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VERIFICATION OF THE MULTIBLOCK COMPUTATIONAL TECHNOLOGY IN CALCULATING LAMINAR AND TURBULENT FLOW AROUND A SPHERICAL HOLE ON A CHANNEL WALL

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A methodological numerical investigation of the three-dimensional flow of an incompressible viscous fluid around a deep spherical hole on a channel wall has been carried out within the framework of the multiblock approach on the set of intersecting rectangular and cylindrical grids.

1. The necessity of solving the topical problems of vortex intensification of heat-exchange processes in the case of flow around reliefs with spherical holes [1, 2] stimulated the development and employment of multiblock computational technologies, first of all, for analysis of the physical mechanism of self-generation of large-scale vortex structures in isolated holes. The preliminary stage of their development was refined numerical modeling of three-dimensional separated flow and heat exchange in a deep spherical hole on the plane based on solution of the Navier–Stokes equations by the factorized finite-volume method with the use of multiblock cylindrical grids [3, 4]. The main elements of multiblock algorithms on structurized intersecting grids have been substantiated in calculating two-dimensional flow around bodies with vortex cells with consideration for the intensification of circulation motion in the cells as a result of the rotation of central bodies or the suction from their surface as well as for the influence of nonstationarity and turbulence [5].

The three-dimensional version of multiblock computational technologies has been successively developed and used in [6–14] as applied to the interpretation of vortex dynamics and convective heat exchange in the neighborhood of isolated holes in flow, in motion of an air flow in a channel with a passive vortex cell, and in the case of fire in a moving subway car. The computational algorithms are tested based on the comparison of the results of numerical modeling and the experimental results obtained in the course of special physical investigations. This work specifies and complements information on verification of the tools developed for analysis of laminar and turbulent flow around a deep spherical hole located on one wall of a plane-parallel channel. We have selected [15, 16] as experimental prototypes.

2. The multiblock computational algorithms are developed on the basis of the implicit factorized methods of solution of the Navier–Stokes and Reynolds equations with the use of multiblock structurized grids with their partial superposition. A computer-aided analysis of the computational subregions with separation of computational and connected cells in each of the grids considered holds a central position in the technology [5]. In cells of the first type, the initial equations written in increments of dependent variables are solved with the use of the SIMPLEC procedure for a pressure correction, the upwind scheme of quadratic interpolation for approximation of the convective flows on the implicit side of the equations, means for controlling the convergence of the computational process, and the method of incomplete matrix factorization. In cells of the second type, the parameters are determined by the method of linear interpolation by the values at the computational points of the covering grid. Such an approach makes it possible not only to describe multiply connected regions with a complex geometry within the framework of the grids of simple topology, but also to substantially refine the solution in the separated subregions with marked changes in the characteristics of the flow and of the heat exchange: in the boundary layers, in the regions of near and far wakes, and in the local vortex and separation zones. The Reynolds equations are closed with the use of well-tested semiempirical

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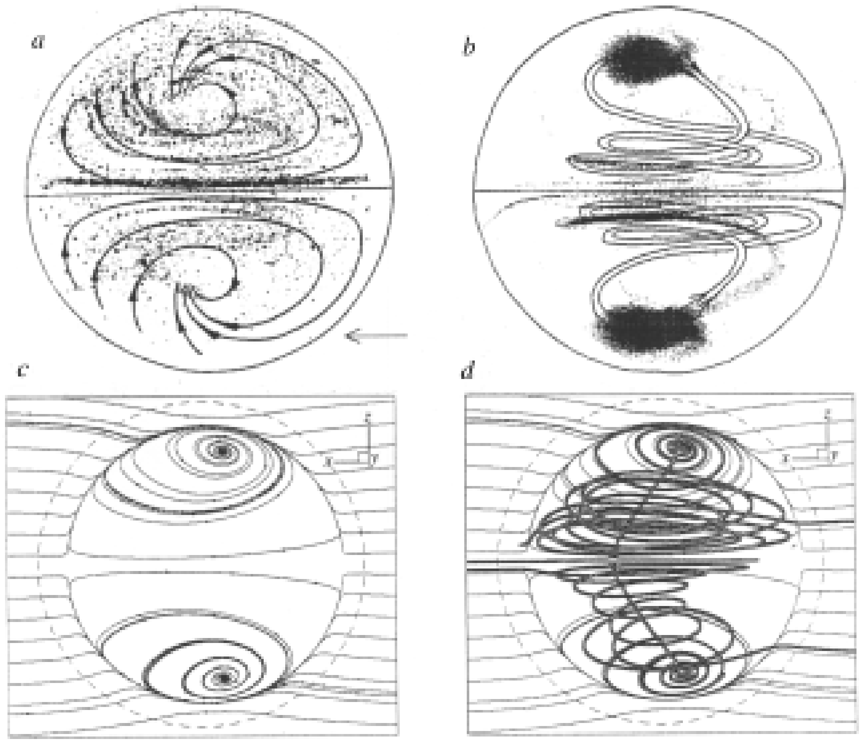

Fig. 1. Comparison of the experimentally observed [15] pattern of spreading of the fluid on the surface of the spherical hole of depth 0.22 (a) and structure of the vortex flow in it (b) to their calculated analogs (c, d) at Re = 2500.

two-parameter models of turbulence of the type of the k-ε dissipative model of Launder and Spalding and Menter's k–ω model [5].

3. To solve the problem of laminar flow around a deep spherical hole with a rounded sharp edge (with a rounded radius of 0.1), for a more precise resolution of different-scale structural elements of the flow (shear layer, the zone of reverse flow), a ring cylindrical subregion surrounding the hole is separated and built into the outer rectangular subregion covering the plane on which the hole is located. For better resolution of the near-wall flow in the neighborhood of the axis of the cylindrical subregion, a "patch" having the shape of a curvilinear parallelepiped is introduced. The multiblock grid consisting of intersecting curvilinear nonorthogonal grids of the O and H types contains about 250,000 cells. A detailed distribution of the grid points is presented in [13].

It is assumed that the velocity profile at the inlet boundary of the computational region corresponds to the Pohlhausen profile for the laminar boundary layer with a thickness equal to the depth of the hole. At the outlet boundaries, soft boundary conditions are realized (continuation of the solution from the internal points to the boundary of the region). The adhesion conditions are fulfilled on the wall. The velocity of the incoming flow outside the boundary layer and the diameter of the hole (the site of transition from the curved region to the plane) are prescribed as the dimensionless parameters. The Reynolds number is assumed to be close to the experimental one and equal to $2.5 \cdot 10^3$ [15].

As is seen from Fig. 1, where the structure of the vortex flow in the near-wall layer is demonstrated, physical visualization of the laminar flow in the hole is very close to its computer analog. The common hydrodynamic features in the form of singular points of the type of focuses with two symmetric vortex cells are seen. The physical model of the three-dimensional structure of the flow in the hole and its calculated analog also have similar features. Although the interaction of swirling jet flows gives rise to the outflow of the fluid from the center of the hole to the periphery, as is predicted in Fig. 1b, it also forms a jet flowing out of the hole in the neighborhood of the symmetry plane.

4. Turbulent flow in a narrow channel with a hole on one wall is calculated within the framework of the solution of the Reynolds equations closed using the two-parametric dissipative model of turbulence. A plane-parallel channel with overall dimensions $6.35 \times 1 \times 0.13$ with a spherical hole of depth 0.104, diameter 0.323, and rounded

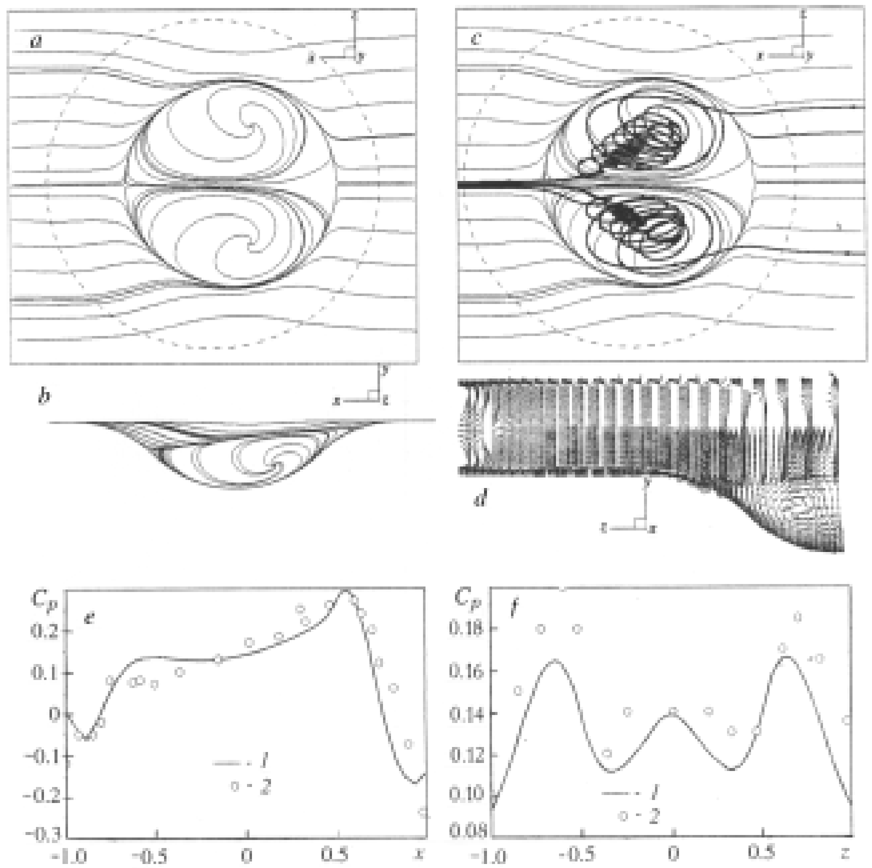

Fig. 2. Pattern of spreading of the fluid on the surface of the hole [a) top view, b) side view], vortex structure in the hole (c), pattern of directions of the secondary-flow-velocity vectors in the cross section of the hole (d), and graphs of distributions of the coefficient of surface pressure in the longitudinal (e) and transverse (f) planes [1) calculation; 2) experiment [16]].

radius of 0.173 is considered. The center of the hole is located at a distance of 2.52 from the inlet cross section. The Reynolds number is assumed to be equal to $4.4 \cdot 10^4$. The diameter of the hole is selected as the linear scale.

The rectangular grid with bunching of the points (the minimum near-wall step is assumed to be equal to 0.0017) to the walls of the channel contains $56 \times 48 \times 48$ cells. A cylindrical grid covering the hole and containing $30 \times 60 \times 30$ cells (the near-wall step is equal to 0.0009) is superimposed on it. The "patch" superimposed on the axis is subdivided by a grid with $17 \times 17 \times 30$ cells.

At the entrance to the channel, we prescribe a flow with a change in the velocity by the law 1/7 in the initial thickness of the boundary layer (which is assumed to be equal to 0.06) and its uniform distribution in the core. The turbulence parameters as a whole correspond to the experimental data [16]. Soft boundary conditions are realized at the exit from the channel. The method of near-wall functions is used in calculating flow in the neighborhood of the walls.

Turbulent vortex flow in the neighborhood of the hole in the channel whose structure is shown in Fig. 2a–d retains, on the whole, the features of the laminar analog. Symmetric vortex cells and tornado-like jet flows flowing out of the neighborhood of singular points of the type of a focus are characteristic elements for deep holes with very smoothed edges. It should be noted that the calculated and experimental data on the pressure coefficient in the longitudinal and cross sections of the hole are in good agreement.

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NOTATION

x, *y*, *z*, Cartesian coordinates; *k*, energy of turbulent pulsations; ε and ω, rate and relative rate of dissipation of turbulent energy; C_p, pressure coefficient; Re, Reynolds number.

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