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Influence of blowing a jet from a thin tube on the generation of a tornado-like vortex and the intensification of a developing swirling turbulent flow in an inclined groove on a channel wall

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A numerical study of the effect of blowing a jet from a thin air tube on the vortex motion in an inclined groove on the wall of a plane-parallel channel is performed using StarCCM$^+$ calculation codes. It is shown that in the range of change in the flow rate in the jet from 0 to 0.1% in fractions of the air flow rate in the channel, the blowing of the jet does not affect the self-organized tornado-like vortex in the inlet part of the groove. With an increase in the relative flow rate, the outflowing trickle is gradually drawn in, and, starting from 0.08%, it is completely captured by a helical vortex emerging from the central part of the groove with an inclination angle of 45°. In this case, the swirling flow in the tail part of the groove is intensified due to the resulting pressure drop between the zones of stagnation on the windward slope and rarefaction at the bottom of the groove.

Keywords: Separated flow, jet, groove, plane-parallel channel, intensification, numerical simulation.

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A high intensity is the specific feature of a tornado-like flow in an inclined groove in a single-row sparse package on the wall of a narrow channel in a stabilized flow [1]. It was demonstrated in [2] that the maximum velocities of reverse and secondary flows at an inclination angle of 30–70° are on the order of the mass-averaged and maximum flow velocities in a plane-parallel channel. An anomalously high (in magnitude) negative friction, which exceeds the friction on a smooth wall by a factor of 4, is attained in the median longitudinal section in the inlet part of a groove. The minimum of relative negative friction in individual inclined grooves on the wall of a narrow channel is two times higher (on the order of -2) [3]. It was demonstrated in reviews [4,5] that an anomalous intensification of separation flow and heat transfer in inclined grooves on a plate and the wall of a channel is attributable to the emergence of an extra-ordinary pressure drop between the zone of stagnation on the windward slope and the zone of a low negative pressure at the site of generation of a tornado-like vortex at the inlet spherical segment. It should be noted that the results of measurement of pressure in individual inclined grooves on the wall of a channel [6] verified the validity of numerical predictions regarding the pressure drops, which were determined by solving Reynolds-averaged Navier–Stokes equations [7]. The interrelation between an anomalous intensification of separation flow and extra-ordinary pressure drops in a groove on a plate with the inclination angle varying from 0 to 90° was established in [8]. Taken together, the results of detailed experimental [3–8] and numerical [1–5,7,8] studies of jet-vortex structural features of flow and heat transfer in a narrow channel with inclined grooves allow one to characterize this flow as an anomalous one in terms of the high intensity of relative velocities of reverse and secondary swirling flows.

It is known that jet blowing and a coolant bleed hole in spherical dimples provide an opportunity to enhance the performance of energy devices. Specifically, it was found in [9] that the blowing of cooling air through orifices in spherical dimples allows one to form (at certain process and geometric parameters) a more uniform air curtain and reach a higher cooling efficiency than the one achieved with blowing through orifices in a smooth wall. At the same time, the introduction of a bleed hole [10,11] provides a 10–20% enhancement of the heat exchange on a dimpled surface.

A digital version of the experimental setup found at the Research Institute of Mechanics of the Moscow State university [6] is examined. This test stand is a plane-parallel channel with a groove with shard edges, which is oriented at an angle of 45° to an incoming turbulent air flow, on its lower wall. Channel height H is 0.05 m, its width is 0.2 m, and its length is 0.6 m. The groove is made of two halves of a spherical dimple with spot diameter $D = 0.03$ m connected by a cylindrical insert 0.12 m in length. The groove depth is 0.0075 m and the groove length is 0.15 m is positioned in the middle of the channel at a distance of 0.3 m from the inlet. A thin tube 0.003 m in diameter and 0.01 m in length is connected to the center of the groove bottom. Air is blown through this tube. The intensity and the scale of turbulence of the flow in the channel are 1.5% and 0.003 m, respectively. Cartesian coordinate system X, Y, Z with its origin matching the projection of the groove center onto a plane coincident with the channel wall is introduced. Cartesian velocity components U, V, W and blowing parameter $m = V_{in}$ are taken relative to incoming flow velocity $U_c = 5.2\,\mathrm{m/s}$.

A single-block unstructured grid with refinement in the vicinity of the groove and predominantly hexagonal cells is used to divide the computational domain into control volumes. A prismatic layer of cells is constructed near the walls. The height of the first of them is $0.00017D$. The approximate number of grid cells is 6.7 million. A uniform flow with Reynolds number $\mathrm{Re} = 1.7 \cdot 10^4$, which is calculated based on the incoming flow velocity and the channel height, is set at the inlet boundary. The constant-pressure condition is set at the outlet boundary. The no-slip condition is imposed on all walls. Air flow rate Q through the tube varies from 0 to 0.1% of air flow rate Q_{in} at the channel inlet (0, 0.008, 0.034, 0.084, and 0.1%), and blowing parameter m assumes the corresponding values of 0, 0.115, 0.48, 0.96, and 1.44.

The turbulent flow in the channel with the groove is modeled by solving Reynolds-averaged Navier–Stokes equations (RANS approach) closed with the k–ω SST turbulence model equations with the Durbin correction [12]. A second-order upwind scheme with a gradient limiter [13] is used for discretization of convective terms. The system of algebraic equations is solved using a finite volume solver with an algebraic multigrid (AMG) and a conjugate-gradient preconditioner [14]. StarCCM$^+$ calculation codes are applied. A methodological study on substantiating the choice of grids and a turbulence model for the calculation of flow past an inclined groove in a single-row package on the wall of a plane-parallel channel in a stabilized section of air flow was performed in [15].

Some of the results of calculations are presented in Figs. 1 and 2. Figure 1 presents the results of structural analysis of the flow near the channel wall with an inclined groove and blowing of a jet from a thin tube at the center of the bottom with an increasing intensity ($Q/Q_{in} = 0.008$, 0.034, and 0.084%). Images are generated with the use of tracer particles released at height $Y/H = 0.03$ above the wall. The surface fields of pressure coefficient C_p are also compared in Fig. 1.

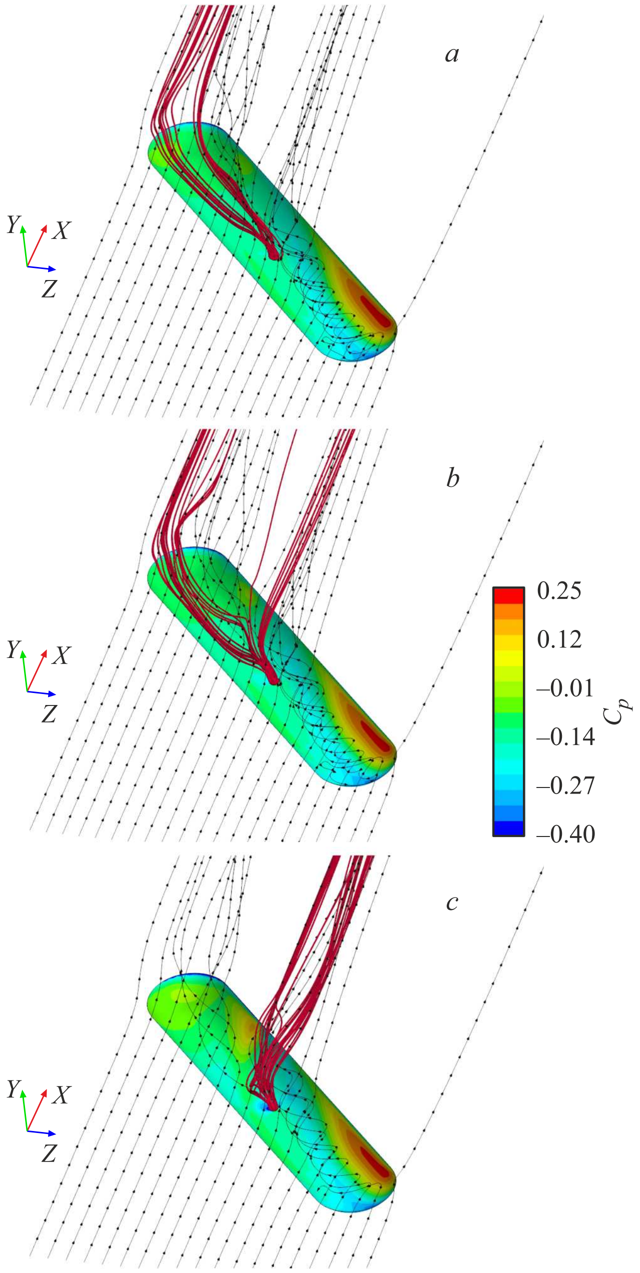

Figure 1. Comparison of fields of pressure coefficient C_p with indicated trajectories of tracer particles (released from height $0.03H$) in the flow near a wall with an inclined groove and in the jet blown from a thin tube at the center of the bottom at relative flow rates $Q/Q_{in} = 0.008$ (a), 0.034 (b), and 0.084% (c).

The first thing of note are the emerging significant static pressure drops between the zone of stagnation of flow entering the groove on the windward slope and the zone of negative pressure in the inlet part at the site of generation of a tornado-like flow in the groove. The obtained vortex flow patterns and surface pressure distributions are independent of the jet blowing intensity and are similar to the ones determined earlier for individual and single-row inclined grooves on the wall of a channel oriented at an angle of 45° [1–4,6,13]. The swirling flow formed in the inlet part splits downstream of the center of the groove, and the produced helical vortex leaves the groove. With weak blowing, the outflowing trickle is drawn completely into the vortex flow in the tail part of the groove. At a moderate ($Q/Q_{in} \sim 0.03\%$) blowing intensity, the jet is split and captured partially by the helical vortex. At a high ($Q/Q_{in} \sim 0.08\%$) blowing intensity, the structure of flow at the groove outlet is rearranged, and the entire outflowing jet is forced into the helical vortex. A stagnation zone then forms on the windward groove slope, and an outlet swirling flow develops in the tail part.

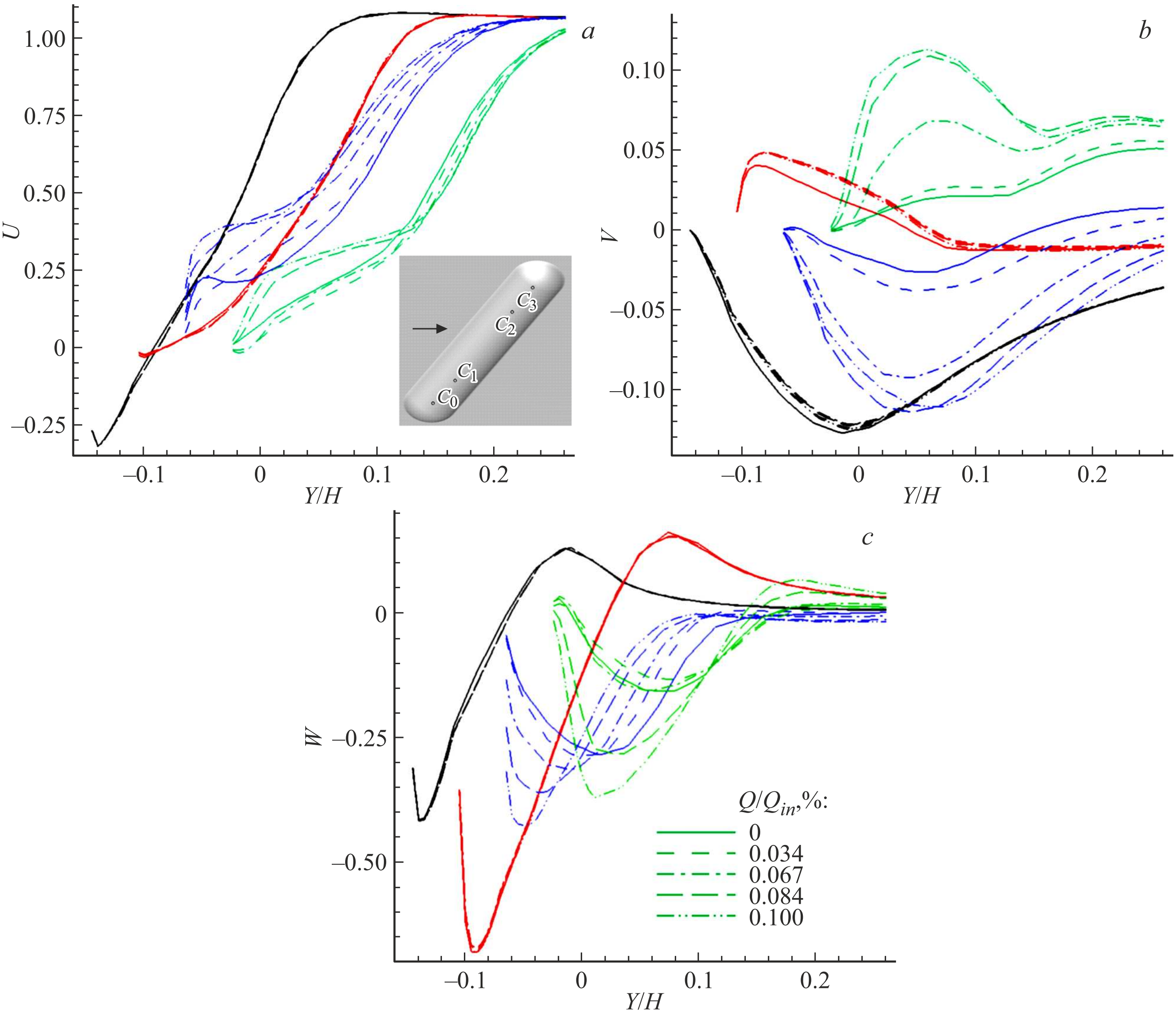

Figure 2. Profiles of Cartesian velocity components $U(Y/H)$ (a), $V(Y/H)$ (b), and $W(Y/H)$ (c) at control points C_0 (black curves), C_1 (red curves), C_2 (blue curves), and C_3 (green curves) in the inclined groove with relative flow rates Q/Q_{in} varying from 0 to 0.1%. The reference points in coordinate Y/H in the plots for C_1, C_2, and C_3 are shifted by 0.04, 0.08, and 0.12, respectively. A color version of the figure is provided in the online version of the paper.

The profiles of Cartesian velocity components of longitudinal U, vertical V, and transversal W flows made dimensionless with respect to the flow velocity at the channel inlet are analyzed at several characteristic points on the bottom of the groove (C_0, C_1, C_2, and C_3) at different blowing intensities Q/Q_{in} (Fig. 2). Profiles are plotted along vertical coordinate Y normalized to channel height H. C_0 and C_3 are the centers of sections of coupling of inlet and outlet spherical segments, and C_1 and C_2 are the centers of segments between the groove center and points C_0 and C_3 in the median longitudinal section.

In the inlet part of the groove at points C_0 and C_1, the profiles of Cartesian velocity components are almost independent of jet blowing intensity Q/Q_{in}. Slight changes are seen only in the $V(Y/H)$ dependences for vertical component V determined with and without blowing. While point C_0 is in the separation flow zone (the reverse flow velocity is approximately 30% of the velocity at the channel inlet), point C_1 is located in the through-flow zone with an insignificant negative velocity U at the bottom of the groove in the median section. Interestingly, the flow in the groove undergoes significant changes in transition from point C_0 to C_1. The downward flow at point C_0 with a minimum velocity on the order of -0.14 transforms into an upward flow with a maximum velocity of 0.05. Somewhat surprisingly, the swirling flow is intensified with an almost twofold enhancement of the maximum absolute value of velocity W, which increases from 0.36 to 0.68.

The influence of blowing intensity on the profiles of Cartesian velocity components becomes fairly noticeable on crossing the center of the groove in the median section. The through flow intensifies at point C_2 with increasing Q/Q_{in}; at the wall, the longitudinal velocity component maximum approaches 0.4 at $Q/Q_{in} = 0.1\%$. In contrast to the upward flow at C_1, the vertical flow at point C_2 becomes downward, and the velocity minimum decreases monotonically with increasing Q/Q_{in}, eventually reaching -0.12. As Q/Q_{in} increases, the swirling flow at point C_2 intensifies with the absolute value of W increasing moderately from around 0.27 to 0.37 at $Q/Q_{in} = 0.1\%$.

The through flow in the tail part of the groove (point C_3), which is characterized by velocity component U, is fairly weak within the range of Q/Q_{in} variation from 0 to 0.067%. At Q/Q_{in} above 0.084%, the through flow is intensified dramatically; the velocity in the near-wall zone grows rapidly to 0.25. The upward flow intensifies monotonically at point C_3: the V velocity maximum reaches 0.07 already at $Q/Q_{in} = 0.067\%$ and goes to 0.11 at 0.1%. As Q/Q_{in} grows above 0.084%, the maximum absolute value of W increases profoundly, varying from 0.15 at $Q/Q_{in} = 0.067\%$ to 0.3−0.4 at $Q/Q_{in} > 0.084\%$.

Thus, jet blowing from a thin tube in an inclined groove on the wall of a channel with the relative flow rate varying from 0 to 0.1% does not weaken the self-organized high-intensity tornado-like vortex in the inlet part and intensifies considerably the swirling outlet flow at relative flow rates above 0.084%.

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Conflict of interest

The authors declare that they have no conflict of interest.

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