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Formation of turbulent tornadolike structures in a longitudinally oriented groove on the channel wall during tip deflection and vortex heat transfer enhancement

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The paper considers formation on the channel wall of a turbulent tornadolike vortex with increasing length of the longitudinally oriented groove tip deflected by the angle of 45°. Rearrangement of the separated flow structure in the groove inlet part is associated with formation of an increasing transverse extraordinary pressure drop and is accompanied by a drastic intensification of the swirling flow in the groove and of the vortex heat transfer.

Keywords: separated flow, tornadolike vortex, narrow channel, longitudinal groove with deviated tip, intensification, heat transfer, numerical modeling.

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Separated flows are characterized by formation of various vortices. For instance, when a backwardfacing step is flown around, a transversely oriented vortex is formed downstream of it [1], and a spiral vortex arises on the channel wall behind the inclined rib [2]. Tornadotype swirling flows may arise under natural conditions [3] and, at the same time, get selforganized in dimples on the energyefficient structured surfaces [4]. The mechanisms for generating such structures at side walls of the channel with a transverse circular rib [5] and on side walls of a spherical dimple during its deepening [6] show that swirling flows in the separation zones do not possess high intensity and are characterized by moderate velocities of about 30% of the characteristic one. When inclined grooves on the plate are flown around, tornadolike vortices are generated in them. Therewith, a correlation has been established of the intense return and swirling flows with ultrahigh velocities comparable to the characteristic velocity and extraordinary concentrated static pressure drops between the stagnation zones on the windward slope of the groove inlet part and rarefaction (negativepressure) zones in the tornadolike vortex core [7–9]. The pressure drop magnitudes are comparable to the pressure difference between critical points of flowing around a blunt body like a transverse cylinder or sphere. As the heat flow measurements have shown [10], varying the groove inclination angle from 0 to 90° leads to intensification of its heat exchange.

A rectangular channel $H = 0.05\,\mathrm{m}$ in height (height is assumed to be a characteristic dimension) has the dimensionless width of 2 and length of 12. All the linear dimensions are taken in fractions of H. Air flow entering the channel working section was assumed to be uniform and having the boundary layer thickness of 0.1. The Reynolds number determined based on the characteristic inlet flow velocity U_0 and H was set to $1.65 \cdot 10^4$. The x, y, z Cartesian frame of reference is related to the middle of the channel lower wall in the inlet crosssection; the axes are oriented vertically and transversely to the channel. Velocity Cartesian components U, V, W are related to characteristic velocity U_0. The longitudinal groove oriented along the flow consists of two spherical dimple halves connected by a trench insert. Its width is 0.6, depth is 0.15, and length is 3. Its tip inlet section deflects at the angle of 45°, its relative length ξ varies from 0 to 0.15. When relative length ξ ranges from 0.05 to 0.075, the curvature radius at the point of the grooveś inclined and longitudinal parts junction is 0.5. If ξ is greater than 0.1, the curvature radius becomes equal to 1. The radius of the groove edge rounding is 0.02. The groove is located in the middle of the channel at the distance of 6 from the inlet. Dimensionless pressure P is related to the double dynamic head determined from characteristic velocity U_0. The degree of turbulence in the inlet crosssection is assumed to be 0.5%; the turbulence scale is taken equal to H. The noslip condition is specified for the walls, while for the outlet boundary the conditions for continuing the solution are specified. At the channel inlet, the air flow is isothermal with the temperature of $T_{ref} = 293\,\mathrm{K}$. The lower flownabout channel wall with the groove is heated at the constant heat flow q. Being converted into the dimensionless form via formula $q^* = q/(\lambda \cdot \mathrm{Pr} \cdot \mathrm{Re} \cdot T_{ref}/H)$, it is assumed to be $3.4 \cdot 10^{-5}$. Here λ is the air thermal conductivity, $\mathrm{Pr} = 0.7$.

Table 1. Comparison of experimental and calculated relative Nusselt numbers on the windward and leeward slopes of the straight groove tip in the characteristic crosssection of transition from the spherical segment to the trench part at slope angles of 0 and 45°

Slope angle, deg	Nu/Nu_{pl}		$Nu/Nu_{pl\,w}$	
	Experiment [10]	Calculation	Experiment [10]	Calculation
0	0.6	0.62	1	1
45	0.4	0.5	3.1	3.2

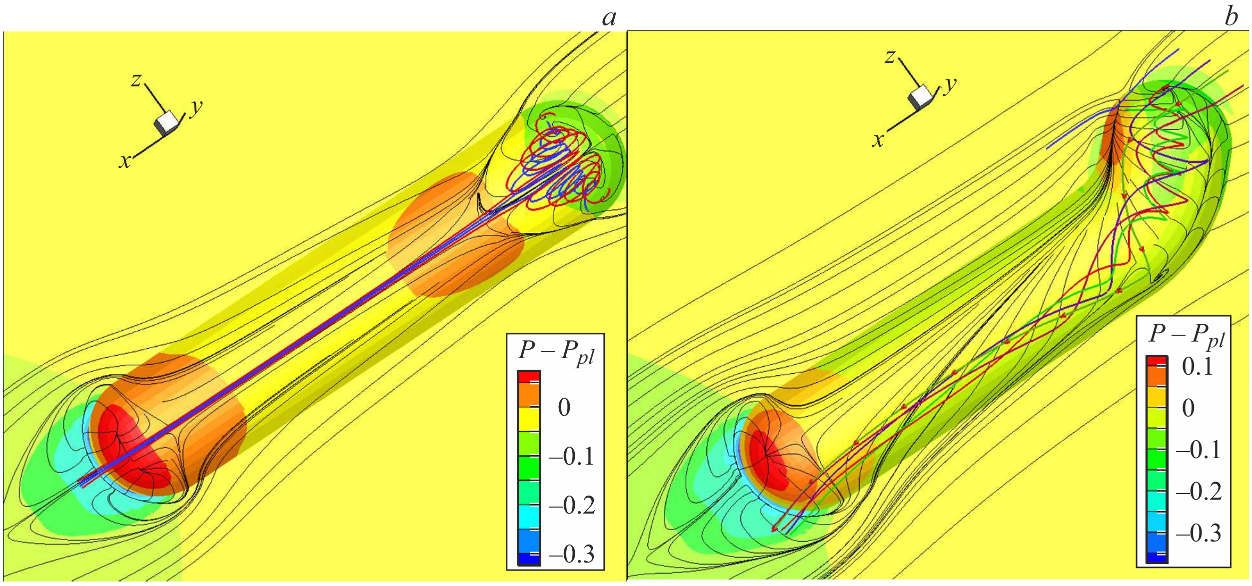

Figure 1. Surface fields of pressure drops $P - P_{pl}$ in the longitudinally oriented groove (a) and deflectedtip groove $\xi = 0.15$ in relative length (b) with applied spreading patterns and spatial vortex structures.

Side walls of the channel are adiabatic; the upper wall is isothermal with temperature T_{ref} selected as the non-dimensionalization scale. At the channel outlet, temperature T meets soft boundary conditions. Nusselt number Nu is determined from the temperature gradient on the wall and difference between the wall temperature and average mass temperature in the relevant channel crosssection.

The convective heat transfer in a turbulent lowvelocity flow in the channel with a longitudinallyoriented groove located on a heated wall and having a deflected variable-length tip will be numerically simulated based on the Reynoldsaveraged Navier–Stokes equations defined for an incompressible fluid and also on energy [6–8]. The set of equations will be closed using the Menterś shear stress transfer model [11]. The set of initial stationary equations in the linearized form will be solved using multiblock computing technologies and partially intersecting different-scale structured grids [12]. The multiblock computing grid consisting of four fragmentary grids contains about $4 \cdot 10^6$ cells. The nearwall pitch is 10^{-5}.

Validation of the calculation model is illustrated in Table 1. Here a satisfactory agreement between the numerical predictions and experimental data [10] is observed for relative Nusselt numbers on the windward $Nu/Nu_{pl\,w}$ edge and leeward Nu/Nu_{pl} slope of the groove in the characteristic crosssection of transition from the spherical segment to trench part of the longitudinally oriented groove and the groove inclined at 45°. Characteristics with index *pl* are taken at the planeparallel channel points corresponding to projections of the curved wall of the channel containing the groove.

Figs. 1–3 and Table 2 present some of the results obtained. On the pressure and temperature fields on the heated wall surface with a longitudinally oriented groove, including that with the deflected tip, there are applied spreading patterns that are flow lines in the nearwall layer 10^{-5} thick (in Fig. 3, arrows indicate the velocity vector directions). Fig. 1 demonstrates jetvortex structures illustrated by spatial trajectories of liquid particles introduced, for instance, at specific points like spreading pattern focuses.

As Fig. 1, a shows, flowing around the channel lower wall with a longitudinally oriented groove is characterized by the return flow separation zones in the tip and end parts with spherical segments; thereat, the separation zone gets formed on the plane channel wall behind the groove rear edge. At the same time, the flow in the trenchpart contains no secondary separations. A symmetrical vortex structure with a pair of counterrotating vortices and two swirling jets interacting in the plane of symmetry, which get selforganized on the groove tip lateral slopes, is similar

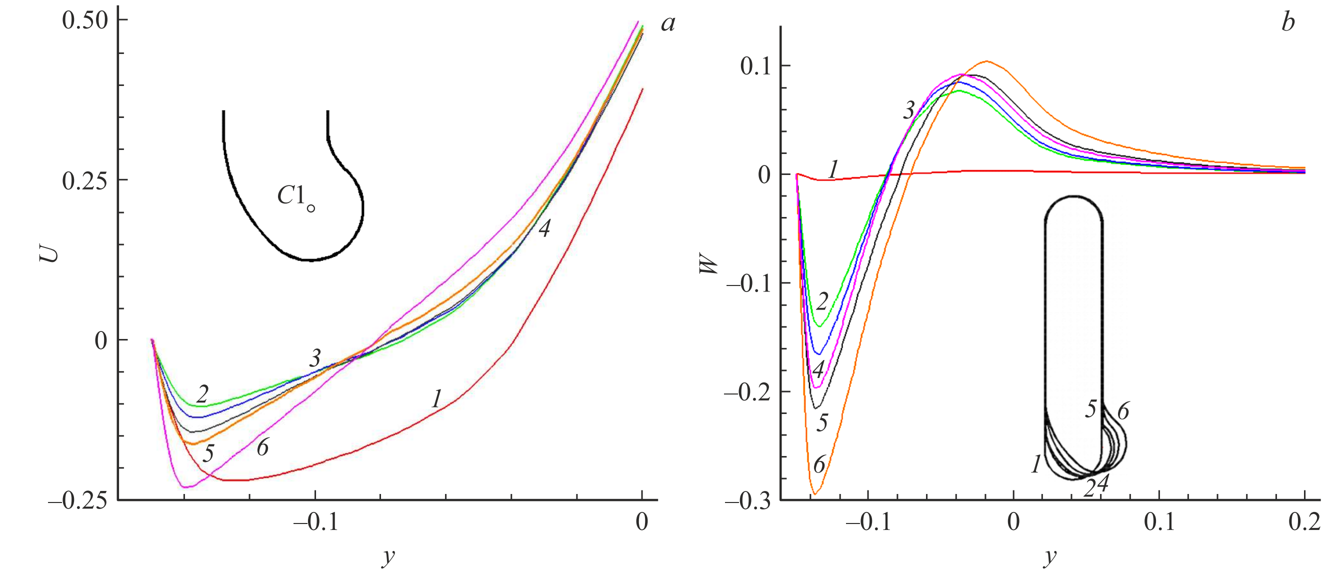

Figure 2. Comparison of profiles of the Cartesian longitudinal U (a) and transverse W (b) velocity components at different relative lengths of the grooveś inclined tip ξ in the center of the crosssection of transition between the spherical segment and trench part $C1$. $\xi = 0$ (*1*), 0.05 (*2*), 0.06 (*3*), 0.075 (*4*), 0.1 (*5*) and 0.15 (*6*). The figure depicts contours of the grooves under consideration.

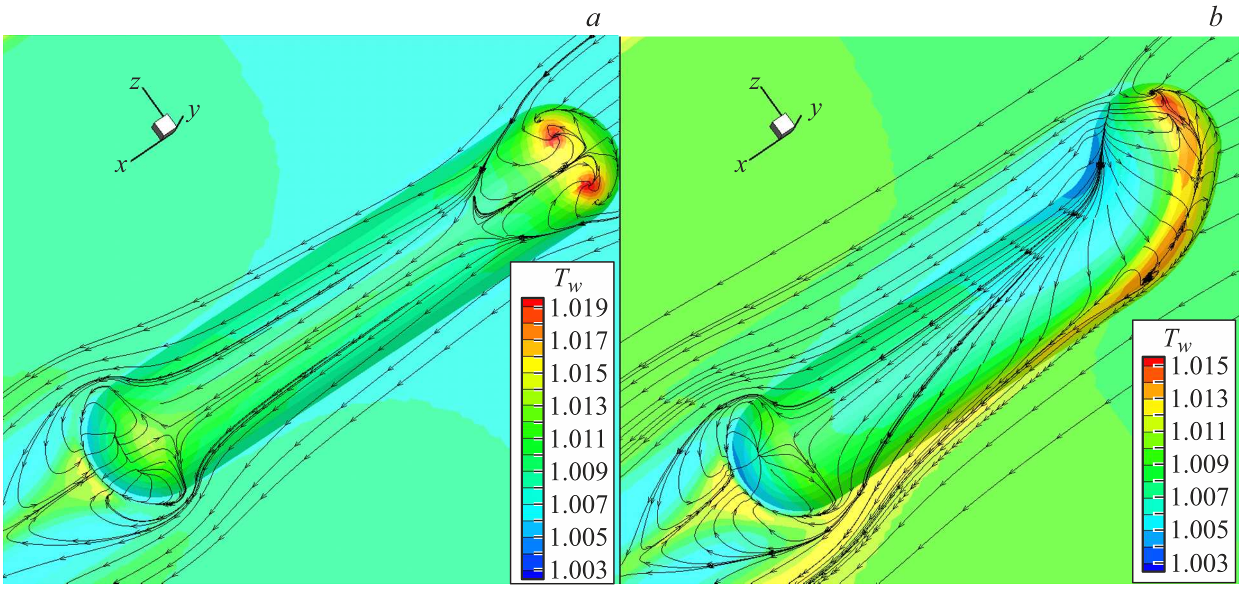

Figure 3. Surface temperature fields in the longitudinally oriented groove (a) and groove with the deflected tip having relative length $\xi = 0.15$ (b) with applied spreading patterns.

to vortex structures in a shallow spherical dimple on the channel wall [6]. As shown in Fig. 2, a, velocity profile $U(y)$ in the center of the tip $C1$ characteristic crosssection has a filled shape typical of return currents with the minimum of -0.245. The vortices in the tip separation zone occur in the region of negative excess pressure $P - P_{pl}$ free of transverse pressure drop.

When the deflected tip is formed, a tornadolike vortex structure selforganizes in it; as ξ increases, the vortex structure creates a swirling flow propagating along the groove trench part (Fig. 1, b). The jet swirling intensity increases; therewith, the transverse velocity maximum W at $\xi = 0.15$ reaches 0.3 (Fig. 2, b), while minimum U amounts to (-0.247). The length of the return flow nearwall zone becomes considerably shorter. Intensification of the separated flow is caused by increasing static pressure drop $P-P_{pl}$ between the stagnation zones on the windward deflected tip slope and negativepressure zone behind the leading edge in the tornadolike vortex core similarly to variation in the groove inclination angle [7]. It reaches 0.3 at $\xi = 0.15$. Note that formation of a tornadolike vortex structure within the separated flow in the longitudinally

Table 2. The effect of relative elongation of the inclined tip of the longitudinally oriented groove ξ on relative hydraulic losses ζ/ζ_{pl} and $\zeta_d/\zeta_{d\,pl}$ and also on relative Nusselt numbers $Nu_m/Nu_{m\,pl}$ and $Nu_{md}/Nu_{md\,pl}$ averaged over the areas of the reference region and rectangular region restricted by the groove contour

ξ	ζ/ζ_{pl}	$\zeta_d/\zeta_{d\,pl}$	$Nu_m/Nu_{m\,pl}$	$Nu_{md}/Nu_{md\,pl}$
0	1.056	1.084	0.998	0.958
0.05	1.065	1.079	1.005	0.984
0.075	1.072	1.086	1.013	1.024
0.1	1.082	1.111	1.020	1.067
0.12	1.093	1.121	1.029	1.089
0.15	1.108	1.131	1.040	1.145

oriented groove with inclined tip develops gradually. As shown in Fig. 2, *a*, the almost filled profile $U(y)$ inherent in separated flows at point $C1$ persists within the ξ variation range of 0.05 to 0.1. As noted in [7], profile $U(y)$ exhibits at $\xi = 0.15$ a nearwall return flow and shear section corresponding to an intense swirling jet flow.

Deviation of the longitudinal groove tip intensifies heat exchange and promotes enhancement of hydraulic losses (see Table 2). Relative Nusselt numbers $Nu_m/Nu_{m\,pl}$ will be determined in the square reference region 3.3×3.3 in size surrounding it, while numbers Nu_{md}/Nu_{mdpl} will be determined in the region restricted by the contour of the groove with deflected tip. Values of ζ/ζ_{pl} will be calculated by the method described in [12] between the channel crosssections passing along the front and rear boundaries of the reference region, while ζ_d/ζ_{dpl} will be estimated between the crosssections passing through the extreme front and rear edges of the groove. Transition from the canonical separated flow with strong return jets and weak swirling jets in the longitudinally oriented groove to formation of the separated flow with tornadolike structure and swirling flow results in a rather moderate increase in relative values of heat transfer and hydraulic loss in the reference region. At the same time, the rate of the $Nu_{md}/Nu_{md\,pl}(\xi)$ growth in the region restricted by the groove contour increases considerably. Note that the temperature maxima on the groove surface appear to be at the places of swirling jets selfgeneration on the lateral slopes at $\xi = 0$ (Fig. 3, *a*) and on the spherical deflected segment of the tip, as well as on the spreading line on the leeward slope (Fig. 3, *b*). As length ξ increases from 0 to 0.15, the temperature T_w maximum decreases significantly from 1.019 to 1.015. Also noteworthy is increasing windward edge chilldown on the inclined edge of the tip groove part.

Thus, rearrangement of the separated flow structure in the inlet deflected part of the longitudinally oriented groove, which is associated with formation of the tornadolike vortex, takes place in the variation range of the ξ relative elongation (0.05 to 0.15). It is associated with formation of an increasing transverse extraordinary pressure drop and is accompanied by drastic intensification of the swirling flow in the groove trench part and of vortex heat exchange.

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Conflict of interests

The authors declare that they have no conflict of interests.

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