Turbulence and heat exchange inside the dome room of lidar station. Experiment and simulation

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Abstract. The structure of air turbulent motion inside the dome room – Primary Mirror (diameter 2.2 m) closed shaft at Siberian Lidar Station of V. E. Zuev Institute of Atmospheric Optics of Siberian Branch of the Russian Academy of Science has been experimentally and theoretically studied. Research is needed to forecast a laser radiation distortion. Results of experiments performed using the ultrasonic compact portable weather station are presented. The main heat exchange directions of air flows inside the shaft are determined. Theoretical results have been obtained by numerical solving of boundary value problem for Navier-Stokes equations. Solitary large vortices (coherent structures, topological solitons) are observed inside the shaft. Coherent decay of such vortices generates the coherent turbulence. It is determined that inside the primary mirror shaft one may expect the weakening of phase fluctuations of optical radiation, and thus improvement the lidar optical imaging. This increases the efficiency of Lidar Station.

1. Introduction

The coherent structures [1-5] are elucidated in experimental measurements of turbulence both in open atmosphere and indoors [6-11]. A hydrodynamic coherent structure – the compact formation, including the long-living spatial vortex structure (cell), resulting from the prolonged exposure of thermodynamic gradients, and the products of its discrete coherent cascade decay. In broad sense, the coherent structure – the solitary solitonic solution of hydrodynamics equations (topological 3D-soliton, solitary wave). It is either one-soliton solution or one soliton in multisoliton solution [6-11].

As stated in [6-11], the turbulence, resulting from decay of the major vortex in a single coherent structure, is coherent and deterministic. It contains both large-scale and small-scale decay products. Therewith, the turbulence one-dimensional spectrum (of velocity components and temperature) has the faster decrease in inertial interval (usually 8/3-power decrease, which becomes the stronger 12/3-decrease at high-frequency part of inertial interval) in comparison with Kolmogorov 5/3-power decrease [6-11, 16].

This paper presents the results of experimental and theoretical study of heat exchange and turbulence structure inside the dome room – closed shaft of the Primary Mirror (diameter 2.2 m) at Siberian Lidar Station of V. E. Zuev Institute of Atmospheric Optics of Siberian Branch of the Russian Academy of Science (IAO SB RAS) (figure 1). This research is needed to forecast a laser radiation distortion near the Primary Mirror and near the focus inside the dome room of lidar station. It allows to estimate (and forecast) the efficiency of the lidar station.
2. Experiment

The experimental studies of heat exchange characteristics and turbulence characteristics inside the dome room have been implemented in December 2015. Measurements were executed by the compact portable ultrasonic weather station at different points (figure 2) inside the shaft.

Figure 1. Model of the Primary Mirror shaft. Common South-East corner view

Figure 2. Location scheme of registration points: light spheres – experiment, dark dots - simulation. Near sector is truncated. North-West view

Figure 3. Model fragment – constructions and equipment at the focus. South-East upper view

Figure 4. Model fragment – Primary Mirror (diameter 2.2 m). Shield is folded. South-East view

Figure 5. Experimental temporal frequency spectrum of temperature fluctuations at lower point

Figure 6. The same as figure 5, at upper point

Earlier, authors of this paper have performed the similar measurements inside the domes of several different telescopes, for example, astronomical telescopes AZT-33 and AZT-14 at Sayan Solar Observatory, Institute of Solar-Terrestrial Physics of RAS [16-19], and Large Altazimuth Telescope
Bolshoi Teleskop Alt-azimutalnyi, BTA) at Special Astrophysical Observatory of RAS in the Caucasus Mountains [12, 13].

The theoretical results have been obtained by the solving numerically of boundary value problem for the equations of hydrodynamics (Navier-Stokes equations).

Figures 5, 6 show the experimental temporal frequency spectrum of temperature fluctuations $W_T$ for some measuring points. In these cases the relatively extended inertial interval with 8/3- or 12/3-power decrease is observed in the spectra, it corresponds to the coherent turbulence [6-13, 19, 20].

3. Simulation

Our earlier numerical simulation results [12, 13] show that the solitary large vortices (coherent structures, topological solitons) are observed inside closed air volume over the homogeneously heated surface. The coherent decay of such vortices generates the coherent turbulence.

To explore the structure of air turbulent motion inside closed volume (without exchange of internal and external medium through the borders) the boundary value problem for hydrodynamics equations (Navier–Stokes) is solving. For numerical solving the hydrodynamics boundary value problem we have used The Gerris Flow Solver [14] – "a Free Software program for the solution of the partial differential equations describing fluid flow" (Navier–Stokes). The open-source code is available free of charge. The efficiency and the required accuracy of Software [14] had been tested and confirmed on the wide class of 100 typical test problems [15], which solutions give the satisfactory results.

The model of the shaft with constructions and equipment have been simulated (figures 1, 3, 4) on the basis of in-situ measuring the dimensions and the surfaces temperature, the assembly drawings have also been used.

4. Boundary Value Problem

For the numerical simulation we formulated the following boundary value problem for Navier-Stokes equations:

Dirichlet boundary conditions: temperature of shaft surfaces – corresponds to the experimentally measured temperature; boundaries velocity: $x$-, $y$-, $z$-component of velocity is zero (no-slip impermeable boundaries).

Initial conditions: temperature of medium (air) indoors – corresponds to the experimentally measured temperature; pressure $P_0 = 1013.25$ mbar.

Medium: the fluid like the air: kinematic viscosity $\nu = 17.3 \cdot 10^{-6}$ m$^2$/s; density $\rho = 1.2$ kg/m$^3$.

Constructions and equipment: indoors there are large optical elements and constructions of the lidar (figures 1, 3, 4), including Primary Mirror (elliptical paraboloid): diameter 2.2 m, focal length 10 m.

The shaft (figure 1) dimensions (w×h×d): 5.2×15.6×5.2 m. Location scheme of registration points inside the shaft is on figure 2.

As a result of solving the boundary value problem, the pattern of air motion inside the shaft was found in parameters of velocity vector field, temperature scalar field and pressure scalar field (figures 7, 8). We can see the solitary large vortices (coherent structures, topological solitons) indoors. We consider these vortices together as an analogue of Benard convection cell, formed in the closed rectangular volume with internal constructional contents of complex geometry.

5. Evolution of convective cells (theoretical and experimental data)

Figures 7, 8 illustrate the patterns of air flows inside the shaft model at different simulation timepoints. We note the prevailing influence of major inhomogeneities in the air motion. The geometry of constructions (the horizontal gangways and the vertical cylindrical blind) spatially causes the large vortex cells within each floor. The insignificant contribution of small vortices should appear as a more rapid decrease of the turbulence spectrum at high frequencies.

Experimental measurements have revealed the presence of air flows (up to 0.4 m/s) inside Primary Mirror shaft throughout its height (15.6 m), including the flows in technological gaps between the construction elements.
The following heat-exchange directions of air motion inside the shaft were identified as a result of theoretical and experimental studies: 1) vertical downward direction inside the blind (made as a vertical tube of circular cross-section); 2) vertical upward – on external southern side of the blind (in gap between the blind and the horizontal gangways); 3) vertical downward one – on external northern side of the blind. The causes of these air flows, as it turned out, were the gradients of average temperature: 1) increasing the temperature at shaft lower part at places adjoining the shaft entrance doors from the adjacent warm room; 2) lowering the temperature at shaft upper part as a result of external cooling of the shaft sliding roof.

6. Spectral analysis
Figures 9, 10 present the temporal frequency spectrum of temperature fluctuations in simulation. We see in the theoretical spectra like in the experimental ones (figures 5, 6) there is a relatively extended inertial interval with 8/3- or 12/3-power law. It corresponds to the coherent turbulence too.
The vertical directions of the air flows, similar to experimentally fixed ones, are observed in the simulation mainly at non-stationary mode. The air, chilled by contact with the shaft cold roof, falls down mostly inside the blind, which due to its geometry (vertical tube) collects it into a relatively narrow downdraft. The warm air from the rabbet ledge of shaft entrance door on ground floor (being displaced by the downdraft cold air) rises in the structural gaps between the gangways and the blind.

Such experimentally observed directions of air flows occur less frequently and become less expressed at steady thermal mode in the developed model. This follows from the fact that the shaft is not hermetically closed: the cold outdoor air flows into the shaft while the warm air flows out through the small gaps at the junction of shaft roof. The model developed here assumes a hermetically sealed room what leads to the pattern of air motion insignificantly different from the experimental one. At the same time, spectral analysis and comparison of the experimental and simulation data point to the fact that the developed model of shaft reasonably well reproduces the structure of turbulent air motion inside the shaft, confirming the presence of a coherent turbulence.

7. Conclusion
Thus, the scientific results of experimental and theoretical studies performed in the closed shaft at lidar station can be formulated as follows:

1. As a result of theoretical and experimental studies the heat-exchange directions of air motion inside the shaft were specified: 1) vertical downward direction inside the blind (made as a vertical tube of circular cross-section); 2) vertical upward – on external southern side of the blind (in gap between the blind and the horizontal gangways); 3) vertical downward one – on external northern side of the blind. The gradients of average temperature cause these air flows.

2. Both experiment measurements and numerical simulation indicate the presence of coherent turbulence inside the Primary Mirror shaft at lidar station. As is known, the coherent turbulence (compared to Kolmogorov turbulence) is depleted of small-scale inhomogeneities [6-11, 19, 20]. Therefore, on the basis of data [6-11], inside the closed shaft we expect the weakening of the phase fluctuations of the optical radiation, and therefore [6-11], we also expect the improvement of lidar optical images.

3. We consider the performed complex of actions for studying the structure of air turbulent motions inside the closed shaft at lidar station (the experimental measurement and numerical simulation without exchange of internal and external medium through the borders) as the first step to study the efficiency of Siberian Lidar Station of IAO SB RAS. The next step – the study of the structure of air turbulent motions inside the open shaft in conditions of free heat exchange and mass exchange between the shaft and open atmosphere.

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