Journal of Engineering Physics and Thermophysics, Vol. 72, No. 4, 1999

NUMERICAL ANALYSIS OF THE WIND REGIME IN THE NEIGHBORHOOD OF PULKOVO AIRPORT

S. A. Isaev, L. Yu. Belousova, and P. A. Baranov

UDC 532.517.4

The wind field in the neighborhood of Pulkovo airport is investigated by numerically solving the Reynolds equations by the finite-volume method, closed by means of the dissipative two-parameter turbulence model, and using multilayer near-wall functions.

1. As is known, the problem of providing a high degree of safety of take-off and landing of aircraft is determined to a large extent by peculiarities of metereological conditions caused by the influence of the aerodynamic surface in the neighborhood of airports. Therefore it seems urgent to create an automatic forecasting complex which allows modeling of the orography in proximity of an airfield and an analysis of its influence on the formation of wind regimes, the conditions in the near-ground atmosphere layer which are dangerous and complicated for aviation. From the practical point of view this complex is intended not only for determination of rational location of airports constructed or reconstructed but also can serve as a basis of an operating system of routine determination of wind shear conditions that are critical for take-off and landing of aircraft in active airports of the country and, in particular, in regions with a complex relief. It should be noted that the ecological problems to which the problem under consideration pertains enter the catalog of fundamental problems of the current computational hydrodynamics along with turbulence modeling and conjugated problems.

The genesis of these problems [1-3] is related, on the one hand, with improvement of calculation instruments in the field of local eddy aerohydromechanics [4] and their extension to so-called mesoscale models [5] and, on the other hand, with development of ecological monitoring, with construction engineering problems, with evaluation of the harmful influence of transport, etc. [6]. Undoubtedly, numerical modeling in metereology has long held a firm place since without it weather forecasting is unthinkable. An analysis of agrophysical processes is of no less significance. However, the methods of investigation of the indicated processes take into consideration, first of all, their geoscale and they are too rough and approximate as applied to mesoscale phenomena. In fact, there are correct calculation approaches based on solution of spatial equations of motion of an air medium with corresponding equations of closing models. Here, only the works [7, 8] should be mentioned, where in [7] a numerical study is made of impurity transfer between regions, while in [8] a flow around a complex relief is considered. Here, numerical modeling of a three-dimensional near-ground flow is accomplished within the framework of the finite-volume procedure of solution of Reynolds equations closed by means of the two-parameter turbulence model of differential type. A calculation is made on the locality, a relief of which is prescribed in the electronic chart; the ordinary near-wall functions for an impermeable smooth wall are chosen as boundary conditions.

In the present work a universal forecasting tool for solving the three-dimensional problem of motion of a turbulent air flow in the vicinity of an airport is developed with the concept of the two-scale approach taking into account the influence of the curvilinear relief of a locality with the use of a calculation grid matched with a streamlined surface of the calculation grid and the influence of variable roughness by prescribing near-wall functions of a special type. Such a statement of the problem seems to be original.

In the course of solving the problem for Pulkovo airport, taken as an example, the following operations have been carried out:

Academy of Civil Aviation, St. Petersburg. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 72, No. 4, pp. 672-677, July-August, 1999. Original article submitted October 2, 1998.

a) numerization of the locality in the form of electronic relief and roughness charts;

b) creation of an application package for wind forecasting in the vicinity of the airfield (10 × 10 km), which includes an *editor* (preprocessor) for constructing a three-dimensional nonorthogonal grid; a *problem solver* for determination of the parameters of an air medium at points of the three-dimensional grid constructed by using the finite-volume implicit factorized procedure of separation with respect to physical processes to solve the Reynolds-averaged Navier–Stokes equations closed with the aid of the two-parameter dissipative turbulence model; a *graphical interpretator* (postprocessor) of the calculated data obtained;

c) determination of a rational structure of the database for making parametric calculations of evaluation of the influence of a wind profile at the inlet boundaries on formation of a wind regime;

d) an analysis of numerical results on the influence of the direction of a moving air flow and the thickness of the atmospheric boundary layer on wind speed distribution along glissade.

2. The core of the calculation software complex is a solver of the equations of motion of an air medium designed under the assumption that the processes under consideration depend mainly on convective transfer and turbulent diffusion. Taking into account that the primary interest is recovery of wind shear flows developed around the airport near the ground, in the first stage it is targeted to neglect the temperature stratification and moisture effect.

The well tested implicit factorized algorithm of solution of the Navier–Stokes equations, which is based on the concept of separation with respect to physical processes and realized in the pressure correction procedure SIMPLEC, is used to calculate three-dimensional flows of an incompressible viscous fluid. The governing equations in the delta-form for increments of dependent variables, for which natural variables, i.e., the cartesian velocity and pressure components are chosen, are written in arbitrary curvilinear coordinates matched with a streamlined surface. Digitization of the convective terms of the explicit part of the transfer equations using the Leonard scheme [4] allows minimization of the influence of the effects of numerical diffusion, which are rather substantial in modeling of separated flows, in particular, at high Reynolds numbers. The high computational efficiency of the calculation procedure is attributed to digitization of the convective terms in the implicit part of the transfer equations using the counterflow scheme of the first order of approximation in combination with introducing extra diffusion, which provides obtaining of a solution without false oscillations (monotonicity of the solution), and applying the method of incomplete Boolean array factorization in the Stone version of the SIP procedure. The computation pattern is centered, i.e., all variables are determined in the center of a calculation cell. Therefore, in writing the pressure correction equation use is made of the Rhi–Chou approach related to introducing a monotonizer (or a regularizer, as it is called in some works) of pressure correction. A distrinctive feature of implementation of the algorithm considered is the use of the simplified approach in interpretation of metric coefficients on the basis of their analytical representation. Such a formulation is rather simply accomplished in the context of separation of variables. This approach is possible owing to the a priori chosen grid architecture, i.e., Cartesian grids in the plane $x-z$ and oblique grids generated in transverse and longitudinal sections with a family of vertical grid lines perpendicular to the direction of incoming flow. This approach makes it possible not only to save computational resources but also to eliminate, in fact, the errors related to the difference approximation of a metric. Implementation of the constructed calculation algorithm as applied to the two-dimensional problems of turbulent flow around curvilinear objects is described in detail in [9].

An analysis of the velocity profiles in an atmospheric turbulent boundary layer [10] shows that their diversity and sometimes a considerable difference from the logarithmic law is attributable to the orographic roughness effect. Here, the decisive factor in the deformation of profiles is not only the scale but also the qualitative evidences (for instance, buildings, forest stand, grass cover, and other categories of roughness are distinguished).

It is obvious that in the present study it would be difficult to determine immediately the influence of diverse roughness on formation of a velocity profile, the more so since information on some roughness categories mentioned is practically absent. Nevertheless, development of an approach, similar to calculation of vapor-gas flows and related with tabular representation of the roughness effect with respect to the chosen classification system of indicators, is in sight.

Fig. 1. Menu of the application program for graphical processing of the calculated information – postprocessor. A field of isotaches, marked off on the locality relief, at the south wind and with a thickness of the boundary layer of 100 m.

In a simplified statement the problem is solved within the framework of the concept of separation of a locality relief into the relief as such and the roughness marked off on it, i.e., the so-called two-scale approach is implemented. A massif of heights corresponding to the relief is prescribed based on the electronic chart of the locality and is put, as the initial data, into the construction block matched with the streamlined surface of the curvilinear calculation grid. The second massif characterizing the roughness size distribution is connected to the block of calculation of wall boundary conditions with the use of wall functions. In the work, the modified wall functions [11] written in an approximation of homogeneous sand roughness of variable size are chosen.

For creation (and elimination) of roughness a special roughness generator is developed which makes it possible to separate zones of different geometry on a relief, give different dimensions to them, and provide their input into the corresponding massif of the initial data.

The development discussed leans mainly upon a computer analog of a wind tube experiment when the locality relief investigated is arranged in the working section of the tube and is blown by a specially formed flow, i.e., with regulation of the velocity profile of the incident flow. As in this laboratory experiment, in implementation of numerical modeling the problems of conjugation of a relief with a flat wall, and of the influence of boundary conditions on flow pattern in the neighborhood of an object considered emerge. They are solved by creating a buffer transition zone outside the object and arranging the boundaries of the working region at a sufficient distance from the zone of focused attention.

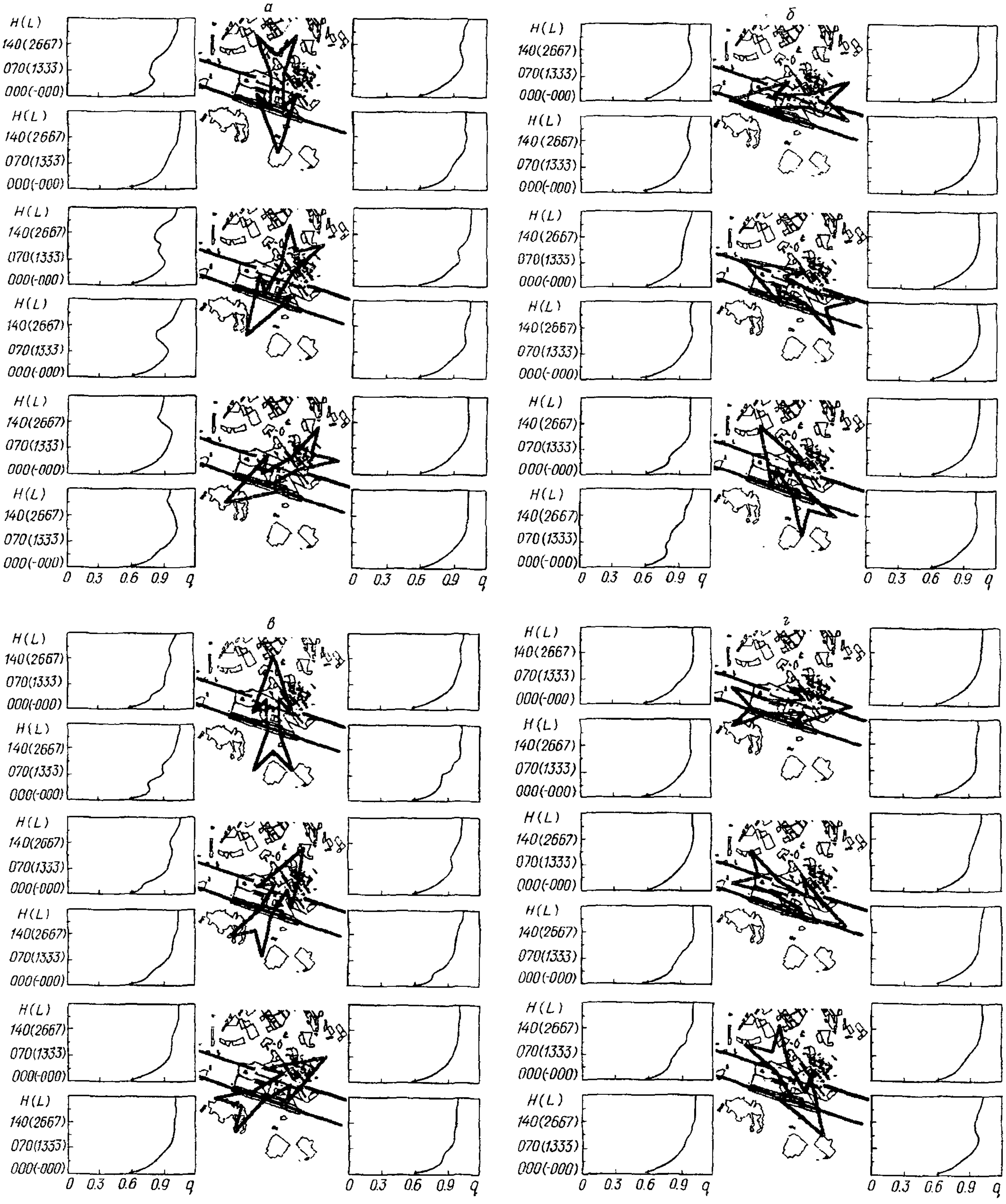

Fig. 2. Wind speed distribution along glissades in Pulkovo airport at a thickness of the atmospheric boundary layer of $h = 100$. Changes of the direction of undisturbed wind flow, shown by an asterisk, at steps of 30°: a) $\theta = 0-60°$; b) 90–150°; c) 180–240°; d) 270–330°.

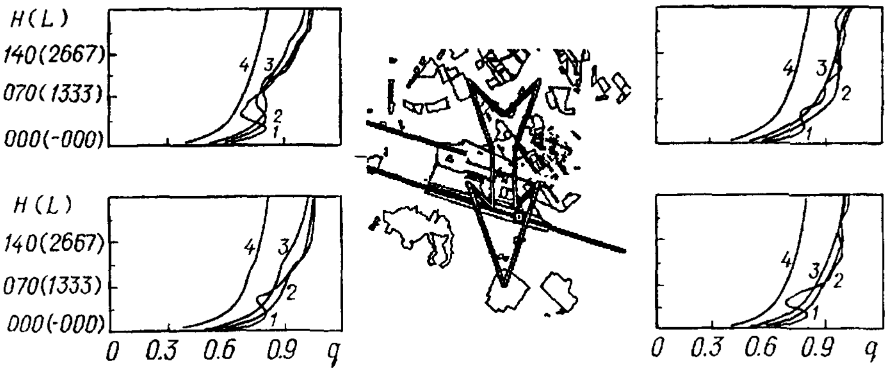

Fig. 3. Wind speed distribution along glissades in Pulkovo airport at different thicknesses of the atmospheric boundary layer: 1) $h = 50$ m, 2) 100, 3) 200, 4) 1000.

The reliability and validity of the numerical results obtained is provided by comprehensive testing of procedures, algorithms, and program complexes as applied to three-dimensional test problems, including solution of the problem of a viscous fluid flow around a spherical hole [12]. The present development is made as applied for Pulkovo airport.

Consideration is given to the 10,000 × 10,000 m region surrounding the airport, in which a square oriented relative to the prescribed direction of an incoming wind flow is separated. The center of the region coincides with the airport center. The calculation region is a parallelepiped, one of the bases of which is the indicated square, with a height of 5000 m.

At the input boundaries the weak boundary conditions are prescribed (the conditions of continuation of a solution from internal points to the region boundary). For solid surfaces the boundary conditions corresponding to local equilibrium of wall turbulence are fulfilled. Calculation of a steady-state flow around the curvilinear surface with a constructed roughness is made on the grid containing 51 × 31 × 51 meshes with thickening to the center of the region.

3. Figures 1, 2, and 3 show some of the results obtained for the turbulent near-ground low-velocity air flow part of a relief of the locality in the neighborhood of Pulkovo airport at $\mathrm{Re} = 10^5$ and with the direction of wind changing from 0 to 360° (circular blowing).

Figure 1 demonstrates the functional capabilities of the graphical interpretator of calculated results: distribution of isotaches over a reference curvilinear surface equidistant from a streamlined wall with drawn contours of the relief and airport buildings, including take-off strips. A provision is made for processing of all dependent flow parameters, turbulence characteristics, vorticity components, moduli, and the local flow velocity. Here, the fields of the quantities are represented as isolines and numeralized color charts in the characteristic sections of the calculated region: planes xy, xz, yz and curvilinear reference surfaces arranged above the relief. It is also interesting to analyze a velocity profile at each point of the relief in order to relate its deformation to the change in roughness and height drop over the locality.

Based on information about space characteristics of the wind flow in the neighborhood of the airport obtained in parametric calculations, a database (DB) has been developed for speed distributions along the characteristic trajectories of aircraft take-off-landing glissades. The input parameters in the DB are the wind direction and the thickness of the atmospheric boundary layer. Provision is made for DB extension to natural conditions by means of input of data of wind speed measurements at heights of 10 and 700 m as well as of wind direction at a height of 700 m. Here, using the interpolation procedure the corresponding thickness of the atmospheric boundary layer is determined on the assumption that a logarithmic speed profile is formed in the vicinity from the ground and thus the wind speed distribution is restored along glissades and in the airport zone as a whole.

An analysis of the wind speed profiles (Fig. 2) constructed along glissades, with circular blowing of the region of Pulkovo airport, reveals a relationship between the profiles deformations and the roughness distribution in the zone under consideration. It is interesting to note that the most pronounced wind shifts are observed along the glissade nearest to airport buildings within the range of angles θ 0–60°, i.e., for north and northeastern winds. Here, it should be taken into account that the thickness of the boundary layer in the situations depicted in Fig. 2 is rather large and makes 100 m.

As is shown in Fig. 3, upon decreasing the thickness of the atmospheric boundary layer to 50 m the speed shifts become more pronounced. At the same time for thick boundary layers (of about 1000 m) the response of the speed profile to local roughness is practically absent.

The work was carried out under financial support from the Russian Fund for Fundamental Research (grants Nos. 99-02-16745 and 99-01-00722).

NOTATION

x, y, z, longitudinal, vertical, and transverse Cartesian coordinates; u, v, w, Cartesian speed components; Re, Reynolds number; q, modulus of the local velocity of the wind flow; $q = \sqrt{u^2 + v^2 + w^2}$; H, L, vertical and longitudinal coordinates of glissade points reckoned from the site of landing of an airplane, m; h, thickness of the atmospheric boundary layer, m; θ, angular coordinate of the wind flow reckoned from the north direction, deg.

REFERENCES

1. S. A. Isaev and A. I. Leont'ev, in: *Proc. of the All-Russia Conf. "Microclimate of Landscapes,"* St. Petersburg (1995), pp. 80-85.
2. S. A. Isaev, P. A. Baranov, and L. Yu. Belousova, in: *Proc. of the Int. Symposium "Hydrometeorology: Science and Practice, Contemporaneousness and Prospects,"* St. Petersburg (1997), pp. 28-30.
3. P. A. Baranov, L. U. Belousiva, and S. A. Isaev, in: *Proc. of the 2nd East European Conf. on Wind Engineering,* Prague (1998), pp. 155-160.
4. I. A. Belov, S. A. Isaev, and V. A. Korobkov, *Problems and Calculation Methods of Stalled Flows of an Incompressible Liquid* [in Russian], Leningrad (1989).
5. A. A. Vasil'ev, in: *Proc. of the Int. Symposium "Hydrometeorology: Science and Practice, Contemporaneousness and Prospects,"* St. Petersburg (1997), pp. 19-20.
6. S. A. Isaev and A. G. Sudakov, in: *Proc. of the 6th Annual Scientific Conf. "Universities on the Eve of the Third Millennium: Noospehere, Ecology, Education"* [in Russian], St. Petersburg (1998), pp. 55-57.
7. M. Kadja, J. Anagnostopoulos, and G. Bergeles, in: *Proc. of the 7th Int. Conf. Comp. Fluid Dynamics*, Beijing (1997), pp. 1-7.
8. P. K. Chaviaropoulos and D. I. Douvikas, in: *Proc. of the 4th European Comp. Fluid Dynamics Conf. Athens*, Vol. 2, Pt. 2 (1998), pp. 842-848.
9. S. A. Isaev, N. A. Kudryavtsev, and A. G. Sudakov, *Inzh.-Fiz. Zh.*, 71, No. 4, 618-631 (1998).
10. S. S. Zilitinkevich, *Dynamics of an Atmospheric Boundary Layer* [in Russian], Leningrad (1970).
11. I. Nezu, H. Nakagawa, and A. Tominada, in: *Proc. of the 5th Int. Symposium on Refined Flow Modeling and Turbulent Measurement*, Paris (1993), pp. 629-636.
12. S. A. Isaev, V. B. Kharchenko, and Ya. P. Chudnovskii, *Inzh.-Fiz. Zh.*, 67, No. 56, 373-378 (1994).