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INTENSIFICATION OF TORNADO TURBULENT HEAT EXCHANGE IN ASYMMETRIC HOLES ON A PLANE WALL

S. A. Isaev,[a] **A. I. Leont'ev,**[b]
A. V. Mityakov,[c] **I. A. Pyshnyi,**[a] **and**
A. E. Usachov[d]

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A numerical investigation of the influence of the shape of an isolated asymmetric hole of moderate depth, located on a plane wall, on the convective heat exchange in the case of turbulent flow of an incompressible viscous fluid around it has been carried out within the framework of the multiblock approach to solution of steady-state Reynolds equations closed using Menter's zonal model of shear-stress transfer and the energy equation.

Intensification of vortex heat exchange in the case of flow around walls covered with spherical holes is a problem of thermal physics that has not lost its topicality for several decades [1]. As is known, self-organization of large-scale, tornado-like structures within the holes is the basis for the physical mechanism of intensification of heat exchange. In this case, the thermal efficiency of reliefs with holes which is related to the vortex structure of flow around them is substantially dependent on the geometric dimensions of the holes and their mutual arrangement in the packet and on the blocking of the flow and its regime parameters. Moreover, nonstationary regimes of convective heat exchange are typical for deep holes. According to [2], the arrangement of a staggered packet of fairly deep spherical holes on the wall of a narrow channel makes it possible to increase the heat transfer by approximately a factor of 2.4 (in comparison with a plane-parallel channel) at a hydraulic loss growing much more slowly (by approximately a factor of 1.4). Nonetheless, the problem of selection of minimum-drag reliefs which are rational from the viewpoint of heat transfer is far from resolution.

One promising trend in solving this problem is the use of asymmetric holes. The logic of designing them (formal in the context of hydrodynamics) is based on a geometric shape of the type of a tear, i.e., a streamlined elongated configuration extended downstream. Such a shape was used in the ensemble of holes in the experimental investigation carried out in [2] and was found to be more preferable than ordinary spherical holes. It should be noted that in this case, an important fact — the adaptibility of the shape to streamlined production — was not taken into account.

Another logic of designing asymmetric holes is based on the principles of premeditated organization of the vortex structure within the hole. The preliminary investigations of laminar flow around a deep spherical hole on the plane, carried out, in particular, in [3, 4], have demonstrated the development of two symmetric, large-scale vortex cells within it. Their distinctive feature is the interaction of two swirling jet counterflows generated on the side slopes at singular points of the type of a focus. As a result, the fluid entering the spherical hole from the adjacent near-wall layers flows out of it in the form of a jet, which develops in the neighborhood of the symmetry plane passing through the center of the hole.

However, as is known, the symmetric vortex structures generated near a plane wall in flow as a result of the blowing out of the slot jet oriented along the flow (see, for example, [5]) are very weak. On the contrary, the blowing out of this jet at a zero angle to the incoming flow initiates a near-wall spiral-like vortex possessing a much higher intensity of the cross (secondary) flow.

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[a] Academy of Civil Aviation, St. Petersburg, Russia; email: isaev@SI3612.spb.edu; [b] N. É. Bauman Moscow State Technical University, Moscow, Russia; [c] St. Petersburg State Polytechnic University, St. Petersburg, Russia; [d] State Scientific-Research Center "Central Aerohydrodynamics Institute," Moscow, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 76, No. 2, pp. 31–34, March–April, 2003. Original article submitted October 2, 2002.

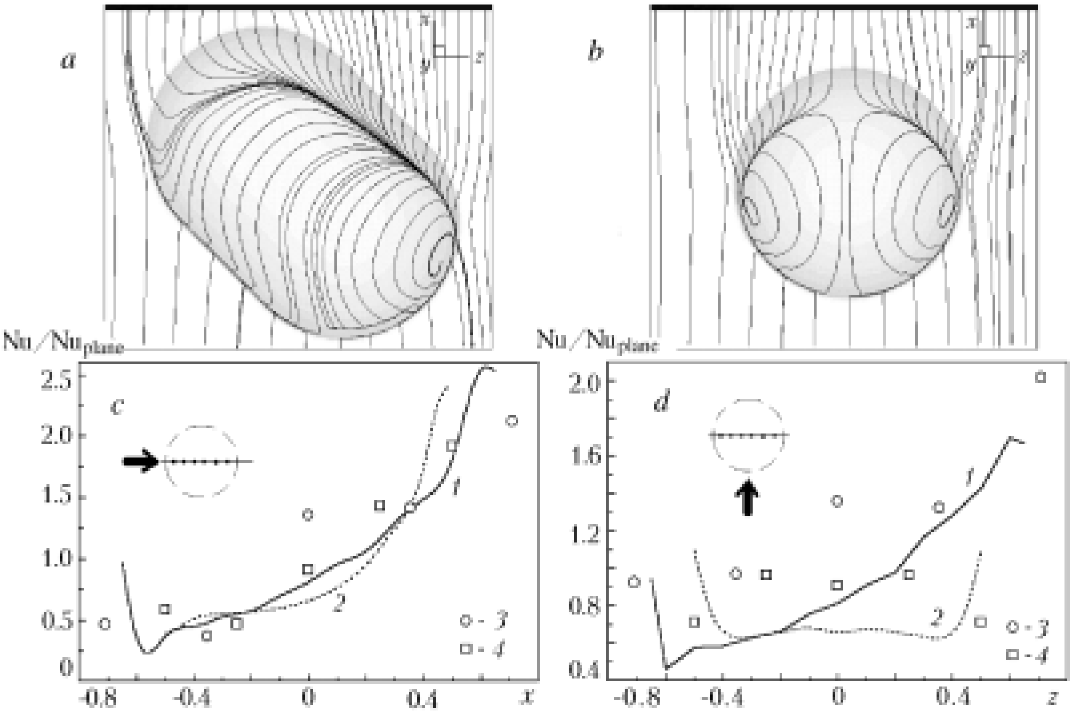

Fig. 1. Comparison of the patterns of spreading of the fluid on the surface of a spherical hole with a cylindrical insert (a) and without it (b) and of the calculated (1, 2) and experimental (3, 4) dependences of the local relative heat transfer Nu/Nu$_{plane}$ in the longitudinal (c) and cross (d) sections of the holes: 1, 3) spherical hole with an insert; 2, 4) spherical hole without an insert.

Analogously, the asymmetry of the shape of a hole, caused by its side (lateral) deformation, makes it possible to transform the vortex structure and enhance the cross flow of the fluid within the hole. The side deformation of the surface of one half of the hole with no change in its contour — the circular line of conjugation of the hole and the plane wall — has been realized in [3, 4] by introduction of a variable rounded radius. The second half remained spherical.

In the calculations carried out in [6–8], one half of the hole had an elliptic contour; the rounded radius was assumed to be constant. Although the two-cell vortex structure was retained in the laminar regime even at a large deformation of the side wall, the heat transfer in the asymmetric hole increased moderately. In the turbulent regime [6, 7] of flow around a deep hole, the deformation of the hole caused the transformation of the flow into a single-vortex, tornado-like structure which occurred with substantial intensification of heat exchange. However, it should be noted that all the considered asymmetric shapes of the holes are not adaptable to streamlined production.

A new shape of an asymmetric hole consisting of two halves of a spherical hole separated by a cylindrical insert of length L has been proposed in [9]. The hole is oriented at an angle α relative to the incoming flow. We note that the diameter of the base spherical hole and the velocity of the undisturbed flow are selected as the characteristic parameters. Thus, the number of initial parameters in the problem of optimization of the relief increases by two (additionally to the depth and the rounded radius), which makes it possible to control the process of flow around such holes to a greater extent. Furthermore, their technological characteristics seem to be quite acceptable.

In the present numerical and physical investigation, we analyze the tornado heat exchange in the case of turbulent flow (Re = 23,500) around a plane wall with an isolated shallow (0.14 in fractions of the hole diameter) hole with sharp-pointed edges of the proposed geometry at $L = 0.5$ and $\alpha = 45^{\circ}$ in comparison with the base spherical analog. The temperature of the wall in the calculations and in the experiments is selected to be 373 K at an incoming-flow temperature of 293 K.

The calculation of the stationary turbulent vortex flow near the hole is based on the concept of splitting by physical processes which was applied to solution of Reynolds equations closed using Menter's zonal model of turbu-

TABLE 1. Integral Coefficients of Relative Heat Transfer from the Separated Element of the Surface With an Isolated Hole

Type of element	Spherical hole	Asymmetric hole	Rectangular region (2 × 1.5) behind the spherical hole	Rectangular region (2 × 1.5) behind the asymmetric hole
Experiment	0.975	1.073	–	–
Calculation	1.0	1.11	1.056	1.17

lence [10]. Its use makes it possible to implement the process of global iterations, whose core is the known SIMPLEC procedure of pressure correction. Local iterations of the solution of the equations for the characteristics of turbulence are carried out at each step.

Within the framework of the multiblock algorithm, in addition to the computational cells in which the system of initial equations is directly solved, there are connected cells at the sites of intersection of the grids. The parameters in the connected cells are found by the method of nonconservative linear interpolation tested in [8].

The general features of the computational algorithm are retained in solving the steady-state energy equation. We note that the Prandtl number of the air medium is taken to be 0.7, while the turbulent Prandtl number is taken to be 0.9.

The computational region represents a curvilinear parallelepiped with the lower boundary coincident with the washed plane on which the hole is located. A uniform flow with a characteristic velocity U and a boundary-layer thickness of 0.175 is set at the entrance to the region. Within the limits of the boundary layer, the longitudinal velocity component changes by the law 1/7, while the other velocity components and the excess pressure are assumed to be equal to zero. The characteristics of turbulence 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 characteristics of turbulence in the near-wall zone are selected according to [10]. At all the other boundaries, the "soft" boundary conditions or, in other words, the conditions of continuation of the solution are set.

To solve the problem with an acceptable accuracy, we introduce four different-scale grids. The computational region with dimensions $12 \times 5 \times 10$ is digitized using an external grid containing $55 \times 50 \times 40$ computational cells. The size of the near-wall step is selected to be 0.008. The area of the spherical hole whose center 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. In the case of an asymmetric hole, a rectangular part resting on the cylindrical insert is built into the cylindrical subregion. The indicated subregion is covered with a cylindrical grid matched with the washed curvilinear wall and containing $40 \times 40 \times 80$ 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 0.25×0.25. 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.

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

Physical modeling of a low-velocity air flow around a spherical hole with a depth of 0.14 is carried out on a small-size setup. The steam heating of the lower wall of the working part of the wind tunnel provides a wall temperature close to 100°C. A base spherical hole of diameter 65 mm and depth 9 mm (in one case) or an asymmetric hole of the geometry considered (in another case) are localized on the heated surface. A feature of the conducted experiments is that the heat fluxes are directly and immediately measured using gradient detectors [11] and the surface of the hole is kept at constant temperature.

The experimentally measured and calculated local coefficients of heat transfer $\mathrm{Nu}/\mathrm{Nu}_{\mathrm{plane}}$ in different regions of isolated holes ($\mathrm{Nu}_{\mathrm{plane}}$ is the Nusselt number on the plane wall) and the coefficients of heat transfer summarized over the elements of the washed surface with a hole, which are related to the analogous characteristics for the elements of a plane wall, are compared in Fig. 1 and in Table 1. It should be noted that quite satisfactory agreement between the results points to the acceptability of the multiblock computational complex developed.

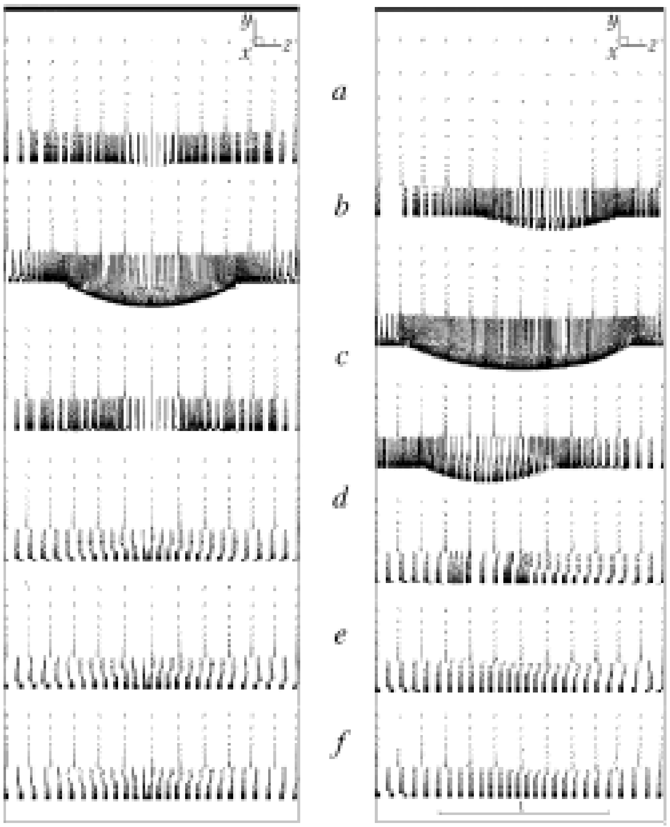

Fig. 2. Comparison of the patterns of the directions of the velocity vectors of the secondary flow in the longitudinal sections of the spherical hole without an insert (left vertical row) and with a cylindrical insert (right row): a) $x = -0.5$, b) 0, c) 0.5, d) 1, e) 1.5, and f) 2 (x is the longitudinal coordinate measured from the center of the hole in the direction of the incoming flow).

Giving an asymmetric shape to the shallow hole leads to the restructuring of flow around it. The two-cell vortex structure in the hole transforms into a single-vortex, tornado-like structure (Fig. 1a and b). The restructuring is accompanied by redistribution of the heat loads within the hole and behind it.

The analysis of the field of the secondary flow (Fig. 2) shows that behind the asymmetric hole there also arises a single-vortex, spiral-like structure of flow, unlike the symmetric two-vortex structure behind the spherical hole. At $L \sim 0.5$, the velocity of the cross fluid flow in the hole exceeds the maximum longitudinal velocity of the separated flow in the spherical hole.

As a result, in the case of an asymmetric hole combining a shallow spherical hole with a cylindrical insert we have a significant (of the order of 10%) increase in the heat transfer from the wall. It should be noted that the self-generated tornado structure is highly stable, which provides the stability of the effect of vortex intensification of heat exchange.

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