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MODELING OF THE INFLUENCE OF VISCOSITY ON THE TORNADO HEAT EXCHANGE IN TURBULENT FLOW AROUND A SMALL HOLE ON THE PLANE

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The influence of viscosity on turbulent flow around a small spherical hole on the plane and on vortex heat exchange is analyzed numerically.

1. One of the "eternal" problems of modern hydromechanics, which has not lost its topicality for several decades, is analysis of the influence of viscosity on separated (detached) flows. The investigations of the influence of the viscosity or the Reynolds number on the circulatory motion of a fluid in a square hole [1, 2] have received much recognition. In them, prominence is given to the evolution of vortex structures with increase in Re. A change in the relation between convection and diffusion and an increase in Re are favorable for intensification of circulatory flow and for generation and evolution of the secondary and then tertiary vortex structures in the hole. It should be noted that the flow in question belongs to the type of separated flows with a fixed separation point. Such flows are usually realized in the neighborhood of bodies with sharp-pointed edges. In [1], the data of investigations of the influence of viscosity on axially symmetric flow around bodies of different geometries (disks, cylinders, and their combinations) and on plane flow around finned plates have been generalized.

Separated flows of the second type are identified as flows with an unfixed separation point. They include, first of all, flows around smooth bodies of the type of a cylinder and a sphere and flows around elongated configurations with smoothed nose and stern parts. A detailed analysis of the influence of Re on two-dimensional laminar flow around a cylinder has been made in [3], while the influence of Re on laminar and turbulent flows around a profile of complex geometry (in the form of a car) in the presence of a mobile shield (baffle) has been investigated in [4].

For years, the analysis of the evolution of separated flows with increase in Re has been restricted mainly to consideration of two-dimensional flows of an incompressible fluid. However, in the last decade, investigations of three-dimensional separated flows have become more active. Marked progress in understanding the mechanisms of vortex intensification of heat and mass exchange processes in the neighborhood of the relief with holes in flow [5, 6], decrease in the drag, and head stabilization of bodies with organized separation of the flow [7] is associated with identification of spatial jet-vortex structures in the zones of developed separated flow. The typical structures characteristic of separated flows in different geometric shapes have been revealed in both a limited space (of the type of a cubic cavity [12]) and a partially limited space (of the type of channel and near-wall flows).

2. The genesis of investigations of the influence of viscosity on separated flows is closely related to the evolution of computational algorithms based on numerical solution of Navier–Stokes equations. It should be noted that at the initial stage of the development of numerical modeling of viscous-fluid flows, the computational resources were limited; that is why two-dimensional problems simple in geometry were considered in combination with representing the initial equations in transformed vorticity-stream function variables. The next stage of the investigations was characterized by the development of efficient and high-accuracy algorithms to calculate circulatory flows, and increased attention was given to the interpretation of the effects of numerical diffusion or system viscosity, associated with the approximation of convective terms of transfer equations [1]. Computational technologies widely used now in different commercial products for numerical modeling of physical-engineering and hydrodynamic processes were formed at about the end of the 1980s–beginning of the 1990s. The finite-volume procedures based on the concept of splitting by physical processes and application of structurized single-block grids have been analyzed in [1] in detail. It should be

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noted that by that time the methodology of solving three-dimensional problems of vortex dynamics was formed on the whole.

It is of interest to track further development of the computational algorithms with the example of the numerical modeling of flow around an isolated hole on a plane wall, especially because this problem is the objective of the present work. There is one more important aspect of the problem, which also concerns the present investigation. We are dealing with the turbulence models used to close the Reynolds-averaged Navier–Stokes equations. We note that at the beginning of the 1990s, the two-parameter dissipative turbulence model proposed by Launder and Spalding and known as the k–ε model was most widely used [1]. Being modified with allowance for the influence of the curvature of streamlines on the characteristics of turbulence, it has been tested successfully in calculating separated flows with a fixed separation point and has shown good performance in solving problems of flow around a cylinder and a profile in the presence of a shield [3, 4]. Its advantages were pronounced in obtaining numerical solutions on fairly coarse grids, which was typical for the beginning of the 1990s.

Thus, in [8–10] the indicated approach with the use of the k–ε model and rectangular grids adapted to the surface of the hole in the transformed computational region made it possible to obtain preliminary information on the vortex structure in shallow and deep holes. However, the accuracy of the predictions was rather low because of the small (of the order of several thousands) number of computational cells within the limits of the separation zone. Nonetheless, the experience gained from the numerical modeling was very important, since it pointed the way for feature research, including the development of advanced computational tools.

The application of a cylindrical grid to analysis of a laminar separated flow in a hole was an intermediate but extremely important stage. This grid made it possible to determine the structure of vortex flow more exactly owing to the increased number (several tens of thousands) of cells within the hole. However, the calculations of turbulent flows on such grids involved difficulties that have been resolved in [11] within the framework of the multiblock approach on the basis of intersecting grids of various types. Thus, the use of an additional rectangular subregion overlapping the near-axis zone of a cylindrical grid is favorable for obtaining a monotonous solution in the indicated zone. On the whole, the approach developed representing a generalization of the two-dimensional discrete multiblock model for analysis of flow around bodies with vortex cells [12, 13] has a very important advantage — it correctly accounts for different-scale flow elements on a set of structurized intersecting grids. It should be particularly emphasized that the location of a fine grid in the near-wall zone made it possible to use the low-Reynolds zonal model of Menter [14], which is more suitable for the near-wall turbulent flows and represents a combination of the low-Reynolds k–ε model of Saffman–Wilcocks and the high-Reynolds k–ε model.

Menter's model of turbulence was tested in solving a number of test two-dimensional problems. They included the problems of motion of a low-velocity air flow in a channel with a circular cavity [15] and of stationary flow around a circular cylinder with a dividing plate in the near wake with a vortex cell mounted into the contour and without it [16]. The results of the numerical predictions of the local and integral characteristics of separated flow have been compared to the corresponding data of physical experiments, including the experiment carried out on the setup of the Institute of Mechanics of Moscow State University.

Mention should be made of the experience gained in the calculations within the framework of the multiblock approach to turbulent flow around isolated holes of different shapes which are located on both the plane and the wall of a channel [17–19]. First of all, it has been established that the character of a large-scale vortex flow in a hole depends on its shape. A two-cell vortex transforms into a single-vortex pattern when the side wall of a spherical hole is deformed [17]. As a result, in an asymmetric hole we have a tornado-like vortex coming out of the hole at an angle of about 45^{o}. The analysis of flow around holes in the case where their degree of asymmetry is varied has shown that when such holes become spherical, bifurcation of the vortex flow in them occurs. It has been established that there is an interrelation between the type of vortex structures and the level of heat transfer from the wall [18]. The comparison of the calculated and experimental distributions of the pressure coefficient in the characteristic cross sections of the hole with smoothed edges made in [19] has shown that they are in acceptable agreement.

It is important to note that the investigations carried out were mainly concerned with the problems of three-dimensional vortex dynamics, while the prediction of vortex heat exchange has received much less attention. Because of this, one aim of the present work is methodological testing of the computational algorithm meant for numerical modeling of vortex convective heat exchange in three-dimensional separated flows.

3. Certain features of the computational algorithm have already been briefly analyzed, especially because an important characteristic of any algorithm, including the algorithm in question, is its succession, i.e., any subsequent version involves the main blocks of the previous one. In the present work, we solve the problem of turbulent convective heat exchange for the three-dimensional vortex flow of an incompressible viscous fluid in the neighborhood of an isolated spherical hole on the plane. In this case, the heat problem is considered separately from the dynamic problem, i.e., the energy equation is solved for the already calculated velocity fields and turbulence characteristics.

As has already been noted, the calculation of the stationary turbulent vortex flow near a hole is based on the concept of splitting by physical processes. It was applied to solution of the Reynolds equations closed with the use of Menter's zonal model of turbulence. Its use makes it possible to realize the process of global iterations, the core of which is the known SIMPLEC procedure of pressure correction. This two-step procedure of the "predicator-corrector" type is meant for determining the Cartesian components of velocity and pressure for frozen fields of the vortex viscosity and turbulence characteristics. The important components of the developed finite-volume algorithm are: a) representation of the initial equations in increments of dependent variables, b) approximation of the convective terms on the explicit side by the Leonard upwind scheme with quadratic interpolation, c) approximation of the convective terms on the implicit side by the upwind scheme with unilateral differences, d) introduction of artificial diffusion into the implicit side for damping high-frequency oscillations, e) use of the Rhee–Chou monotonizer in the pressure-correction unit because of the centered computational template with the coefficient 0.1 determined empirically, and f) solution of the difference equations by the method of incomplete matrix factorization.

In the global iteration process, local iterations of solution of the equations for the turbulence characteristics are also carried out at each step.

Within the framework of the multiblock algorithm, besides the computational cells, in which the system of initial equations is directly solved, there are connected cells located at the sites of intersection of the grids. In such cells, the parameters are determined using the method of nonconservative interpolation described in detail in [16]. Its acceptability has been proved by numerous test calculations [15, 16].

To stabilize the calculation process the lower relaxation with coefficients for the velocity (0.5), the pressure (0.8), the turbulence characteristics (0.5), and the vortex viscosity (0.35) is introduced at each iteration step.

In solving the steady-state energy equation, the general features of the computational algorithm are retained. We note that the Prandtl number of the medium is taken to be 0.7 and the turbulence Prandtl number is taken to be 0.9.

4. In [20], physical modeling of a low-velocity air flow around a spherical hole with a depth of 0.14 (in fractions of the hole diameter) has been carried out on a small-size setup. The steam heating of the lower wall of the working part of the wind tunnel provided a wall temperature close to 100°C. A spherical hole of diameter 65 mm and depth 9 mm was located on the heated surface. A feature of the conducted experiments was that the heat fluxes were directly and immediately measured using gradient detectors (GDHF) and the surface of the hole was kept at constant temperature.

The local heat-transfer coefficients in different regions of a single hole have been investigated experimentally, and the total coefficients have been estimated by the circular (along the edges of the spherical hole) surface element.

Numerical investigation of turbulent flow around a hole of depth 0.14 on the plane and of vortex heat exchange in its neighborhood is carried out under the conditions corresponding to the conducted experiment. The Reynolds number is varied from $2.3 \cdot 10^4$ to $6.4 \cdot 10^4$. The thickness of the boundary layer of the order of the hole depth is selected at the entrance to the computational region. The temperature of the wall is taken to be 100°C, while the temperature of the incoming flow is taken to be 20°C.

The computational region represents a curvilinear parallelepiped with a lower boundary coincident with the washed plane on which the spherical hole is located. It is assumed that at the entrance to the region there is a uniform flow with a characteristic velocity U and a boundary-layer thickness of 0.17. Within the boundary layer, the longitudinal velocity component changes by the law 1/7, and the other velocity components and the excess pressure are assumed to be equal to zero. The turbulence characteristics at the entrance to the computational region correspond to the conditions of the physical experiment; the degree of turbulence of the flow is taken to be 1.5%. Adhesion conditions are set on the wall, and the turbulence characteristics in the near-wall zone are selected according to [14–16]. At all

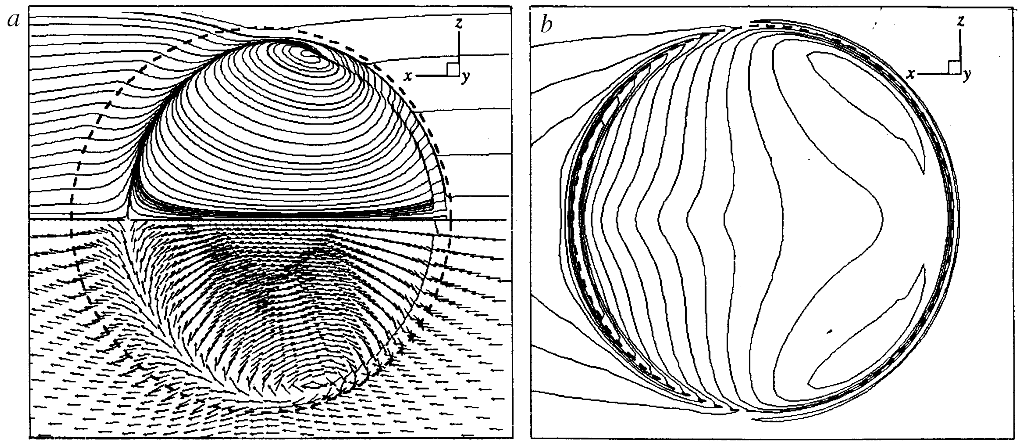


Fig. 1. Pattern of spreading of the fluid over the surface of a spherical hole of depth 0.14 (a) and pattern of isotherms in the near-wall layer at a distance of 0.0004 from the wall drawn with a step of 0.5^o from 92.5 to 99^{o}C (b). $\mathrm{Re} = 2.3 \cdot 10^4$. The dashed lines are the edges of the hole.

the other boundaries, the "soft" boundary conditions or, in other words, the conditions of continuation of the solution are specified. The diameter of the hole *D* is selected as the dimensionless scale.

Four different-scale grids are introduced to solve the problem with an acceptable accuracy. The above-indicated computational region of dimension 12 × 5 × 10 is digitized using an external grid containing 55 × 50 × 40 computational cells. The size of the near-wall step is selected to be 0.0008. The area of the spherical hole, the center of which with coordinates $x = z = 0$ is at a distance of 5 from the entrance boundary, represents a ring-like cylindrical subregion of diameter 2 which looms 0.175 above the plane. The indicated subregion is covered with a cylindrical grid matched with the washed curvilinear wall and containing 40 × 40 × 80 cells. The near-wall step for this grid is equal to 0.0008. The longitudinal step of the grid in the region of the sharp-pointed edge is 0.015. The radius of the inner ring is selected to be 0.1 and the grid in the circumferential direction is assumed to be uniform.

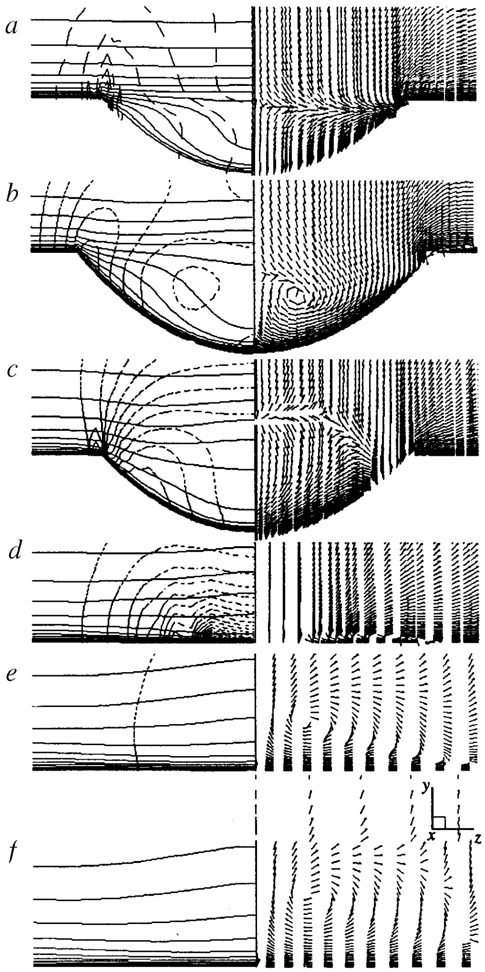
The cylindrical zone inside the ring is covered with a subregion in the form of a parallelepiped with a curvilinear base with square dimensions 0.5 × 0.5. The grid within this subregion is matched along the vertical coordinate with the adjacent cylindrical grid, and the base is subdivided into 12 × 12 uniformly arranged cells. The role of such a "patch" has been discussed above.

To calculate the parameters within the hole and in the wake of it with a proper accuracy, an additional computational subregion in the form of a parallelepiped with dimensions 3.5 × 0.175 × 2, containing 55 × 35 × 30 cells, is introduced. The near-wall step is also equal to 0.0008, and the origin of the subregion is tied to the point with coordinates of $x = -0.75$, $z = 0$.

5. Some of the results obtained are presented in Figs. 1–4.

As is seen from the pattern of spreading of the fluid over the surface of a shallow spherical hole at $\mathrm{Re} = 2.3 \cdot 10^4$, a symmetric two-cell vortex structure is realized within the developed separation zone (Fig. 1a). As in the case of the laminar flow around a hole at high (of the order of $(1.5–2.5) \cdot 10^3$) Reynolds numbers [6], the flow is separated along the line located somewhat lower than the leading (relative to the incoming flow) sharp-pointed edge. But for the selected depth of the hole, the flow is attached on a circular line located at a certain distance from the trailing sharp-pointed edge. It should be noted that the separation point in the bottom region of bodies with sharp-pointed edges of the type of a backward step is located, as a rule, in the neighborhood of the sharp-pointed edge but does not coincide with it [1]. The separation line within the hole, which follows the shape of its edge, degenerates into a streamline that separates the peripheral part of the near-wall layers of the fluid not finding themselves in the hole from the central flow directly forming three-dimensional separated flow.

Because of the limited area of the spherical hole, the attachment of the indicated flow to its curvilinear wall differs significantly from that in the case of a two-dimensional separated flow. It should be emphasized that the two-dimensionality of flow in the separation zone is the degenerate metastable state of a fluid medium. It has been estab-



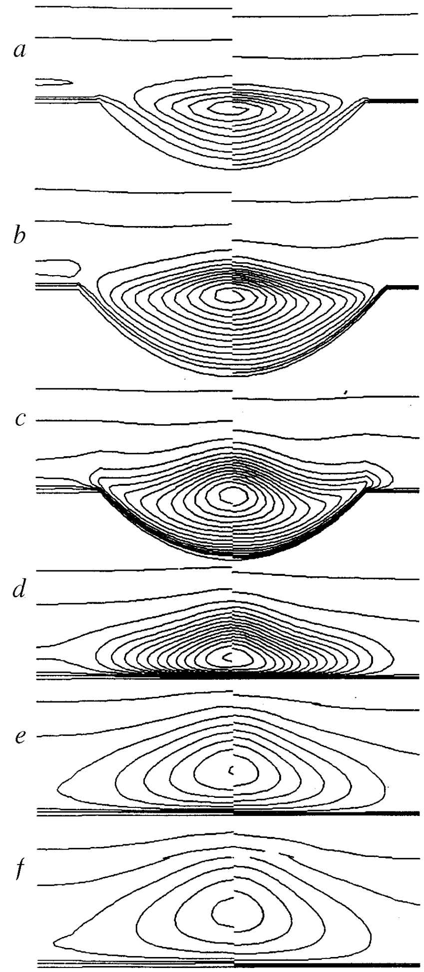


Fig. 2. Patterns of isotherms drawn by solid lines with a step of 5^{o} from 35 to $90^{o}C$ and isobars (dashed lines) (in the left half-plane) and patterns of velocity-vector directions (in the right half-plane) in different cross sections of the flow: a) $x = -0.25$ ($p = \text{const}$ are drawn with a step of 0.002 from –0.02 to –0.008), b) 0 ($p = \text{const}$ are drawn with a step of 0.002 from –0.004 to 0.006), c) 0.25 ($p = \text{const}$ are drawn with a step of 0.005 from –0.005 to 0.045), d) 0.5 ($p = \text{const}$ are drawn with a step of 0.005 from –0.015 to –0.1), e) 1 ($p = -0.015$), and f) 1.5.

Fig. 3. Patterns of isolines of the turbulent pulsation energy drawn with a step of 0.002 from the level 0.002 at $\text{Re} = 2.3 \cdot 10^4$ (in the left half-plane) and $6.4 \cdot 10^4$ (in the right half-plane) in different cross sections of the flow: a) $x = -0.25$, b) 0, c) 0.25, d) 0.5, e) 1, and f) 1.5.

lished experimentally that in "two-dimensional" separated flows of the type of flow past a backward step there exist three-dimensional vortex formations of the type of Hertler vortices with splitting of the flow into vortex cells in the transverse direction. Of course, a certain weakness of spiral-like longitudinal vortex structures, which manifests itself as a low intensity of the transverse fluid flow, indicates that the separated flow in this case is quasi-two-dimensional in character. However, for the spherical hole the formation of such structures in the case of spreading of the fluid over its walls is an important feature of the substantially three-dimensional separated flows in question. As is shown in Fig. 1a, the field of velocity vectors of the flow in the near-wall layer demonstrates that the fluid flows down along the line of attachment of the separated flow in the direction from the periphery of the hole to the symmetry plane. Thus, in the symmetry plane, we have the interaction of two near-wall flows which form the pattern of spreading of the fluid within the hole. It should be noted that there is a small gap between the separating streamline which is a continuation of the separation line and the spreading line. In analyzing the laminar regimes of flow around a hole [6], it has been revealed that the zone of separated flow in the hole is open on the side, i.e., there are side windows through which mass can be supplied to the zone or removed from it. However, of great importance is the degree of opening of the separation zone and the orientation of the windows either in the direction of the incoming flow or in the opposite direction. Thus, for a turbulent flow around a deep spherical hole with a smoothed sharp-pointed edge it has been established that the flow from the peripheral regions moves directly into it through the indicated windows, enhancing convective transfer [17].

As the numerical investigations of the laminar flow around an isolated hole have shown, it is very important to analyze the character of the separated flow on the side slopes of the hole, since it exerts a dominant influence on the formation of the structure of elements forming the flow within the hole. As in the case of Reynolds numbers of the order of $(1–2.5)\cdot 10^3$, in the case of spreading of the fluid over the peripheral part of the hole there are singular points of the type of focuses, which are arranged symmetrically relative to the geometric symmetry plane of the hole in the immediate vicinity of the separation line. In principle, in contrast to a deep hole [17], the source located at the indicated singular point is not of high intensity. As has already been indicated, the character of vortex spreading of the fluid over the surface of the hole is formed to a large extent as a result of the interaction of the flows in the symmetry plane. The counter (relative to the external flow) jet formed is incident onto the front slope of the hole, spreading in the neighborhood of the separation line. Because of the sharp-pointed edge of the hole, the spreading becomes stepwise and discontinuous in character, which manifests itself as a small shift of the streamlines. We can even speak of the fact that the line of spreading of the near-wall jet flow does not coincide with the line of separation of the flow in the hole.

Analysis of the temperature fields in the near-wall zone of the hole shows that the layers are heated most strongly precisely in the neighborhood of the separation zone of the flow, and the largest heat loads arise in the region of the trailing sharp-pointed edge of the hole (Fig. 1b).

Investigation of the secondary vortex flow, demonstrated in Fig. 2 in combination with deformation of the fields of temperature and excess pressure in different cross sections of the neighborhood of the plane wall with a hole, is typical of an analysis of three-dimensional vortex flows. It should be noted that since a shallow hole (0.14) is considered, the scale of the vertical coordinate is doubled for a clearer description of changes in the fields of the characteristics in the cross sections of the near-wall flow (Figs. 2 and 3). The observation of the evolution of the secondary turbulent motion begins in the leading zone of the hole at $x = -0.25$ and ends behind it in its near wake at $x = 1.5$.

As in the near-wall layers, the flow developed in the space of the leading part of the hole (Fig. 2a) is centrifugal (from the symmetry plane) in character. At the same time, there are ascending streams inside the hole and descending streams outside it. The peripheral fluid layers are drawn into the area of the hole, which reflects the "vacuum-cleaner" effect described in [10]. The flow–flow interface located somewhat lower than the plane wall at the level of the separation line is clearly seen. On the whole, the cross section of the hole in question is located in the zone of negative excess pressure with several local maxima in the neighborhood of the sharp-pointed edges. The temperature field does not have any interesting features: temperature stratification is realized in the near-wall layers of the fluid.

The pattern of secondary flow in the middle cross section of the spherical hole differs markedly from the above-considered one (Fig. 2b). Penetration of the external flow into the hole with change in the character of motion in the fluid layers adjacent to the wall is dominant. The flow from the periphery of the hole to the symmetry plane becomes determining, and, in combination with strong descending streams, it gives rise to a large-scale circulatory motion within the hole. In the region considered, there is a zone of decreased pressure ($p = -0.002$), whereas at the edges of the hole the excess pressure is positive and fairly high (p is of the order of 0.006). This occurs despite the fact that the pressure in the area of the hole is decreased (of the order of –0.004), which, to a large extent, is responsible for the effect of entrainment of the near-wall fluid layers by the hole.

The next cross section of the hole (Fig. 2c) is unusually interesting as far as the structure of the flow observed is concerned. First of all, it should be noted that the character of the external fluid motion changes. The flow begins to be rejected by the hole, which, however, is to a large extent attributed to the formation of a high-pressure zone (the maximum of p is of the order of 0.045). However, in this case, in the immediate vicinity of the surface of

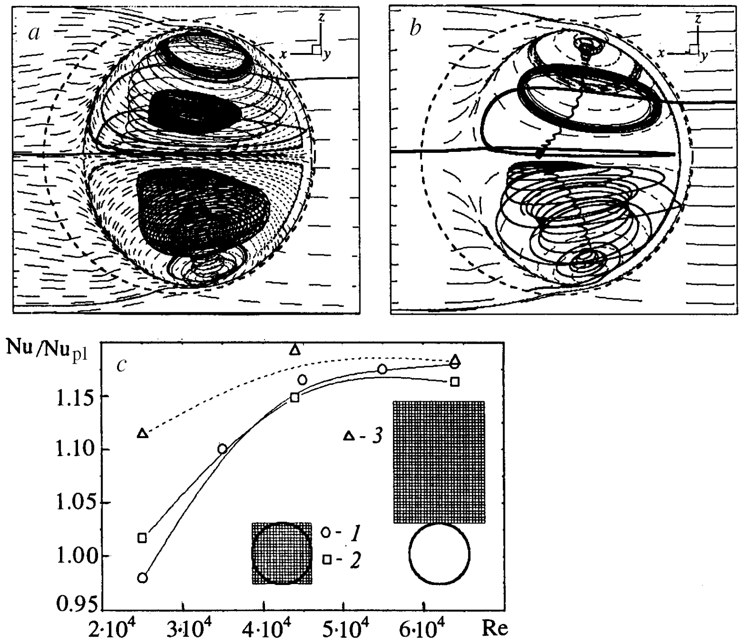


Fig. 4. Computer visualization of three-dimensional jet-vortex structures self-generated in the turbulent near-wall flow in a shallow spherical hole at Re = $2.3 \cdot 10^4$ (a) and $6.4 \cdot 10^4$ (b) and comparative analysis of the relative heat loads on the selected elements of the wall in flow (c): circular element along the edges of the hole (1), square element covering the hole (2), and rectangular element adjacent to the hole (3): 1) experimental data [20]; 2 and 3) calculation results.

the hole there arise descending streams directed to its surface from the source, which is located in the symmetry plane at a certain height above the wall. The flow from the source interacts with the ascending stream from the wall, which moves from the regions of the sharp-pointed edges. There is also the near-wall fluid flow from the edge of the hole to the symmetry plane.

The next cross sections of the flow behind the hole can be considered in combination with each other (Fig. 2d–f). The starting basis for understanding the vortex structure of the flow is the existence of a zone of very low excess pressure near the trailing sharp-pointed edge (of the order of –0.1). The region of negative pressure stimulates the inflow of the fluid from the peripheral near-wall layers to the symmetry plane. In combination with the above-mentioned outflow from the hole, this gives birth to a pair of spiral-like vortex structures and promotes their development. The centers of the indicated vortices rise above the wall and approach the symmetry plane. It should be noted that the pressure behind the hole is rapidly equalized and the vortices propagate in a nearly isobaric zone.

The character of the turbulent motion in the neighborhood of the hole depends little on the Reynolds number. However, the evolution of the separated flow changes somewhat with increase in Re. As for the laminar regime [6], the separated flow is intensified as the number Re increases, i.e., the maximum velocity of the reverse flow within the hole increases by approximately 20% when Re increases from $2.3 \cdot 10^4$ to $6.4 \cdot 10^4$.

It is of interest to analyze the deformation of the isolines of turbulent-pulsation energy in different cross sections of the neighborhood of the plane wall with a hole at given Re numbers of $2.3 \cdot 10^4$ and $6.4 \cdot 10^4$ (Fig. 3).

As is seen, the spherical hole on the plane acts as a turbulence generator. As the longitudinal coordinate x increases, the maximum of the turbulence energy increases within the hole and immediately behind it in the shear layer at the level of the wall, reaching a value of the order of 0.03 at Re = $2.3 \cdot 10^4$ in the transverse cross section of the hole passing through the trailing sharp-pointed edge, which is nearly 5 times higher than the maximum turbulence energy in the turbulent boundary layer on the wall. In the wake of the hole, the energy of the turbulent pulsations decreases quite rapidly. It is of great interest to interpret the regions of increased turbulence as closed lengthy zones which are similar to flattened ellipsoids of revolution creeping out of the hole.

An increase in Re to $6.4 \cdot 10^4$ is favorable for accelerated buildup of the highest level of turbulence energy in the spherical hole. It should be noted that this level k differs not very strongly in a value of the order of 0.032 from the analogous level at $\mathrm{Re} = 2.3 \cdot 10^4$, even though the zones of increased turbulence have a larger length at a higher Re number.

The results shown in Fig. 4 summarize the data on the three-dimensional vortex dynamics in the hole and the dependence of the heat transfer from the isolated elements of the washed grid on the Re number.

As in the case of the laminar and turbulent flows in the neighborhood of deep holes considered earlier [6, 9–11, 17–19], computer identification of the flow-forming structural elements in the hole is carried out by analysis of the trajectories of fluid particles passing through a given point of space. In this case, the TECPLOT 7.5 application package for processing three-dimensional fields of scalar and vector characteristics is used.

As follows from Fig. 4a, three-dimensional separated flow in a shallow hole is circulatory in character. This means that the trajectories of fluid particles reflect their rotary motion within the hole. However the appearance of these vortex formations is different. For example, in the zones adjacent to the symmetry plane there are two vortex rings similar to strange attractors. Such rings have been detected in a deep hole in the case of laminar flow around it. Each of the indicated vortex rings is built into the vortex cocoon representing a curvilinear vortex tube with an inner channel to convey the fluid from the peripheral region of the hole to the central zone. The fluid from this zone flows back to the periphery over the outer surface of the vortex tube. Besides the fluid circulating in the transverse direction of the hole, we have the transfer of the fluid through the hole. And in the case of a shallow hole, this conveying can be of several types serving a single purpose — to remove the fluid from the hole to the region of the symmetry plane. It should be noted, first of all, that the transfer of the fluid from the side neighborhood of the hole to its center is tornado-like. Fluid particles also come to this zone directly from the incoming flow after several revolutions in the separation region.

An increase in the Reynolds number (Fig. 4b) does not markedly change the character of the separated flow, but points to one of its features, namely: the tornado-like flow in the vortex tube moves along the axis of the swirling jet from the zone of the singular point at the side slope of the hole to the neighborhood of the symmetry plane with subsequent outflow back to the peripheral region of the hole. Thus, in contrast to a deep hole [6, 9], the fluid enters the symmetry plane from the singular points not straight but in a roundabout way.

Finally, integration of the heat fluxes over the separated regions of the washed surface with holes (Fig. 4) allows one to determine the integral heat transfer from the corresponding heated portions of the surface, referred to the heat transfer from the corresponding element of the plane wall.

The calculated predictions of the relative heat transfer from the square region bounding a round hole are in good agreement with the data of experimental evaluations [20] for the hole itself. This points to the acceptability of Menter's zonal model of turbulence for analysis of vortex heat exchange. It should be noted that when Re increases from $2.3 \cdot 10^4$ to $6.4 \cdot 10^4$, the relative heat transfer from the hole increases by about 18%.

It is of interest to analyze the vortex intensification of the heat exchange in the wake of the hole. Whereas at $\mathrm{Re} = 2.3 \cdot 10^4$ this effect is practically absent for the zone of a spherical hole, an intensification of the heat exchange of 12% is observed for the zone of the near wake of the hole (of dimension 2×1.5). When Re increases to $6.4 \cdot 10^4$, the relative vortex heat transfer increases by about 20%.

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NOTATION

x, y, z, longitudinal, vertical, and transverse coordinates; U, velocity of the incoming flow; D, diameter of the hole; p, excess pressure; k, energy of turbulent pulsations; ε, rate of dissipation of the turbulent energy; ω, specific rate of dissipation of the turbulence; Re, Pr, and Nu, Reynolds, Prandtl, and Nusselt numbers. Subscripts: pl, plane wall.

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