Visualization of Convective Structures by Methods of the Hilbert Optics and Phase-Shift Interferometry

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Abstract The structure and evolution of thermogravitational buoyant jets in a high-viscosity liquid above a linear source of heat suddenly switched on are studied by methods of the Hilbert optics and shear interferometry. Based on the interferogram structure, reconstruction of the temperature field in the jet is performed. Recovery the phase function and the temperature of the plume was carried out on the interferogram using spline interpolation. Reliability of the results was tested by simulating shear interferogram of the reconstructed field and comparing it with the experimentally obtained fringe pattern. Such jets can be considered as a model of an upward flow in the spreading zone in geodynamic problems associated with the behavior of the Earth's mantle at large depths.
Keywords: optical diagnostics of the flow, Hilbert optics, interferometry, thermogravitational convection, buoyant jets.

1 Introduction

In optical flow diagnostics the most popular methods are traditional shadowgraphy and schlieren techniques [1, 2]. Their recent evolution was stimulated by the development of optical information technologies based on the Fourier and Hilbert transforms and on filtration and analysis of space-time phase structures induced by the examined medium in light fields [3, 4]. One of the most important problems of global geodynamics is physical modeling of mantle plumes and buoyant flows in the spreading zone [5, 6]. Thermogravitational free-convective jets above a linear or point source of heat are of undoubted interest for constructing such a model. For the experimental investigation of the dynamic structure of these jets are needed not disturbing technology, realized by means of optics. In [7, 8] the structure of the phase of the optical density of plumes was visualized by trace flow visualization techniques and Hilbert optics and discussed the possibility of reconstruction of temperature field. Development and expansion of the scope of these methods is the motivation of this work.

2 Method of Investigations and results

A simplified layout of the experimental setup used for studying the structure and evolution of thermogravitational buoyant jets is shown in Fig. 1. The setup includes an illumination module consisting of light sources *1* and *1'*, lenses *2* and *2'*, beam splitter *3*, lens *4*, and slotted diaphragm *5*. The slotted diaphragm is located in the focal plane of the objective *6* forming the probing field in the examined medium *7*, which is a layer of a high-viscosity PES-5 fluid poured into a rectangular bath *8* with transparent walls made of optical quality glass. The inner size of the bath is 60×90×40 mm. The height of the fluid layer is 98 mm. In the central section along the bath, there is a Constantan wire *9* aligned parallel to the axis of the optical system and to the bottom. The distance between the wire and the bottom is 6.2 mm. Controlled heating of the wire performed by d. current from a stabilized power source *10*. The temperature at two specified points of the examined medium is monitored by thermocouples *11*. The objective *12* forms the Fourier spectrum of the light field disturbed by the examined medium in the frequency plane *13*. The Fourier plane of the objective *12* contains a quadrant Hilbert filter *14*. The objective *15* performs the inverse Fourier transform of the filtered light field. The Fourier-conjugate field formed by the objective *15* is recorded by a digital camera *16*. The outputs of the digital camera and the thermocouple system are connected to a computer *17* processing the results. This optical setup is arranged on the basis of the IAB-463M shadowgraph with a modified illumination system and systems of optical signal filtration and image recording. The probing field formed by the Fourier objective *6* from the slotted source *5* passes through the examined medium where a thermogravitational convective flow in the form of buoyant jets is induced by the heat source *9*. The objective *12* forms the Fourier spectrum $s(K_x,K_y)$ of phase disturbances of the probing field induced by the examined medium in the frequency plane K_x,K_y. The quadrant space-frequency phase filter *14* placed into the Fourier plane is described by the coherent transfer function.

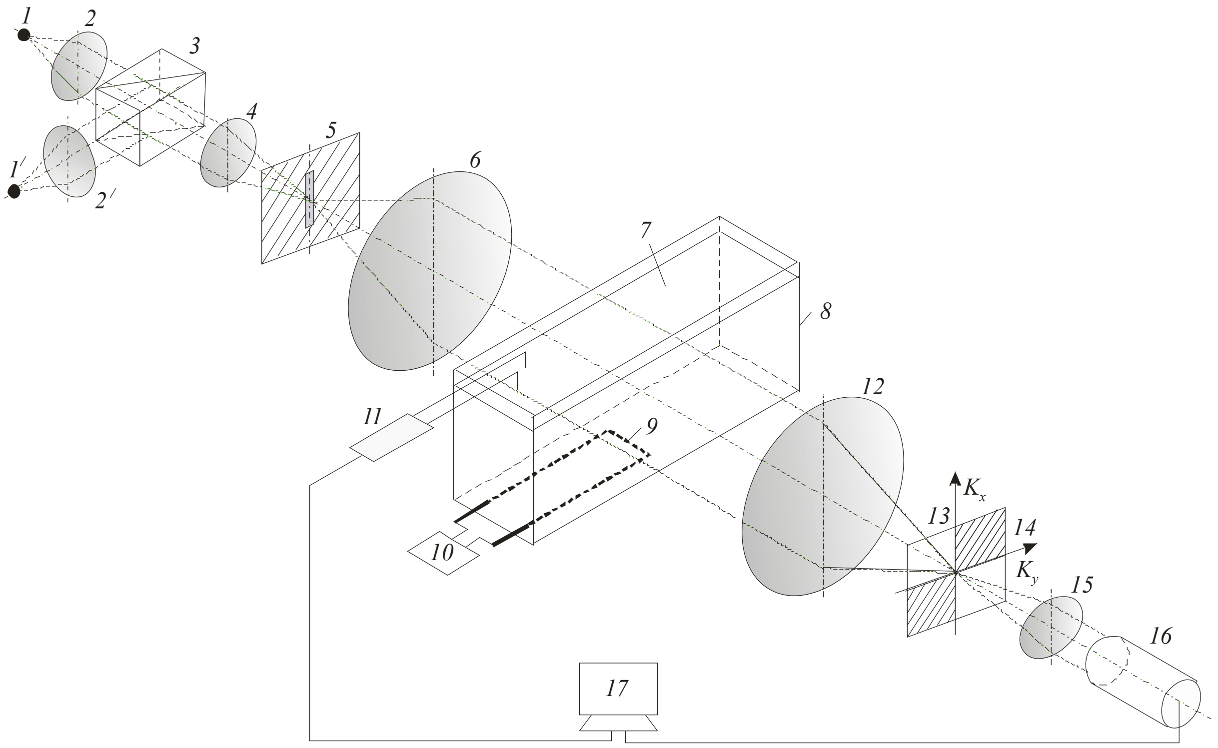


Fig. 1 Sketch of the experimental setup

Comparative studies of the phase structure of the thermogravitational jets in the same flow regimes were performed by methods of the Hilbert optics and interferometry. For this purpose, we used a modified RP-452 add on device to IAB-463M, which was fabricated in accordance with the mirror shearing interferometer scheme [1] (Fig. 2). It contains lenses L_1 and L_2 forming the light beam entering the interferometer, which consists of mirrors M_1 and M_2 and beam splitter plates M_0 and M'_0. The channel of interference pattern recording contains a lens L_3 and a digital camera. Visual monitoring is performed through another channel containing a mirror M_3, lens L_4, and screen S.

The modification implied addition of lenses L_1 and L_2, which correlate the interferometer with the frequency plane of the Hilbert visualizer to the optical scheme. In this scheme, the image of the slotted source 5 (see Fig. 1) is projected onto the surface of the mirror M_1. The light beam is split by the semi-transparent mirror M_0 into two beams, which recombine on the semi-transparent mirror M'_0. The shift between the wave fronts is ensured by rotating the mirror M_1. The interference pattern is recorded by the digital camera and is observed on the monitor either directly or with the help of an additional telescope. Tuning to fringes of a necessary width and orientation is performed regardless of the direction and magnitude of the shift between the wave fronts of the interfering beams. During the experiment, the interference add on device is placed behind the frequency plane instead of the system performing the inverse Fourier transform of the filtered signal and its registration. The source is the laser diode *1'* (see Fig. 1) emitting at the wavelength λ = 0.64 µm.

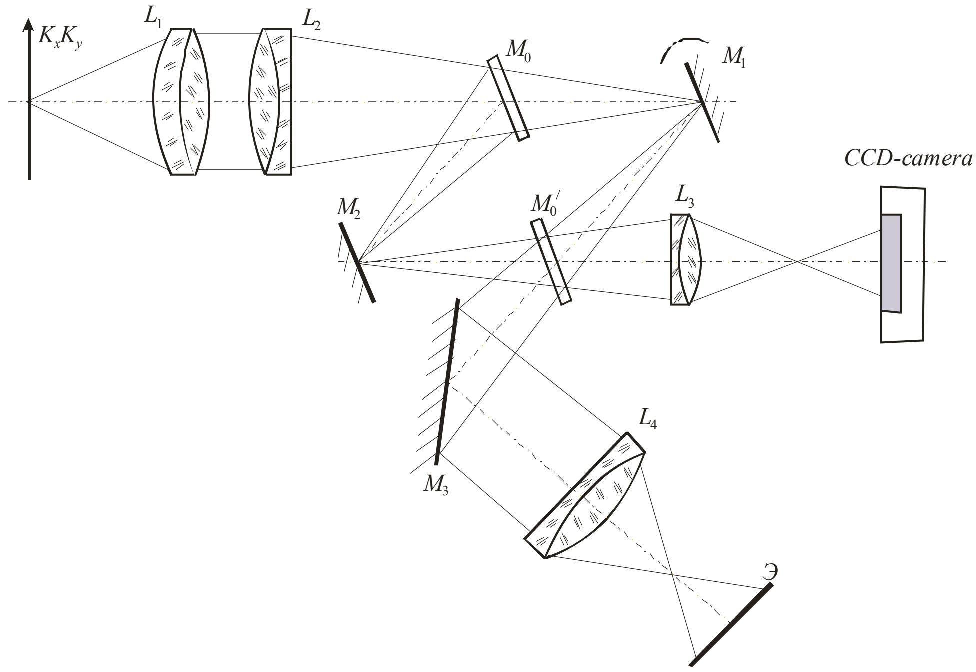


Fig. 2 Shear interferometer scheme

Fig. 3 shows an example of the experimentally obtained sequence of Hilbert and shear interferogram images of the plume induced suddenly turned the heat source at a current of 0.4A. This figure also shows the sequence of the fringe patterns to illustrate the evolution of the plume under the same conditions as the Hilbert-visualization. The shear interferometer was set to endless fringe. The frame interval is 40 s. The temperature field calculated from the shear interferogram with taking into account the known linear dependence of the refractive index of the liquid PES-5 on the temperature. The distribution of the interference fringes shows the distribution of the phase gradient optical density. The reference temperature is determined with a thermocouple in the undisturbed area. Interference fringes approximated with Bernstein polynomials. Analytical representation of curves describing the interference fringes allows determine their coordinates in any part of the fringe pattern. Recovery of field of optical phase-density is carried out in the approximation in which the optical phase perturbations in the plume were averaged and integrated over the thickness of the liquid layer in which the buoyant jet is induced. Recovery the phase function and the temperature of the plume carried out on the interferogram using spline interpolation in the environment of Matlab. Fig. 4 shows the temperature field plume reconstructed using the method described above and with using the experimental shear interferogram shown in Fig. 5. Reliability of the results was tested by simulating shear interferogram of the reconstructed field and comparing it with the experimentally obtained fringe pattern. Fig. 6 shows the synthesized shear interferogram. Comparison of fringe patterns presented in Figures 5 and 6 illustrate degree of certainty of the reconstructed temperature field. The developed method can be useful for the study of convective structures of various physical nature. Examples of such structures may be convection currents arising in the filled with water space between two heat exchangers. If the temperature of the upper heat exchanger is maintained at a level below the freezing point and if the temperature of the lower heat exchanger is above freezing point the convection currents simulating processes in the underwater part of the sea ice arise up. The developed method of research convective structures and reconstruction of temperature fields is adequate to this task.

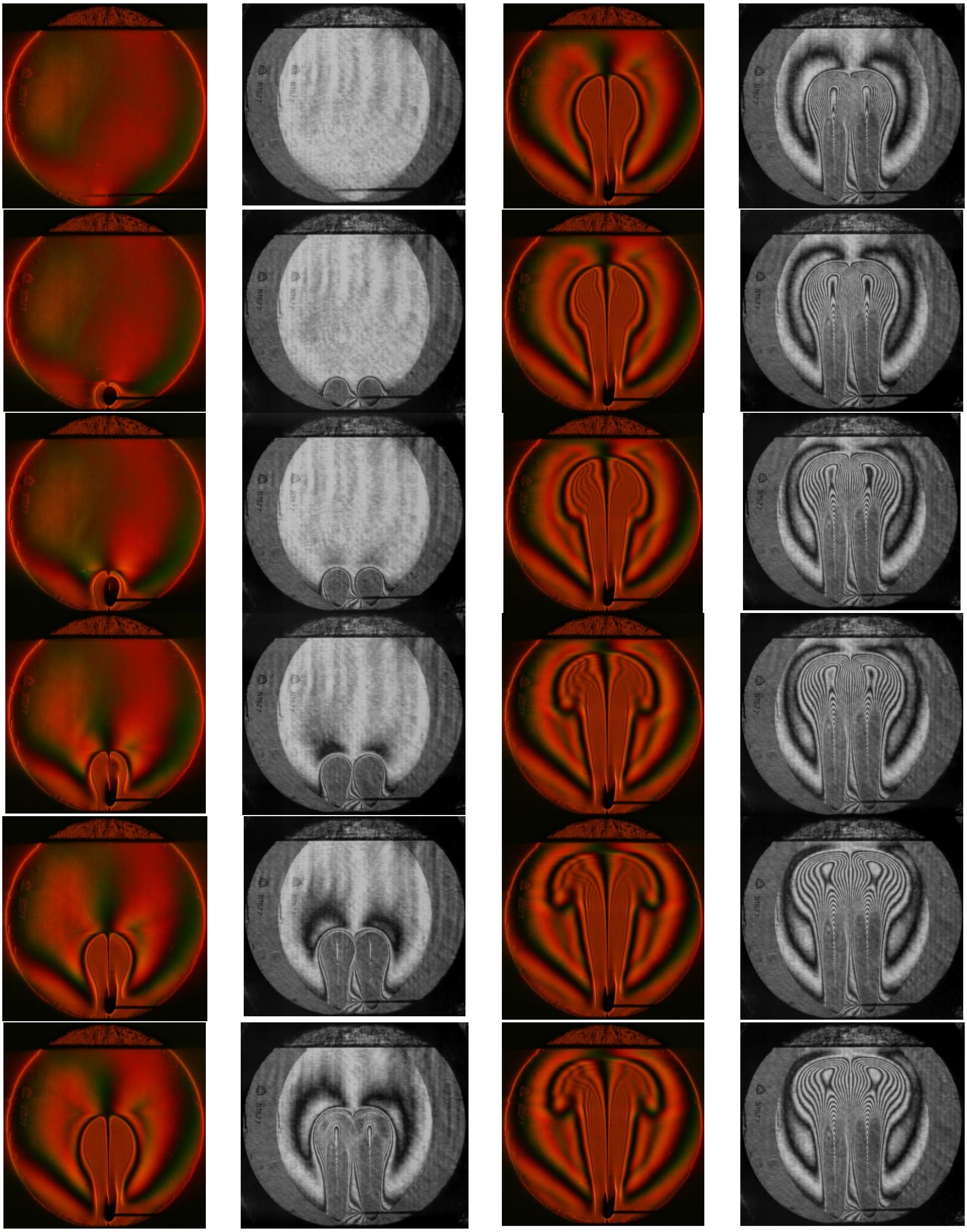
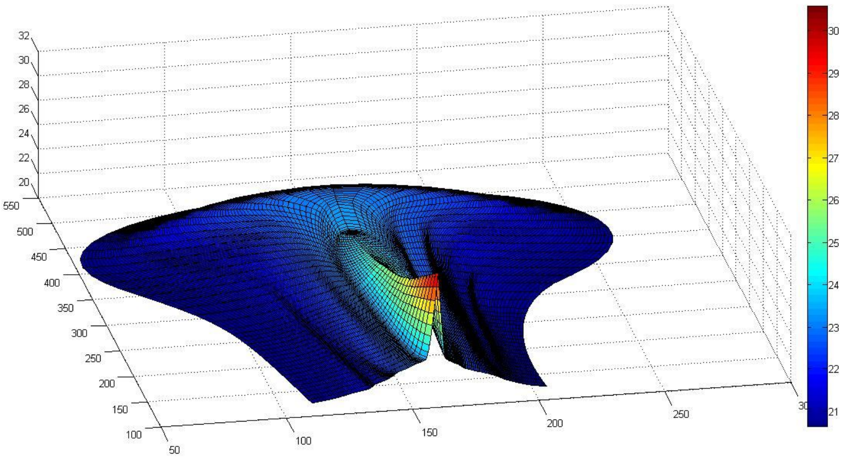
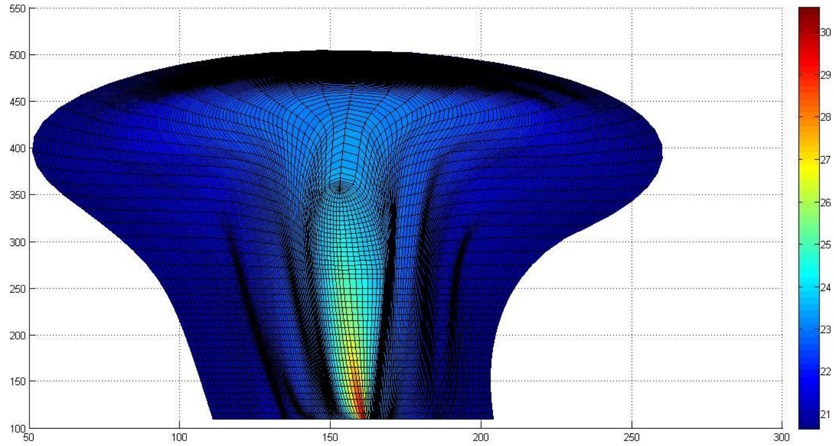


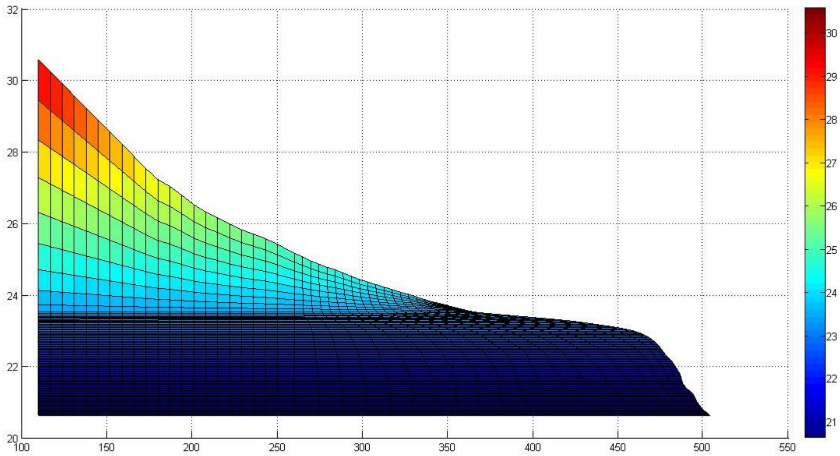
Fig. 3 Sequence of Hilbert and shear interferogram images of the plume



a



b



c

Fig. 4. Temperature field plume: *a* – 3D-reconstruction; *b* – top view; *c* – side view.

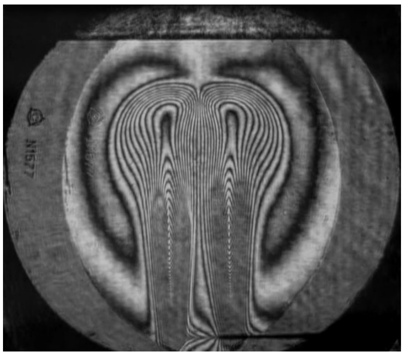


Fig.5. Experimentally obtained fringe pattern

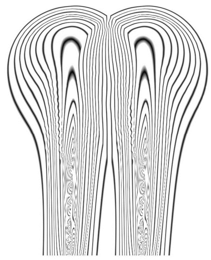


Fig. 6. Synthesized shear interferogram

Conclusions

The structure and evolution of the buoyant jets in a high-viscosity liquid above a linear source of heat suddenly switched on are studied by methods of the Hilbert optics and shear interferometry. Such jets can be considered as a model of an upward flow in the spreading zone in geodynamic problems associated with the behavior of the Earth's mantle at large depths. Based on the fringe pattern structure, reconstruction of the temperature field in the jet performed. Recovery the phase function and the temperature of the plume carried out on the interferogram using spline interpolation in the environment of Matlab. Reliability of the results was tested by simulating shear interferogram of the reconstructed field and comparing it with the experimentally obtained fringe pattern. The developed method can be useful for the study of convective structures of various physical nature.

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