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ANALYSIS OF VORTEX HEAT TRANSFER IN A TRANSVERSE FLOW PAST A TRENCH ON A PLANE USING MULTIBLOCK COMPUTATION TECHNOLOGIES AND DIFFERENT SEMI-EMPIRICAL MODELS OF TURBULENCE

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Vortex dynamics and heat transfer in a viscous incompressible fluid flow past shallow and deep trenches on a plane wall are studied methodically within the framework of the multiblock approach to solution of steady-state Reynolds equations closed by the Menter and Spalart–Allmaras turbulence models and the energy equation.

A detached flow of viscous fluid in the vicinity of a trench on a plane wall has drawn the attention of hydromechanicians [1]. Trenches as well as protrusions on a washed wall are of interest to them first of all from the point of view of the contribution of the mentioned elements of roughness to the total resistance of bodies of complex geometry. Simultaneously, thermal physicists consider trenches or grooves as elements of enhancement of heat-transfer processes in near-wall flows [2, 3].

In many respects, interest in investigation of vortex dynamics and heat transfer in flow past a trench on a plane wall is also predetermined by the fact that lunes are a three-dimensional analog of trenches. As is known (see, e.g., [4]), lune technologies are a very promising tool of heat and mass transfer enhancement with very low hydraulic losses for pumping of a heat-transfer agent. Therefore, in order to analyze the governing mechanism of self-generation of vortex structures in concavities, thorough measurements of the parameters of flow past spherical lunes and two-dimensional trenches with a generatrix that copies the shape of the lune in the middle cross section were conducted at the N. É. Bauman Moscow Higher Technical School at the beginning of the 1990s [5]. We should also mention a series of experimental works performed at the Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences [6] with an emphasis on the effect of a three-dimensional character of flow in trapezoidal short trenches.

The genesis of numerical simulations of an incompressible viscous fluid flow past trenches, as well as of the whole computational fluid dynamics (CFD), is closely related to the progress made in computer technology, the development of methods of solution of the Navier–Stokes equations, and improvement of semiempirical models of turbulence. It should be emphasized that the problem under consideration ranks among the classical problems, and its numerical solution for a laminar flow is quite satisfactory and has long been known. Of course, problems still remain, which are related, first of all, to interpretation of unsteady flows past bodies. However, the calculations of turbulent detached flows always presented the greatest difficulties. In the 1970–80s, a two-parameter dissipative model of turbulence or the Launder–Spalding k–ε model was widely used to close the Reynolds equations [7]. In the standard high-Reynolds variant it was supplemented by near-wall functions, since it was inapplicable in the immediate vicinity of the wall. Within this approach, detached flows with a fixed detachment point in the neighborhood of a recess [8] and technological joint [9] were calculated; in the latter case, calculations were made on the algebraic net in curvilinear coordinates matched to the body. In [10], a flow past a trench with smoothed edges was modeled on a curvilinear, close to orthogonal, net calculated by the marching procedure of solving differential equations.

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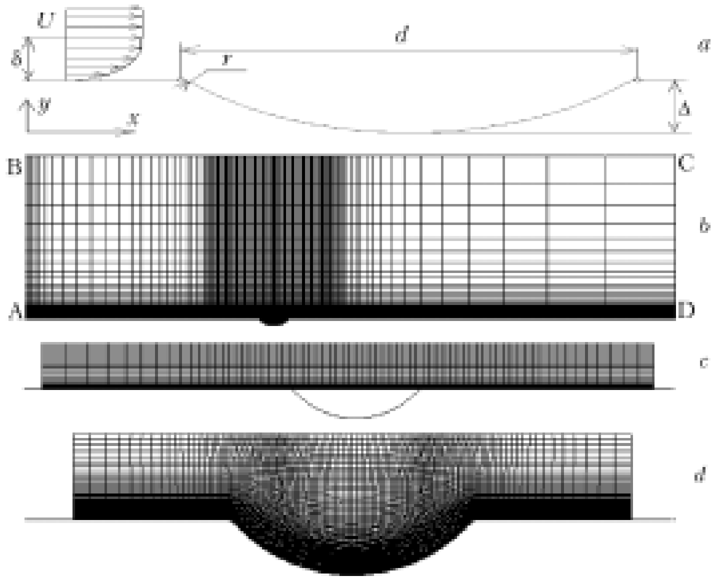

Fig. 1. Schematic of the trench on the plane wall (a) and multiblock computational nets: outer Cartesian (b), inner Cartesian (c), and trench (d).

The 1990s, which became an industrial stage in the development of computational fluid dynamics, were marked by the development and widespread propagation of computation technologies embodied in specialized and universal packages of applied programs and codes. Of special note is the multiblock approach to solution of problems of hydromechanics and heat transfer [11, 12], which allowed one, using a combination of inserted and intersecting computation nets of simple topology, to rather accurately map not only objects of complex geometry but also different-scale structural elements of detached flows, such as boundary and shear layers, circulation zones, the wake behind a body, etc. It is important to emphasize the successful evaluation of new semi-empirical models of turbulence that were developed during the mentioned period, in particular, the Menter two-parameter model of transfer of shear stresses [13] and the Spalart–Allmaras (SA) model with one differential equation for eddy viscosity [14].

Within the framework of the multiblock approach using the Menter model, a turbulent flow in two-dimensional plane-parallel [15] and diverging [16] channels with a circular trench with a rotating cylinder inside it (one variant of an active vortex cell [11]) was studied numerically. In this case, introduction of different-scale nets allowed one to rather accurately map a flow past rounded sharp edges. Good agreement between the calculated results and the data of the measurements of velocity profiles and pressure distributions made at the Institute of Mathematics of Moscow State University was noted. The suggested multiblock approach was generalized for solution of three-dimensional problems and was used for analysis of vortex dynamics and heat transfer in a turbulent flow past a spherical lune on a plane wall [17] and the wall of a narrow channel [18], with the lune depth being varied within a wide range.

This work has, in general, a methodological character and is directed, first of all, toward a comparative analysis of numerical predictions with the available experimental data for shallow and deep trenches, which are presented in [5]. The developed multiblock approach to solution of the steady-state Reynolds equations is combined with testing of two models of turbulence: the Menter and SA models. Much attention is paid to estimation of the effect of the initial thickness of the boundary layer and the radius of rounding of a sharp edge on flow and heat transfer in the vicinity of the shallow trench.

Problem Formulation. A plane turbulent flow of incompressible viscous fluid and convective heat transfer in the near-wall region in the plane with a trench that has the shape of a circle are analyzed numerically. As has been indicated above, for this class of problems, when a small-scale concavity is considered, the trench width d, which is the distance between the points of its matching with the plane, rather than the diameter of the circular arc forming the trench, is taken as the characteristic size (Fig. 1a). The characteristic linear dimensions of the problem are the trench depth Δ, the radius of rounding of the sharp edge r, and the initial thickness of the boundary layer δ, and the dimensions of the computation domain are given in fractions of d. The velocity of a uniform flow of viscous incompressible fluid at a distance from the wall U is taken as the scale of nondimensionalization of the parameters. The number Re constructed by U and d is given equal to $4 \cdot 10^4$, which corresponds to the experimental value [5]. The number Pr for an air medium is assumed to be 0.7 and the turbulent Pr number is 0.9.

The computation domain ABCD (Fig. 1b) includes a part of the washed wall with the trench AD on which the conditions of adhesion are set and the wall temperature is maintained constant and equal to 377 K. On the inlet boundary AB the parameters are fixed. A velocity profile of 1/7 is set on the initial thickness of the boundary layer δ. Above the layer the flow is uniform. The energy of turbulent oscillations in this region corresponds to the 1.5% level of turbulence characteristic of typical wind tunnels. The turbulence scale is taken to be of the order of the trench width. In the boundary layer, the parameters of turbulence, as is adopted in a number of works (see, e.g., [19]), are determined according to the traditional Prandtl model of mixing length. The temperature of the incoming isothermal flow is kept at a "room" level equal to 293 K. The indicated level of temperature is taken as a typical one.

On the outlet boundaries BC and CD, "mild" boundary conditions (conditions of solution continuation) are set. The flow-through boundaries are far enough apart from the trench, with the distance to them being determined from the condition of a negligible effect of the separation zone on distribution of flow parameters in the vicinity of these boundaries.

The length of the calculated module in horizontal and vertical directions is 17 and 5.175, respectively. Here 0.175 is the vertical size of the near-wall subregion where the turbulent boundary layer with an initial thickness of 0.05 is calculated. At larger values of δ this size increases correspondingly. The distance from the trench to the inlet boundary is taken to be 6. The initial thickness of the boundary layer δ varies within a wide range from 0.05 to 0.5, and the radius of rounding r — from 0.03 to 1. Shallow and deep individual trenches with a depth of 0.0625 and 0.22, respectively, are considered.

The multiblock net, shown, for example, for calculation of flow past a deep trench (Fig. 1b–d), consists of three different-scale nets of different structures. The first of them, given in Fig. 1b, is a Cartesian net (with nonuniform pitches in longitudinal and transverse directions and thickening to the wall and the vicinity of the trench) covering the entire computation domain and having 129×48 meshes. The second net, which is shown in Fig. 1c and is intended for mapping the near wake behind the trench, is also a Cartesian, near-wall net surrounding the vicinity of the trench of size 4×0.175; it consists of 68×33 meshes. And finally, the trench, curvilinear, close to orthogonal, and matching the surface net, which is calculated in solving the elliptic equations, covers the trench zone with outer dimensions 1.8×0.175 and has 133×54 meshes. In this case, the near-wall pitch is taken to be equal to 0.0005, but in general it varies from 10^{-4} to $5 \cdot 10^{-4}$.

Interpretation of the Multiblock Computational Algorithm. Turbulent flow and heat transfer in the distinguished calculation module are described on the basis of the finite-volume solution of the Navier–Stokes and energy equations by an implicit factorized algorithm based on the concept of splitting by physical processes [11]. The modified matched SIMPLEC procedure of pressure correction forms the basis of this algorithm. The two-step "predictor–corrector" procedure is intended for determination of increments of the Cartesian components of velocity and pressure. In a pre-linearized system of initial equations, convective terms in the explicit part are approximated by the one-dimensional version of the concurrent Leonard scheme with square interpolation for momentum equations and by a version of the TVD scheme for equations relative to turbulent characteristics. To provide stability of the computational algorithm in the implicit part of the transfer equations, approximation of convective terms is done by the countercurrent scheme with one-sided differences. In order to damp high-frequency oscillations, the diffusion terms in the implicit part contain additional artificial diffusion with the coefficient of transfer proportional to kinematic viscosity. The choice of the centered computation pattern stipulates use of the Rhi–Chou monotonizer in the block of pressure correction with an empirically determined coefficient of 0.1. Solution of difference equations is done by the method of incomplete matrix factorization in the Stone version (SIP) [18]. In the procedure of global iterations, several iterations in the block of pressure correction and a limited number of iterations in the block of calculation of turbulent characteristics account for one local iteration in solution of the momentum equations.

Construction of the multiblock algorithm was initiated by numerical simulation of vortex flows in multiply connected regions as applied to bodies with vortex cells [11]. An original approach based on decomposition of the computational domain of complex geometry (see, e.g., Fig. 1) to fragments with subsequent use of intersecting nets of

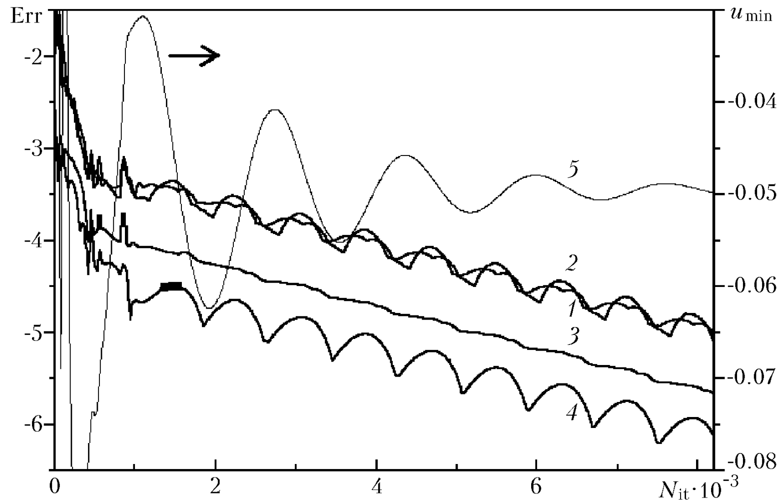

Fig. 2. Trajectory of convergence for calculation of flow past a shallow (0.0625) trench with $r = 0.03$ at $\delta = 0.05$: dependences of the number of iteration steps of maximum increments u (curve 1) and v (2), p (3), k (4), and u_{min} (5) on maximum velocity of the back flow.

a simple topology is developed. For determination of the parameters in the regions of intersection of nets the procedure of linear interpolation is used.

Solution of the dynamics problem ceases on reaching an appropriate accuracy of calculation of local and integral parameters. Thus, for increments of the components of velocity and pressure an accuracy of 10^{-5} is set, and for increments of turbulence energy, $5 \cdot 10^{-6}$.

The thermal problem is solved separately from the dynamics problem, using the calculated fields of velocity and eddy viscosity.

The coefficients of relaxation in calculation of increments of the velocity components are taken to be equal to 0.5, pressure corrections 0.8, and temperature increments 0.9. The value of the E-factor (see, e.g., [11]) is set to be equal to 100 in order to provide high convergence of the iteration process.

Testing of the Multiblock Computational Algorithm. The testing of the algorithm of the selected models of turbulence that we performed is to a great extent related to the experimental study [5], where two configurations of trenches were considered in detail: shallow ($\Delta = 0.0625$) and deep ($\Delta = 0.22$). It should be noted that despite the great body of information, it, unfortunately, lacks data on the thickness of the boundary layer in the region of trenches and the degree of turbulence of an oncoming flow. This introduces an element of uncertainty to the numerical study conducted, which must be taken into account in comparative analysis of the calculated and experimental results, i.e., some scatter of them is possible.

Computational efficiency of the specialized program complex VP2 (velocity–pressure–two-dimensional version) developed on the basis of the multiblock factorized finite-volume algorithm is illustrated in Fig. 2. It is of interest to note that convergence of the iteration process of solution of the problem of flow past the shallow trench, which is determined by the behavior of the increments of the dependent variables (velocity components, pressure, turbulence characteristics) as N_{it} increases, is virtually linear in the logarithmic coordinates. The dependence of a maximum velocity equal to 10^{-5} of the back flow near the trench bottom on N_{it} indicates that convergence of the computation process is reached on realization of the condition of its discontinuity on accuracy for the increments of the velocity components. It is important to emphasize that sometimes convergence of iterations in solution of hydrodynamic and thermophysical problems by universal packages of the type of Star CD, FLUENT, CFX is determined only by the behavior of the increments of the dependent variables when an accuracy of order 10^{-4} is chosen. As follows from the analysis of Fig. 2, this method of completion of the iteration process is not completely adequate since at this level of errors of the velocity components the amplitude of oscillations of u_{min} is still rather large to consider the velocity field as steady-state.

One typical requirement on the accuracy of numerical predictions is convergence of the results by nets, i.e., their receptivity as net nodes becomes smaller. Figure 3 shows quite satisfactory convergence of the calculated surface

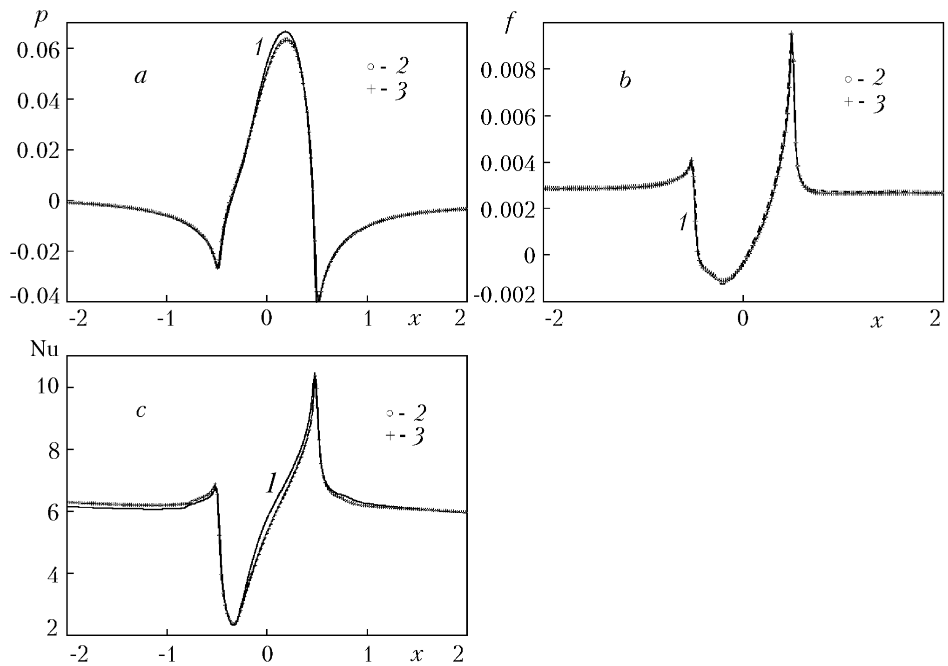

Fig. 3. Comparative analysis of the distributions of pressure (a), friction (b), and heat transfer (c) for convective heat transfer in the vicinity of a shallow (0.0625) lune with r = 0.03 at δ = 0.05 and Re = 10^4 for near-wall steps h = $5{\cdot}10^{-4}$ (1), $2.5{\cdot}10^{-4}$ (2), and 10^{-4} (3).

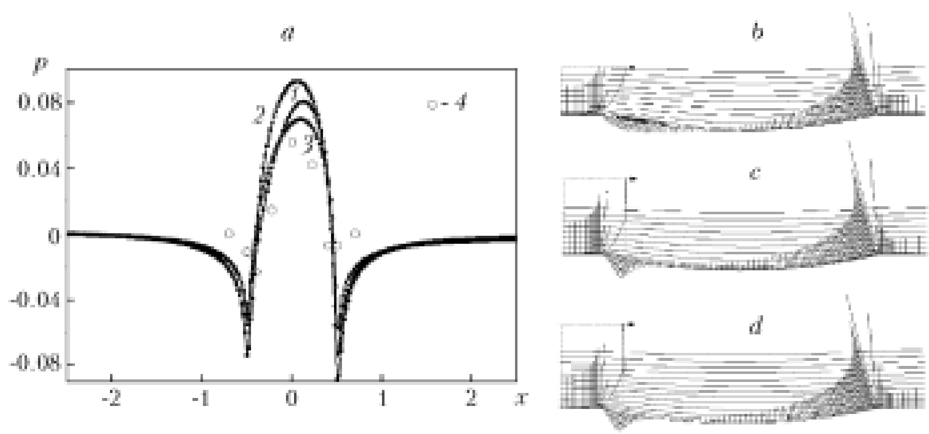

Fig. 4. Comparison of the patterns of flow, profiles of surface pressure (a), and friction — for a shallow (0.0625) trench with r = 0.03 at δ = 0.05 for the Menter (1 and b), Spalart–Allmaras (2 and c), and k–ε (3 and d) models; 4) experiment [5].

distributions of local characteristics of flow and heat transfer in the vicinity of a shallow lune of depth 0.06 (r = 0.03, Re = 10^4, δ = 0.05) in variation of the near-wall step h within a wide range from 10^{-4} to $5{\cdot}10^{-4}$. The given profiles are actually superimposed, which indicates the appropriateness of h equal to a value of $5{\cdot}10^{-4}$ selected for a parametric numerical study.

Comparative analysis of the turbulence models is one of the urgent problems of this paper. As has already been mentioned, the Menter two-layer model of transfer of shear stresses, which is the basic model of the CFX package [20], and the SA model with one differential equation for eddy viscosity are assuming their primary places in the list of best models of the last decade. As is shown by preliminary methodical studies of a number of semi-empirical models of different levels of complexity, which were performed on the test problem of a circulation flow in a square

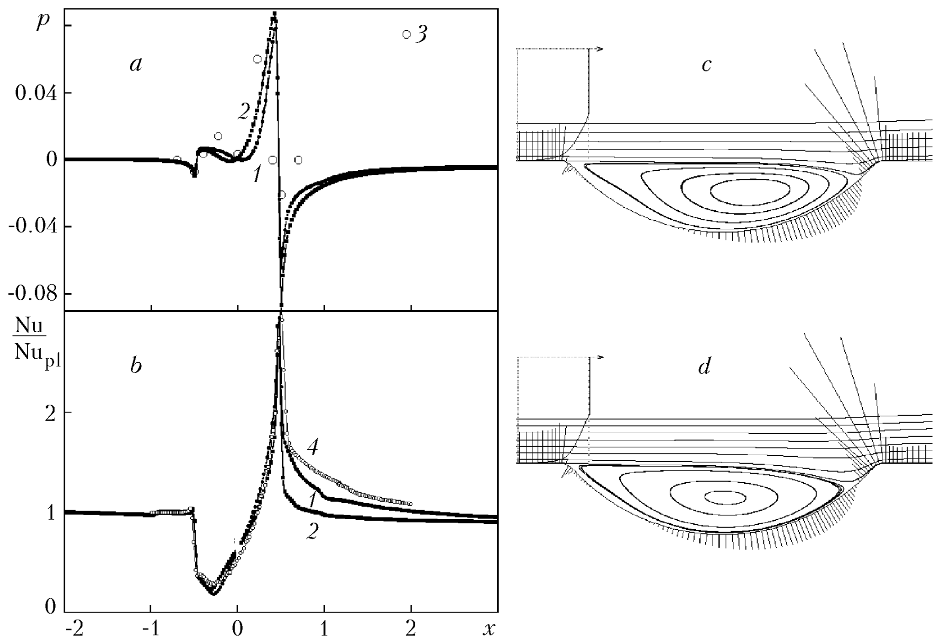

Fig. 5. Comparison of the patterns of flow, profiles of surface pressure (a), relative heat transfer (b), and friction (c, d) for a deep (0.22) trench with r = 0.03 at δ = 0.05 for the Menter (1 and b) and Spalart–Allmaras (2 and c) models; 3) experiment [5]; 4) calculation for a spherical lune.

TABLE 1. Influence of Resistance and Heat Transfer on Integral Characteristics in Flow past Shallow and Deep Trenches of the Selected Model of Turbulence and the Near-Wall Step of the Net

Model	$C_{xf\mathrm{tr}}$	$C_{xp\mathrm{tr}}$	$C_{x\mathrm{tr}}$	$\mathrm{Nu}_{\mathrm{tr}}$	$C_{xf\mathrm{wake}}$	$\mathrm{Nu}_{\mathrm{wake}}$
Menter, $\Delta = 0.0625$, $h = 5\cdot10^{-4}$	0.00176	0.00416	0.00592	18.16	0.00378	18.55
Menter, $\Delta = 0.0625$, $h = 10^{-4}$	0.00181	0.00399	0.00580	18.96	0.00390	19.81
SA, $\Delta = 0.0625$, $h = 5\cdot10^{-4}$	0.00247	0.00295	0.00542	18.13	0.00397	19.21
Menter, $\Delta = 0.22$, $h = 5\cdot10^{-4}$	–0.00043	0.01481	0.01439	19.24	0.00385	23.84
SA, $\Delta = 0.22$, $h = 5\cdot10^{-4}$	–0.00048	0.02082	0.02034	19.51	0.003025	20.80
Menter, $\Delta = 0$, $h = 5\cdot10^{-4}$	0.00411	0	0.00411	18.79	0.00399	17.91
Menter, $\Delta = 0$, $h = 10^{-4}$	0.00420	0	0.00420	19.05	0.00408	18.29
SA, $\Delta = 0$, $h = 5\cdot10^{-4}$	0.00431	0	0.00431	19.37	0.00424	18.79

cavern with a moving lid, the indicated models possess an undeniable advantage in accuracy of numerical prediction of detached flows compared with the models of the k–ε type (true enough, without corrections for the curvature of streamlines), which greatly (by a factor of 1.5) underestimate the flow rate of a flow circulating in the cavern [21]. These models are tested in the paper in numerical analysis of a flow past the considered trenches on the plane. Some results obtained in testing the models are given in Figs. 4 and 5 and Table 1. We should note that the integral parameters presented in Table 1 refer to two distinguished elements of the washed surface: the trench region (denoted by the subscript "tr") and the zone of a near wake directly behind the trench of unit length (denoted by the subscript "wake").

The low-Reynolds Saffman–Wilcocks k–ω model (near the wall) and the standard Launder–Spalding k–ε model (in the outer zone) are combined in the Menter two-layer, low-Reynolds model. Thus, in the thin layer adjacent to the wall the flow is calculated by one of the best near-wall models rather than by the near-wall functions that sup-

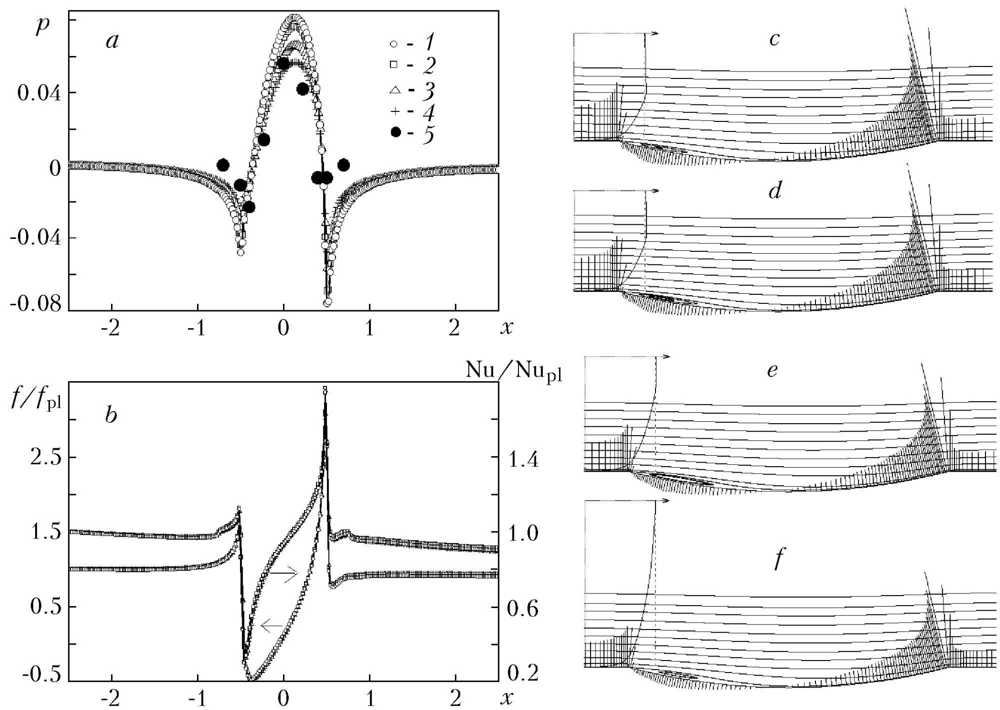

Fig. 6. Comparison of the patterns of flow, profiles of surface pressure (a), relative friction and heat transfer (b) for a shallow (0.0625) trench with r = 0.03 at δ = 0.05 (1 and c), 0.1 (2 and d), 0.25 (3 and e), and 0.5 (4 and f); 5) experiment [5].

plement the high-Reynolds k–ε models and are not quite correct first of all in the vicinity of critical points. At a distance from the wall, the solution is matched to the k–ε model, which undoubtedly is more preferable for mapping shear layers. In this case, no additional terms are introduced into the system of governing equations for the characteristics of turbulence.

Another distinguishing feature of the Menter k–ω model is related to use of the concept of transfer of shear stresses, which was successfully implemented in the Johnson–King model. The expression for eddy viscosity in the initial variant of the Menter model includes the vorticity modulus. In [20], it is suggested that the modulus of the tensor of deformation rates be used instead of the vorticity modulus. This modification of the Menter model is used in the present work, although it should be noted that the difference in predictions by the new and the initial variants of the model is slight.

The case is different with the SA one-parameter model. It was developed especially for the solution of problems of outer aeromechanics, in particular, as applied to flying vehicles. Its advantage is, first of all, in the computational efficiency of predictions, since only one differential equation of transfer of eddy viscosity is solved instead of the two equations of the Menter model. In [21], however, it was found that the standard (more stable in calculations) variant of the model, which by default is used, for example, in the FLUENT package, differs little from the k–ε-type models, with the reason for the nonphysical behavior of the models being in pumping of turbulence to the core of the flow circulating in the cavern. The unwanted process of pumping can be avoided by introducing a correction for the curvature of streamlines in the k–ε model and by using the correction for the effect of the difference between the vorticity modulus and the tensor of deformation rates in the SA model. It is of interest to note that the results of the numerical simulation of the turbulent flow in the square cavern by the Menter and SA models (with correction) turned out to be rather close [21].

Testing of the same models in this work on the problem of a flow past trenches of different depths confirms, on the whole, this conclusion, although some important differences are revealed. The results obtained for a shallow trench are most similar. This refers to both integral characteristics (Table 1) and distributions of pressure and friction over the washed surface in the vicinity of the trench (Fig. 4). Small differences in the length of the separation zone,

TABLE 2. Influence of δ on Integral Characteristics of Resistance and Heat Transfer in Flow past a Shallow Trench with r = 0.03

δ	C_{xf}tr	C_{xp}tr	$C_{x\mathrm{tr}}$	$\mathrm{Nu_{tr}}$	C_{xf}wake	Nuwake	C_{xf}pl	Nupl
0.05	0.00176	0.00416	0.00592	18.16	0.00378	18.55	0.00451	18.92
0.10	0.00164	0.00400	0.00565	18.14	0.00363	18.67	0.00425	18.93
0.25	0.00141	0.00353	0.00494	17.48	0.00321	18.12	0.00372	18.36
0.50	0.00125	0.00298	0.00424	16.60	0.00283	17.24	0.00329	17.79

TABLE 3. Influence of δ on Extremum Values of Local Characteristics of Flow in the Vicinity of a Shallow Trench with r = 0.03

δ	$u_{\min}$	$k_{\max}$	$p_{\max}$	$\nu_{\mathrm{t,max}}$
0.05	–6.202e–2	1.341e–2	8.166e–2	1.328e–3
0.10	–5.960e–2	1.263e–2	7.691e–2	1.383e–3
0.25	–5.743e–2	1.102e–2	6.647e–2	1.410e–3
0.50	–5.234e–2	9.414e–3	5.695e–2	1.183e–3

more precisely, a detached bubble of small intensity on the leeward side of the trench, which are expressed in a two-fold decrease of the zone in using the SA model, are negligible relative to their influence on local and integral characteristics of flow and heat transfer. It is of interest to note that the low-Reynolds k–ε model gives results on surface distributions of pressure and friction that are rather close to those obtained by the Menter and SA models.

Quantitative similarity of the results of the calculation by different turbulence models of a flow past the deep trench turns out to be more pronounced than for the shallow trench (Fig. 5). This refers to the structure of the large-scale vortex and distributions of pressure and friction within the trench. Some difference is noted only in the near wake behind the trench where the SA model gives somewhat underestimated levels of the friction stress and relative heat transfer, which seems to be of great significance for the considered problems. The difference in local characteristics lead to a 10% underestimation of the predicted heat transfer in the zone of unit length behind the trench.

In Fig. 5, the distribution of the relative heat transfer for the spherical lune whose middle cross section coincides with the deep trench is given. The coincidence of the profiles $\mathrm{Nu/Nu_{pl}}(x)$ within the concavity and a noticeable excess of the relative heat transfer in the wake behind the lune, compared to the two-dimensional case, engage our attention.

The calculated distributions of pressure in the vicinity of the trench are in satisfactory agreement with the experimental data, which confirms the appropriateness of the multiblock computational algorithm and the adequacy of the Menter and SA turbulence models.

Influence of the Initial Thickness of the Boundary Layer. Figure 6 and Tables 2 and 3 give some results of the numerical analysis of the effect of δ on the flow structure, surface distributions of pressure, friction, and heat transfer and integral and local characteristics of a flow past the shallow trench with a very small radius of rounding of the sharp edge.

An increase of the initial thickness of the boundary layer δ from 0.05 to 0.5 in the inlet section lying at a distance of 6 from the trench is accompanied by different rates of increase of the boundary layer on the plate. The thickness of the boundary layer along the wall changes most dynamically at small values of δ, and at δ of an order of 0.25 or higher the boundary layer virtually does not increase. At δ = 0.05 and 0.1, the layer thickness in front of the trench is 0.13 and 0.16, respectively.

An increase of the boundary layer in front of the trench is accompanied by a monotonic decrease of local power and thermal loads, intensity of the detached flow, and decrease of the generated level of turbulence energy and eddy viscosity in the trench and in the wake behind it. It is important to note that as δ increases, the calculated profile of the surface pressure approaches that obtained experimentally [5]. Variation of the relative surface distribution of friction f/f_{pl} and heat transfer $\mathrm{Nu/Nu_{pl}}$, which are normalized by the level of friction and heat transfer on the plane wall, has a self-similar character. It is of interest that as δ increases, the separation zone on the leeward side of the trench does not undergo noticeable changes, although it somewhat loses its intensity.

TABLE 4. Influence of r on Integral Characteristics of Resistance and Heat Transfer in Flow past a Shallow Trench at δ = 0.05

r	$C_{xf\mathrm{tr}}$	$C_{xp\mathrm{tr}}$	$C_{x\mathrm{tr}}$	$\mathrm{Nu_{tr}}$	$C_{xf\mathrm{wake}}$	$\mathrm{Nu_{wake}}$
0.03	0.00176	0.00416	0.00592	18.16	0.00378	18.55
0.10	0.00183	0.00417	0.00599	18.22	0.00378	18.57
0.25	0.00193	0.00402	0.00595	18.28	0.00381	18.56
0.50	0.00206	0.00377	0.00583	18.28	0.00384	18.56
1.00	0.00234	0.00315	0.00549	18.28	0.00390	18.54

TABLE 5. Influence of r on Extremum Values of Local Characteristics of Flow in the Vicinity of a Shallow Trench at δ = 0.05

r	$u_{\min}$	$k_{\max}$	$p_{\max}$	$\nu_{t,\max}$
0.03	–6.202e–2	1.341e–2	8.166e–2	1.328e–3
0.10	–6.189e–2	1.351e–2	8.174e–2	1.330e–3
0.25	–6.031e–2	1.352e–2	8.237e–2	1.329e–3
0.50	–5.872e–2	1.343e–2	8.330e–2	1.327e–3
1.00	–5.491e–2	1.303e–2	8.451e–2	1.321e–3

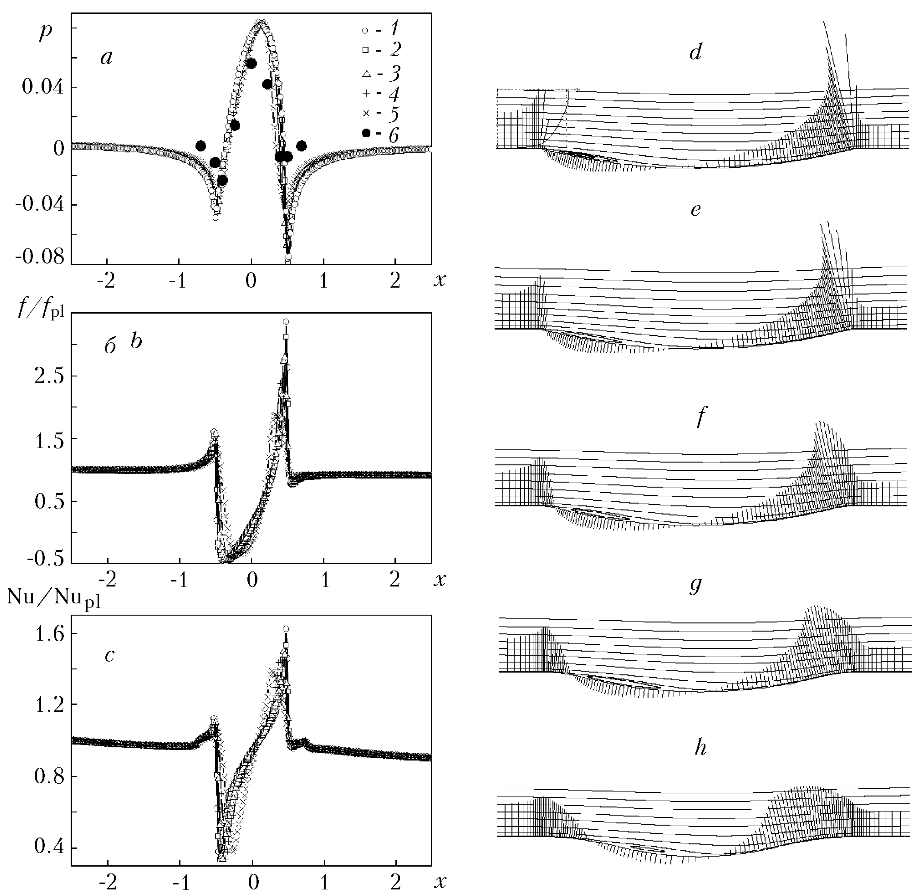

Fig. 7. Comparison of the profiles of surface pressure (a), relative friction (b), heat transfer (c), and flow patterns (d–h) for a shallow trench with r = 0.03 (d), 0.1 (e), 0.25 (f), 0.5 (g), and 1 (h) at δ = 0.05; 6) experiment [5].

Influence of the Radius of Rounding of the Sharp Edge. Variation of edge rounding at a constant width of the trench d indicates substantial variation of the concavity shape, in particular, variation of the radius of its curvature. Some results of the study of the effect of r on the flow structure, surface distributions of pressure, friction, and heat transfer and integral and local characteristics of a flow past the shallow trench at $\delta = 0.05$ are presented in Fig. 7 and Tables 4 and 5.

An increase in r within a wide range (from 0.03 to 1), which corresponds to progressive smoothing of the sharp edge, leads, first of all, to deformation of the structure of the detached flow accompanied by displacement of the detachment point downward along the leeward slope of the trench and gradual weakening of the intensity of the flow circulating in the trench. To a certain measure, this is related to displacement of the point of discontinuity of the contour curvature (the point of junction between the rounded-off edge and the concavity) and also to redistribution of the curvature: its decrease on the inlet portion and increase in the bottom part. As follows from Fig. 7, gradual smoothing of the peaks of friction and heat fluxes occurs at the places of edge rounding. It is interesting to note that, in this case, the surface distribution of pressure changes very slightly. Within the range of small rounding (r within 0.03–0.25), the generated maximum levels of turbulence energy and eddy viscosity virtually do not change. At large radii of rounding, probably due to considerable transformation of the trench shape, its role as a turbulizer becomes weaker.

As should be expected, r exerts a great effect on the resistance of the trench and its individual components. With an increase of smoothing of the edge, the profile component C_{xp} decreases, with this, to greater extent, occurring for large radii of rounding. The decrease in C_{xp} is compensated to certain r (up to 0.25) by an increase in the friction resistance C_{xf}. However, then C_{xp} begins to decrease more quickly than C_{xf} increases, thus leading to a general decrease in the total resistance of the trench. As for the total heat transfer within the trench, it remains virtually constant within the entire range of variation of r. It is of interest that the same situation with heat transfer takes place in the near wake behind the trench. However, the friction resistance of this section of the plate slightly (by 2–3%) increases at large r, i.e., the radius of rounding practically does not affect heat-transfer enhancement behind the shallow trench.

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NOTATION

C_x, C_{xp}, and C_{xf}, coefficients of head resistance, normal-pressure, and friction drag, respectively; c_p, heat capacity at constant pressure, kJ/(kg·K); d, trench width, m; E, relaxation parameter; Err, increment of the dimensionless dependent variable; f, friction stress related to double velocity head, in fractions of ρU^2; h, near-wall pitch of the net, in fractions of d; k, energy of turbulent oscillations, in fractions of U^2; n, coordinate reckoned along the normal to the contour, in fractions of d; N, number of iterations; Nu, Nusselt number determined as $d\theta/dn$; OTL, coefficient of amplification of kinematic viscosity; p, pressure related to double velocity head, in fractions of ρU^2; Pr, Prandtl number, $\mathrm{Pr} = c_p\mu/\lambda$; r, radius of rounding of the sharp edge, in fractions of d; Re, Reynolds number, $\mathrm{Re} = \rho Ud/\mu$; T, temperature, K; u, horizontal component of the velocity vector, in fractions of U; x and y, axial and radial coordinates, m; α, thermal diffusivity, m^2/sec; δ, initial thickness of the boundary layer, in fractions of d; Δ, trench depth, in fractions of d; ε, rate of dissipation of turbulence energy, in fractions of U^3/d; θ, dimensionless temperature, $\theta = (T - T_w)/(T_{inlet} - T_w)$; λ, thermal conductivity, W/(m·K); μ, viscosity, Pa·sec; ν, kinematic viscosity, $\nu = \mu/\rho$; ρ, density, kg/m^3; ω, specific rate of dissipation of turbulence energy, in fractions of U/d. Indices: wake, wake of unit length behind the trench; inlet, parameters at the inlet to the computational domain; it, iterations; min and max, minimum and maximum values; pl, parameters on the plane without a trench; t, turbulent; tr, trench; w, parameters on the wall.

REFERENCES

1. P. K. Chang, *Separation of Flow* [Russian translation], Vol. 2, Mir, Moscow (1973).
2. É. K. Kalinin, G. A. Dreitser, I. Z. Kopp, and A. S. Myakochin, *Efficient Surfaces of Heat Transfer* [in Russian], Énergoatomizdat, Moscow (1998).
3. Yu. F. Gortyshov and V. V. Olimpiev, *Heat Exchangers with Enhanced Heat Transfer* [in Russian], Izd. A. N. Tupolev KGTU, Kazan' (1999).

4. V. V. Alekseev, I. A. Gachechiladze, G. I. Kiknadze, and V. G. Oleinikov, Tornado-like energy exchange in three-dimensional concave reliefs — structure of self-organizing flows, their visualization and mechanisms of flows past surfaces, in: *Proc. 2nd Russ. Nat. Conf. on Heat Transfer*. Vol. 6. *Enhancement of Heat Transfer. Radiative and Combined Heat Transfer* [in Russian], MÉI, Moscow (1998), pp. 33–42.
5. V. N. Afanas'ev, V. Yu. Veselkin, A. I. Leont'ev, A. P. Skibin, and Ya. P. Chudnovskii, *Hydrodynamics and Heat Transfer in Flows Past Individual Dimples on an Initially Smooth Surface* [in Russian], Preprint No. 2-91 of N. É. Bauman Moscow State Technical University, Pts. 1 and 2, Moscow (1991).
6. V. I. Terekhov, Separating flows. Mechanisms of formation and possibilities of control of heat transfer processes, in: *Proc. XIII School-Seminar of Young Scientists and Specialists Headed by Academician A. I. Leont'ev "Physical Principles of Experimental and Mathematical Modeling of Processes of Gas Dynamics and Heat and Mass Transfer in Power Plants"* [in Russian], Vol. 1, MÉI, Moscow (2001), pp. 15–20.
7. I. A. Belov and S. A. Isaev, *Modeling of Turbulent Flows. Manual* [in Russian], BGTU, St. Petersburg (2001).
8. I. A. Belov and S. A. Isaev, Numerical study of separating flows of viscous fluid in recesses and in flows past bodies, in: *Coll. of Papers of A. N. Krylov Sci.-Res. Soc. "Improvement of Flying Qualities"* [in Russian], Issue 462 (1989), pp. 54–63.
9. I. A. Belov and S. A. Isaev, Numerical simulation of near-wall flows with organized circulation zones, *Gazodinamika Teploobmen*, Issue 10, 139–156 (1993).
10. N. A. Kudryavtsev, Hydrodynamics and heat transfer of a transverse flow past a trench, in: *Ext. Abstr. of Papers presented at VIII All-Union School-Seminar Headed by Academician A. I. Leont'ev "Modern Problems of Gas Dynamics and Heat and Mass Transfer and Ways of Improving of the Efficiency of Power Plants"* [in Russian], Pt. 1, MGTU, Moscow (1991), p. 35.
11. A. V. Ermishin and S. A. Isaev (Eds.), *Control of Flows Past Bodies with Vortex Cells as Applied to Flying Vehicles of Integral Arrangement* [in Russian], MGU, Moscow (2003).
12. S. A. Isaev, Development of multiblock computation technologies for solving problems of vortex aeromechanics and thermal physics, in: *Proc. XIV School-Seminar of Young Scientists and Specialists Headed by Academician A. I. Leont'ev "Problems of Gas Dynamics and Heat and Mass Transfer in Power Plants"* [in Russian], Vol. 1, MÉI, Moscow (2003), pp. 13–16.
13. F. R. Menter, Two-equation eddy-viscosity turbulence models for engineering application, *AIAA J.*, **32**, No. 8, 1598–1605 (1994).
14. P. Spalart and S. Allmaras, A One-Equation Turbulence Model for Aerodynamic Flows, *Tech. Rep. AIAA*, No. 92-0439 (1992).
15. S. A. Isaev, S. V. Guvernyuk, M. A. Zubin, and Yu. S. Prigorodov, Numerical and physical modeling of a low-velocity air flow in a channel with a circular vortex cell, *Inzh.-Fiz. Zh.*, **73**, No. 2, 346–353 (2000).
16. S. A. Isaev, P. A. Baranov, S. V. Guvernyuk, and M. A. Zubin, Numerical and physical modeling of a turbulent flow in a diverging channel with a vortex cell, *Inzh.-Fiz. Zh.*, **75**, No. 2, 3–8 (2002).
17. S. A. Isaev, A. I. Leont'ev, P. A. Baranov, and I. A. Pyshnyi, Numerical analysis of the influence of the depth of a spherical lune on a plane wall on turbulent heat transfer, *Inzh.-Fiz. Zh.*, **76**, No. 1, 52–59 (2003).
18. S. A. Isaev and A. I. Leont'ev, Numerical modeling of vortical enhancement of heat transfer in a turbulent flow past a spherical lune on the wall of a narrow channel, *Izv. Ross. Akad. Nauk, Teplofiz. Vys. Temp.*, **41**, No. 5, 755–770 (2003).
19. R. W. Benodekar, A. J. H. Goddard, A. D. Gosman, and R. I. Issa, Numerical prediction of turbulent flow over surface-mounted ribs, *AIAA J.*, **23**, No. 3, 359–366 (1985).
20. F. R. Menter, M. Kuntz, and R. Langtry, Ten years of industrial experience with the SST turbulence model, in: *Proc. Int. Conf. "Turbulence: Heat and Mass Transfer 4*," Begell House, Inc. (2003).
21. S. A. Isaev, N. A. Kudryavtsev, D. A. Lysenko, and A. E. Usachov, A retrospective analysis of semi-empirical differential models of turbulence for calculation of separating flows, in: *Proc. 3rd Int. School-Seminar "Models and Methods of Aerodynamics*" [in Russian], MTsNMO, Moscow (2003), pp. 54–55.