhomogeneity of flow. The dots displacement in the image will be caused by local incline of wave-front. Nowadays in BOS method only the dot displacement in image is considered during processing. The defocusing of dot images also carries information about the flow. Thus, there are two screen images from differences in which the information about the investigated flow can be obtained. These differences mainly connected with the dot image displacement are proportional to the small gradient of the refractive index of investigated flow. The result of the medium influence between the background screen and the image recording device can be described as the light deflection from the rectilinear propagation.

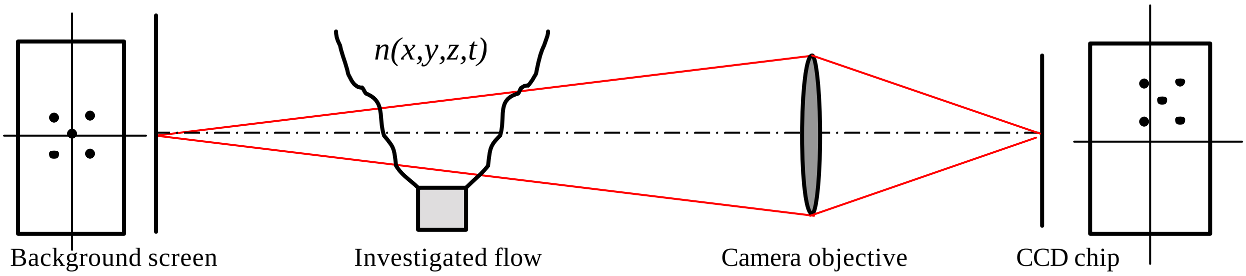


Fig. 2. Optical scheme for the receiving of BOS images of optically inhomogeneous flow

In more general way, image $I(x, y)$ of an screen is a convolution of the background or object function $B(x, y)$ and the transfer channel function $T(x ,y)$:

$$I(x ,y) = B(x, y) * T(x, y).$$

To explore the nature of the transfer channel, a deconvolution seems the appropriate tool. As known, inverse problems in general way are incorrect and ambiguous. Special mathematic methods are developed to solve them. However, in the primary problems some information about the flow (for example, flow borders) can be obtained without solving inverse problems.

3. THE EXPERIMENTAL SETUP

The experimental setup for realization of BOS method is shown in figure 3. It consists of an incoherent light source 1, a background screen 2, an investigated object 3, a digital video camera 4, adjustment system of video camera 5, a personal computer 6, and software.

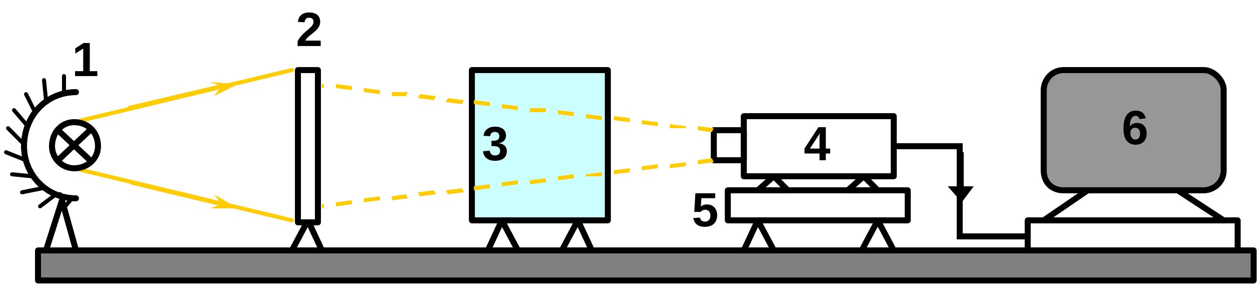


Fig. 3. The scheme of experimental setup.

1 – an incoherent light source, 2 – a background screen, 3 – an investigated object, 4 – a digital video camera, 5 – adjustment system *of video camera, 6 – a personal computer*

For highlighting of the background screen the incoherent light source (incandescent lamp) was used. The pictures containing, for example, chaotically and regularly located dots of different size and density, horizontal and vertical lines of different width with different spaces between them, were used as the background screen. Screen image recording during the process of convection was carried out with the means of three-matrix mini-DV video camera and processing with the means of personal computer of Pentium 3 series.

Follow main principles are use at mathematical and program realisation of correlation method. Then both frames are processed with the same filtration methods. The filtration set depends on the concrete image. Without fall the set must contain the method of edge amplification by Sobel. Then both frames are divided into determined number of rectangles (interrogation areas). The size of the interrogation areas is selected separately for every pair of frames. This mask moving consecutively along the picture using the built-in Mathcad function “corr” finds the correlation index for every pair of rectangles. The mask displacement can be either equal to the size of the interrogation area or smaller than it. That is to say nearby interrogation areas can be situated either one near another or with overlapping.

The correlation index is equal to 1 where the refractive index gradient is not changing and the more change of refractive index gradient is equal to the least correlation index. To get more information about the changes of the refractive index it is necessary to know not only the absolute value of the correlation index but the location of the maximum of the correlation index as well. In order to find it two interrogation areas are displaced so that they partly overlap. In this situation there is a distance between their centers and the centre of the second interrogation area coincides with a point of the first interrogation area.

It is necessary to find the correlation indexes of the overlapping parts for all the locations of the second interrogation area centre within the framework of the first interrogation area. Then these correlation indexes are compared and the arrow is drawn from the center of the first interrogation area to the location of the centre of the second interrogation area which corresponds to the maximum correlation index. The direction of this arrow coincides with the gradient of the refractive index. The location of the correlation maximum is found for every pair of interrogation areas and the vector field representing the gradients of the refractive indexes is built. If we know the distribution of the gradient of the refractive index we can find the distribution of the gradient of the temperature after normalizing.

4. TESTS EXPERIMENTS

4.1. The optical wedge is the test object

The investigation of background screen image forming at the scheme with optical wedge was carried out as first experiment. The background screen is representing white paper with accidental dots with different diameters and gradation of grey. The illumination of background screen was made from behind as shown in figure 3. The parameters of wedge are: diameter – 18 ? ?, minimum thickness – 2.68 ? ?, the angle of wedge – 1.49 ????, refractive index n = 1.56. The geometry of optical experiment is shown in figure 4. The result of correlation processing of background screen image as vector field with marked border of optical wedge is represented in figure 5.

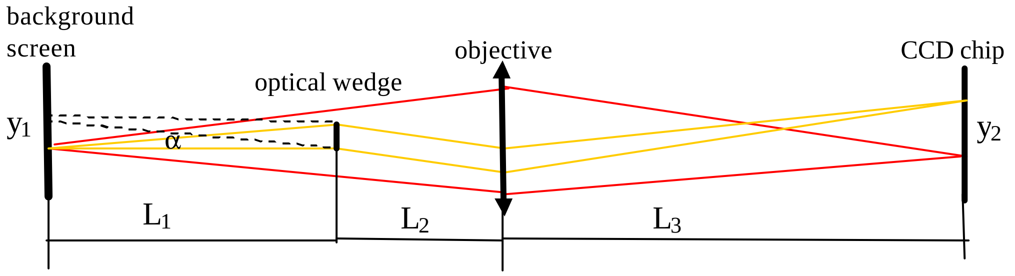
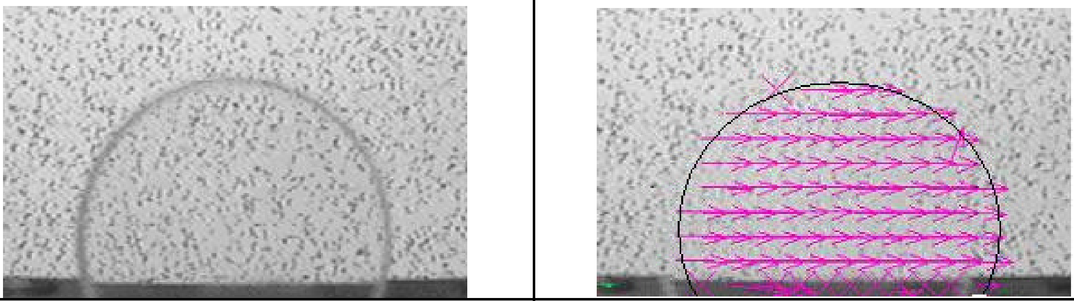


Fig. 4. The optical scheme of BOS image forming with optical wedge

We will use the geometrical optics approximation for rating of optical scheme with presented in figure 4. Then angle by which optical beams passes from background screen to optical wedge is equal to α. Then the height $y_1 = \alpha L_1$. The transformation of beam by lens is describe as $y_2 = M y_1$, where M is magnification coefficient.



?	b

Fig. 5.The BOS images of optical wedge: b – initial BOS image, b – after digital processing

The correlation algorithm as for PIV images was used for these experimental results processing. The measurements of dot displacements in the background screen image were carried out by changing of distance L_1, L_2, L_3. The physical dots displacement and calculated wedge angle on dependence distance L_2 are represented in table 1.

Table 1.

The distance from wedge to video camera, m	0,35	0,38	0,41	0,44
The physical displacement of dot image, mm	1,76	3,12	4,03	5,33
Calculated wedge angle, deg	1,491	1,488	1,485	1,483

The average mean of wedge angle was received 1.487 deg after experimental results processing with taking into account of optical characteristics of video camera. Errors of wedge angle measurements were estimated to be ± 1 %.

This methodic can recommended for testing of BOS optical scheme by unknown parameters of video camera objective.

<u>4.2. The investigation of organic glass heating process</u>

The second test experimental series was carried out by visualization of heating of organic glass bar with thickness 25 mm. Organic glass was choused as test object by two reasons. Firstly it have big coefficient of heat-conducting ($\alpha = -1.6 \cdot 10^{-4}$ 1/deg). Correspondingly, heating velocity and heated layer are greater than for other body. Secondly, the role of edge effects is less than for natural convection near heat body.

The experiment methodic consists of follow. The metal vessel with hot water is placed on upper edge of plexiglass. The water temperature was measure with help of thermometer. The angle of optical beam deviation on boundary layer output is defined follow relation (Hauf 1970)

$$\alpha(y_0,l) = n\int_0^l (\mathrm{d}n/\mathrm{d}T)\,[\mathrm{d}T(y,z)/\mathrm{d}y]\,\mathrm{d}z\,, \qquad (2)$$

where y_0 is coordinate of beam entry in boundary layer; l is bar length; n is bar refractive index; $\mathrm{d}n/\mathrm{d}T$ is coefficient which show the dependence of refractive index on temperature; $\mathrm{d}T(y,z)/\mathrm{d}y$ is temperature gradient in boundary layer.

If temperature gradient depend on coordinate z little few that is $\mathrm{d}T(y,z)/\mathrm{d}y \sim \mathrm{d}T(y_0)/\mathrm{d}y$, then output beam is deviated on angle

$$\alpha(y_0,l) = n(\mathrm{d}n/\mathrm{d}T)\,[\mathrm{d}T(y_0)/\mathrm{d}y]\,l, \qquad (3)$$

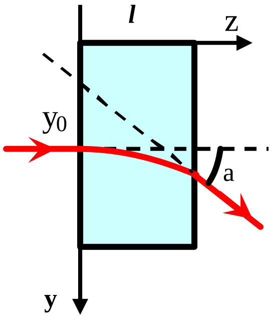


Fig. 6. *The optical beam passing through boundary layer*

For example: n = 1.55; dn/dT = $-1 \cdot 10^{-4}$ 1/°C; $dT(y_0)/dy$ = 1 °C/mm; l = 25 mm, then α = 0.143 deg.

The experimental investigations were carried out for confirmation of theoretical formula and for testing and calibration of BOS method.

The results of refractive index gradient visualization in heated organic glass are given on figure 7a, c by investigations of BOS with lines as background screen.

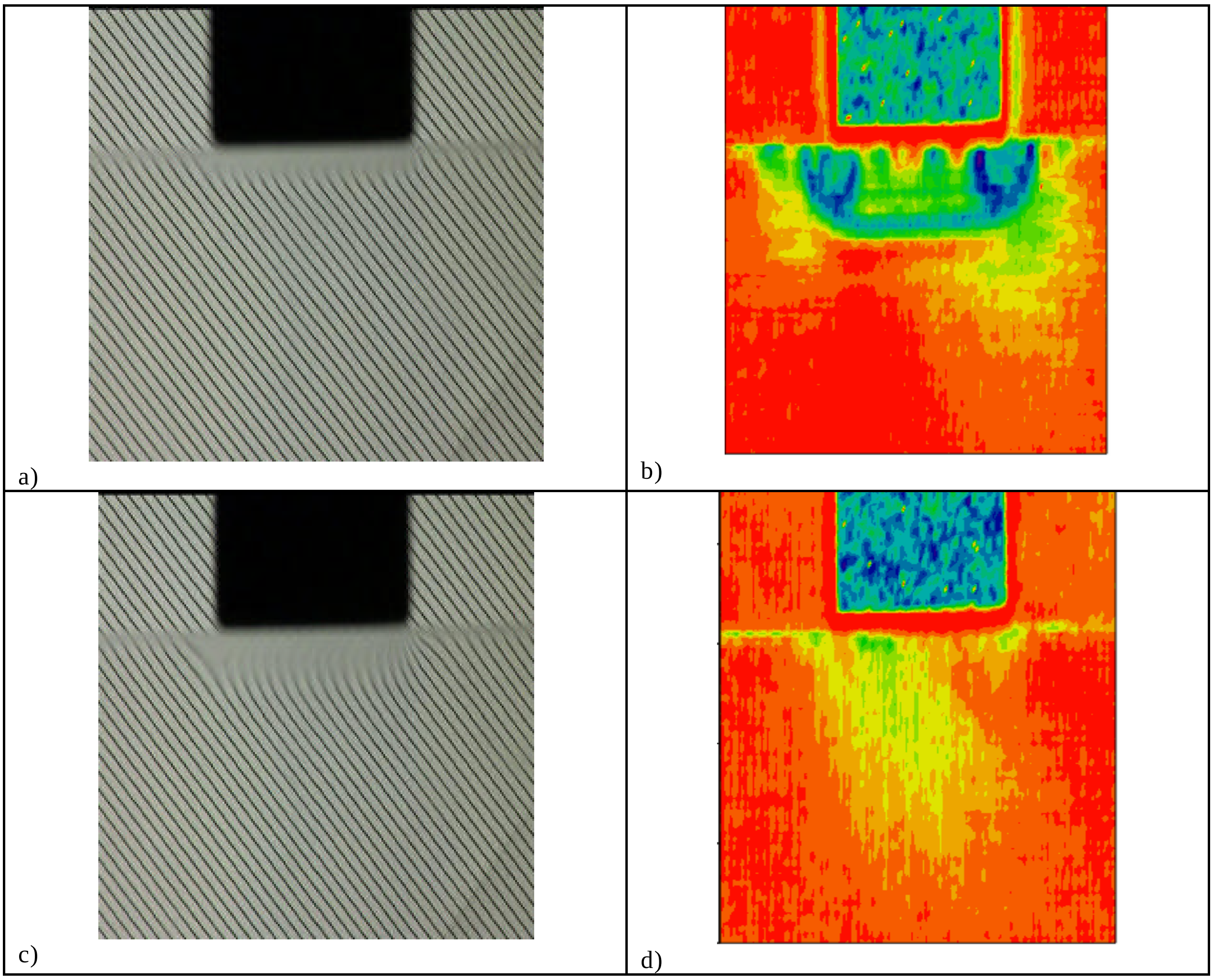


Fig. 7. Visualization and results of correlation processing of images: ?, b – the temperature of hot cylinder is 60 °C, c, d – the temperature of hot cylinder is 24 °C

The visualization of the heat transfer process between hot cylinder and organic glass with lines as background screen is presented in figure 7 a, c. Also the results of image correlation processing for same temperature with dots as background screen are presented in figure 7 b, d.

5. INVESTIGATION OF NATURAL CONVECTION IN THE WATER NEAR THE HEATED SPHERE

Natural convection in the water near the heated bodies was investigated theoretically as well as experimentally with the help of classical optical methods (Gebhard, 1988). The ball placed into the water was chosen as an object of investigation with the means of BOS method. The thin boundary layer and secondary flows are created at the closed volume around heated sphere. The simultaneous visualization of these flows there is difficult with BOS method because it request of the large measurement range by temperature gradient and space resolution. The typical means of boundary layer is equal to less then 10% from sphere diameter. The Laser Sheet Refractometry (LSR) method was used joint the BOS method. The investigating flow is probe by narrow laser sheet at LSR method. The laser sheet distortions are record by help of video camera. The detailed description of this method theory is represented in (Evtikhieva, 2003).

Main peculiarity of the natural convection investigation in water with the means of optical refractive methods is the big gradient of the refractive index. In the BOS method it results in large shifts of screen dot images. That is why correlation methods of image processing are not applicable to large temperature gradients. In such cases computer processing of BOS images with direction field methods is expedient.

Joint experimental setup for the investigation of no stationary convection in water around heated bodies consisted of two independent measuring systems: BOS and LSR. The scheme of the experimental setup is represented in figure 8. BOS system consists of a light source 1; a half transparent structured screen 2; glass box filled with water 3; heated ball 4; digital video camera consisting of an objective 5 and CCD matrix 6. LSR system consists of a semiconductor or He-Ne laser 7, a turning prism 8, cylindrical lenses 9 and 10, a laser sheet 11, transparent screen 12, digital video camera consisting of an objective 13 and CCD matrix 14.

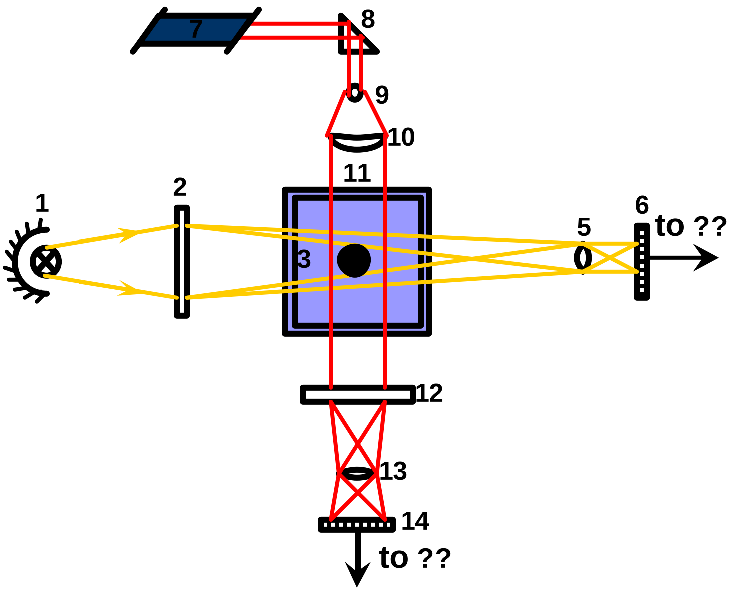


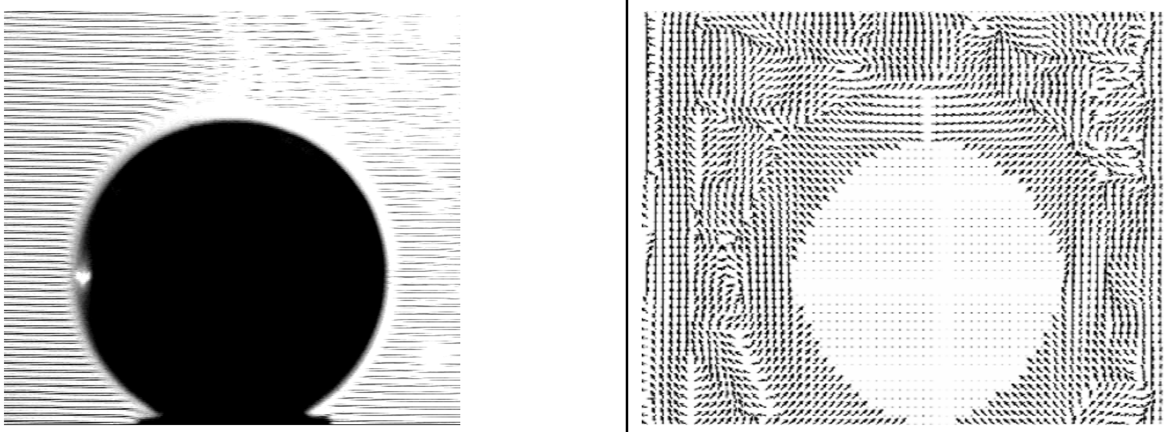
Fig. 8. Joint BOS and LSR setup

The BOS system is destined for receiving of common image of temperature gradient field distribution in all volume around heat sphere. The LSR system is destined for receiving of visualization picture of temperature gradient flow in choosing cross section into boundary layer near heated sphere. The combination of these systems allows investigating of non stationary heat convection processes in liquid near heated bodies. The work principle of both systems is based on light beams refraction on large-scale optical inhomogeneities in liquid. The observation effect is integral as by light beam way diffusion as by beam diameter for BOS and LSR methods.

The principles of investigation consist in following. The steel ball of 43,7 mm in diameter was heated to the temperature 100°? and was put into the box filled with water the temperature of which was 21 ^{0}?. The box is 120?180?200 mm^3 in size. Refraction pictures of BOS and LSR methods are record with help of video cameras. The unstable convection is observed at initial moment of sphere cool downing. The unstable convection is consisted of appearance of thermals (narrow jet of more hot water) which appeared at different points of sphere surface by chance. This picture is disappeared more stable further. This effect is observed at LSR method because it have more spatial resolution, as BOS method.

In figure 9a BOS image of the tank with the heated ball inside is represented. The horizontal lines were chosen as the background screen structure. The lines distortion which depends on refracted index gradients or temperature gradient is observed in figure 9a. This distortion is bigger at upper part of box. More appreciable distortion is at boundary layer around sphere.

The filtering image of natural convection process from heat sphere into water is present in figure 9a. The uniform changing of refractive index gradient from side and under of sphere is shown. The heat flows is observed upper of sphere as at LSR method too.



a b

Fig. 9. BOS image of the heated ball in the water tank: a) initial BOS image with lines; b) BOS image after processing with help of field direction methods

Let us consider the methods of BOS images processing. For small difference of temperatures (when the dots displacement is not bigger than one raw) the correlation processing can be used. The peculiarities of such processing and optimal parameters have been considered earlier [Skornyakova, 2003]. In figure 1 the results of the processing with optimal parameters are represented. The present dependence represents the distribution of correlation index in space. After normalization on corresponding coefficient which is obtained from the LSR method, the building of the temperature distribution field is possible.

The other processing methods are used for large temperature differences and for large refractive index gradient correspond. The application of field direction methods [Skornyakova, 2003] was considered. The result of field direction method processing with plane as approximate function is shown in figure 9b. The arrow shoes direction of gradient changing (direct or inverse). The analysis of presentation BOS images is shown that this method visualize of the common picture of heat flows in volume. The boundary layers is visualize not enough qualitative at this method.

The visualization results of temperature gradient at boundary layer near sphere with help of laser sheet (figure 10a) are shown in figure 10. The laser sheet is direct from three sides of sphere (figure 10c): upper, below, and on the left of sphere. The distance between laser sheet and sphere surface is consist of 0.1 mm. The thickness of laser sheet is 0.3 mm. The images below and on the left of laser sheet are identical (figures 10 c, d). The distortion of laser sheet by sphere diameter is observed. The visualization picture is more difficult by observing of natural convection upper of sphere because the non stationary heat flows are here (figure 10b).

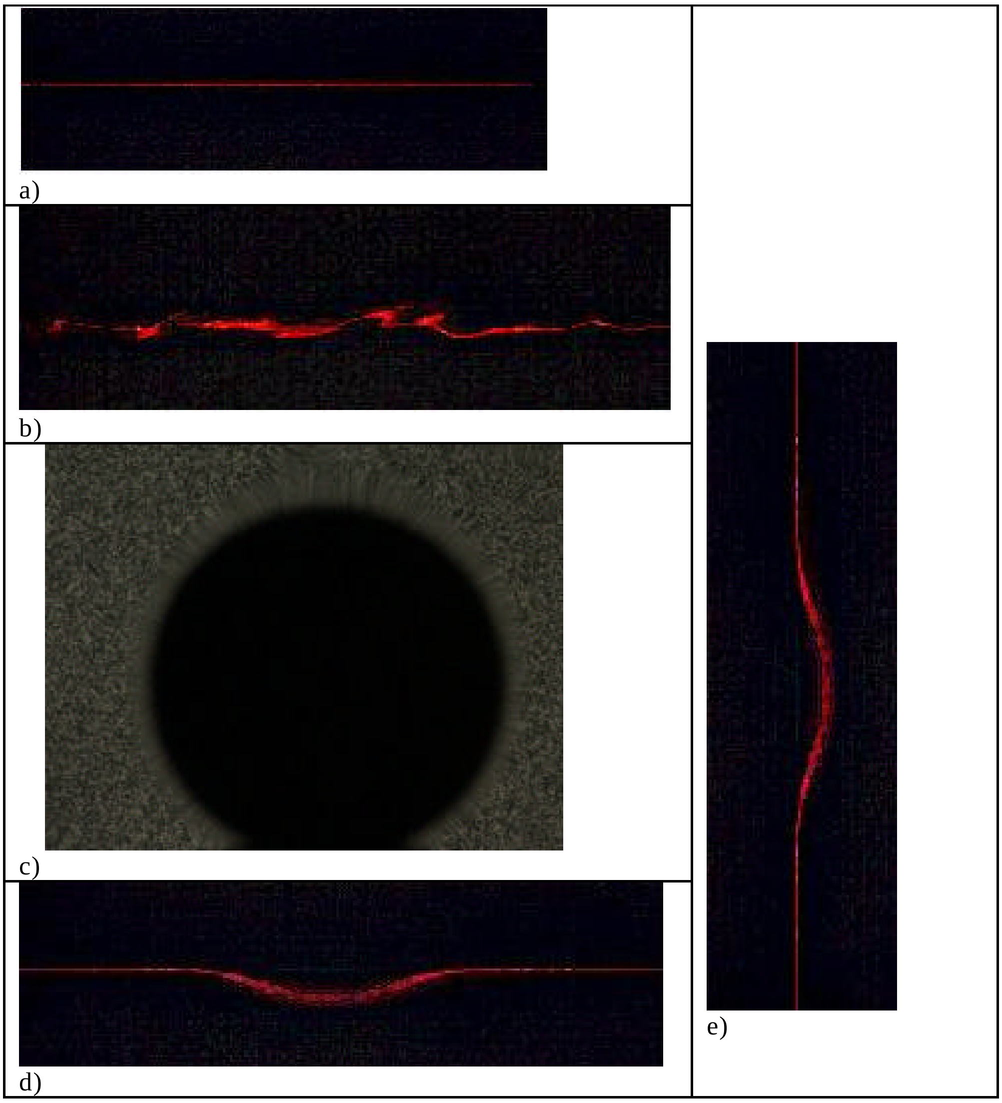
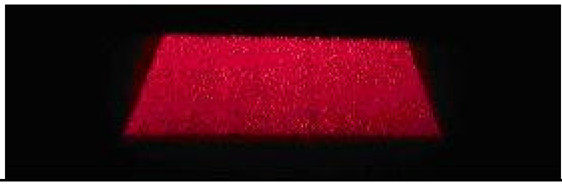
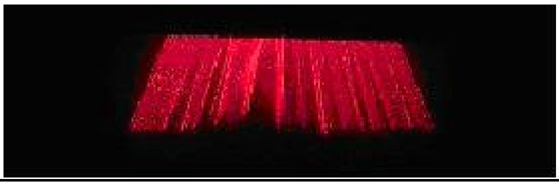


Fig.10. The distortion of laser sheet in boundary layer near sphere: a is initial image of laser sheet; b is laser sheet image upper of sphere; c is laser sheet image under of sphere; e is laser sheet image near sphere

Laser sheet distortion was observed near sphere surface for more detail investigations of flow peculiarities upper of sphere. The video camera was put by small angle to laser sheet for this. It is allowed observed of laser sheet distortions from laser sheet scattering on small particles. The laser sheet distortions are shown in figure 11 at different time moments after immersion of sphere in water. Analysis of these images shows that laser sheet distortions are caused of local disturbance at main.

The methodic of flow area illumination by means of two laser sheets diffused by angle one to other was used for detail investigations of thermals (figure 12a). Two laser sheets 1 and 2 are situated at one flow cross section. The observation of laser sheet image is carried out on internal wall of box 5 by small angle. The accidental in time and space thermals 4 is come off from sphere surface 3.

Two images corresponding different times are shown in figure 12. The laser sheet tracks distorting of thermals and thermals images between sphere and box side because of scattering on small particles are presented.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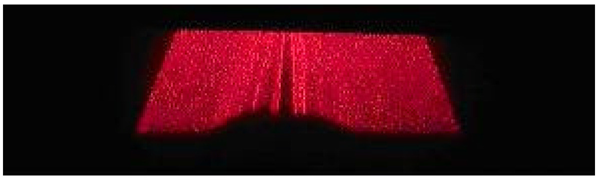
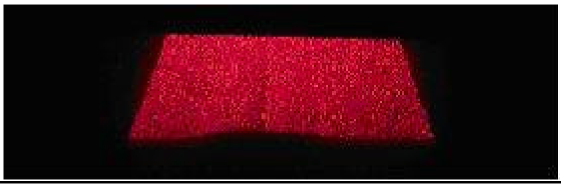
	
21 sec	56 sec

Fig.11. The laser sheet images in scattering light near sphere surface at different time moments

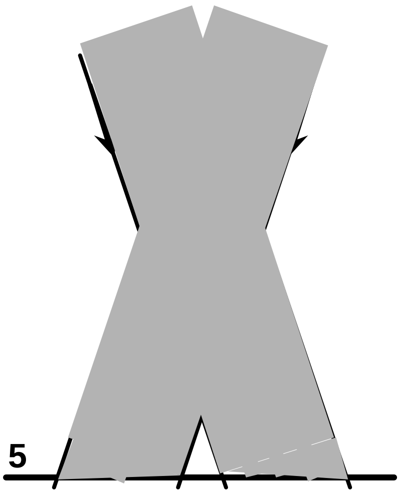
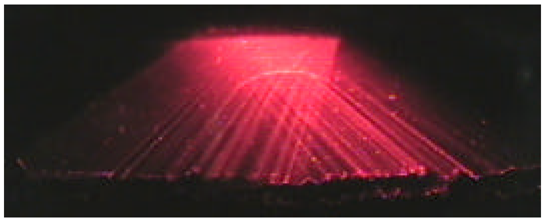
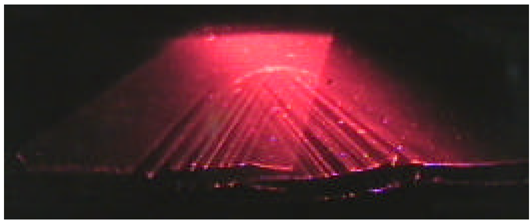
 a	 b
	 c

Fig.12 . Flow visualization by two laser sheets: a is optical scheme of flow probing; b is laser sheet images in scattering light at moment t = 5 sec; c is laser sheet images in scattering light at moment t=8 sec

6. CONCLUSION

At present BOS using at main for investigations of gas flows in aerodynamic tubes and at natural experiments. It is shown that BOS can used for investigations of natural convection around heat and freeze small bodies' (diameter near 1 sm) which situated in box too.

The methodic of BOS calibration with help of known optical wedge was designed. Good coincidence of measuring and theoretical results of wedge angle is received. It is shown that BOS method allows visualization of heat boundary layer in organic glass bar.

The Laser Sheet Refractometry Method can be used for BOS calibration. The joint BOS and LSR experimental setup is designed. It allows simultaneous investigations of temperature gradient distribution in box and in boundary layer.

The thermal was visualized with help LSR method. The thermals form by non stationary convection upper sphere surface. The combination of two methods is useful at other cases of investigations of non-uniformity and non stationary heat flows.

7. ACKNOWLEDGEMENTS This work was carried out with the financial support of INTAS grant 2000-135 (project coordinator is Dr. J. Kompenhans) and the Ministry of Education of Russian Federation.

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