

Validation of approaches to solving the Reynolds-averaged Navier–Stokes equations and eddy-resolving methods in the study of anomalous intensification of turbulent separated flow in a stabilized hydrodynamic section of a structured channel with two-row inclined grooves

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Received November 7, 2025

Revised December 4, 2025

Accepted December 4, 2025

Numerical predictions of turbulent separated flow characteristics in inclined grooves in two-row dense packets in a structured channel in a stabilized section, obtained by solving the averaged Navier–Stokes equations and using a variant of the detached vortex method, are compared with each other and with the results of numerical and physical modeling in a long channel with 26 grooves in each row. Their acceptable agreement confirms the phenomenon of anomalous intensification of separated flow and flow acceleration in the core of the structured channel, with a 1.3-fold increase in maximum velocity compared to a plane-parallel channel.

Keywords: velocity fields, structured channel, inclined grooves, core flow acceleration, RANS, IDDES.

DOI: 10.61011/TPL.2026.04.63194.20564

The effect of anomalous intensification of separated flow and heat transfer (AISFHT) in inclined grooves was established numerically by solving the Reynolds-averaged Navier–Stokes (RANS) equations in a stabilized section of a structured narrow channel [1]. It is associated with extraordinary differences in static pressure in the inlet part of a groove [2] and is accompanied by a manyfold increase in relative values of negative friction and the Nusselt number within the separated-flow region [3]. The choice of the semi-empirical SST turbulence model for RANS calculations of the tornado-like flow intensification in inclined grooves in a stabilized section of a structured channel was substantiated in [3], and its validation was performed by analyzing the AISFHT-related effect of flow acceleration in the core of a long optically transparent channel with two-row grooves at inclination angles of $\pm 45^\circ$ via comparison of the calculated longitudinal velocity profiles with those measured by the SIV method [4]. The issue of using eddy-resolving methods (similar to those used in [5] for modeling the flow around a spherical dimple on a channel wall) for calculation of turbulent separated flows remains relevant. In the present study, this issue is resolved by examining a periodic module in a structured channel with two-row inclined grooves, which is a computer model of an element of the experimental setup at the Kazan Scientific Center of the Russian Academy of Sciences (KazSC RAS) [4]. It should be noted that the detached eddy simulation (DES) method holds a unique position in the list of modern approaches to

modeling of turbulent flows presented in [6]. The results of calculations with RANS-SST and a variant of DES (IDDES) for a periodic module are compared here with each other and with numerical predictions and experimental data for a stabilized section of a long channel with 26 grooves in each row [4].

Following [3], we considered a section of stabilized turbulent air flow and heat transfer in a channel with height H and two-row inclined grooves similar to those presented in [4]. No-slip conditions were set on the section of the isothermal structured wall, on the side heat-insulated walls, and on the lower and upper isothermal walls; periodicity conditions were imposed at the flow inlet and outlet boundaries. All linear dimensions were normalized to H . The calculated periodic module of the channel had a height of 1, a length of 5.06, and a width of 10. Two rows of grooves with a depth of 0.25 and a longitudinal pitch between their centers of 2.53 were positioned on the lower wall (Fig. 1, *a*). The upper wall was maintained at characteristic temperature T equal to 1 (the corresponding dimensional value is 293 K). Grooves with a unit width were combinations of two hemispherical fragments connected by a cylindrical trench with a length of 3.5 and were inclined by $\pm 45^\circ$ to the mid-section of the module. Edge rounding radius R varied from 0 to 0.1. The lower structured wall was heated to 303 K. The Reynolds number determined from characteristic mass-average flow velocity U_0 and H was set to 4300 and is consistent with

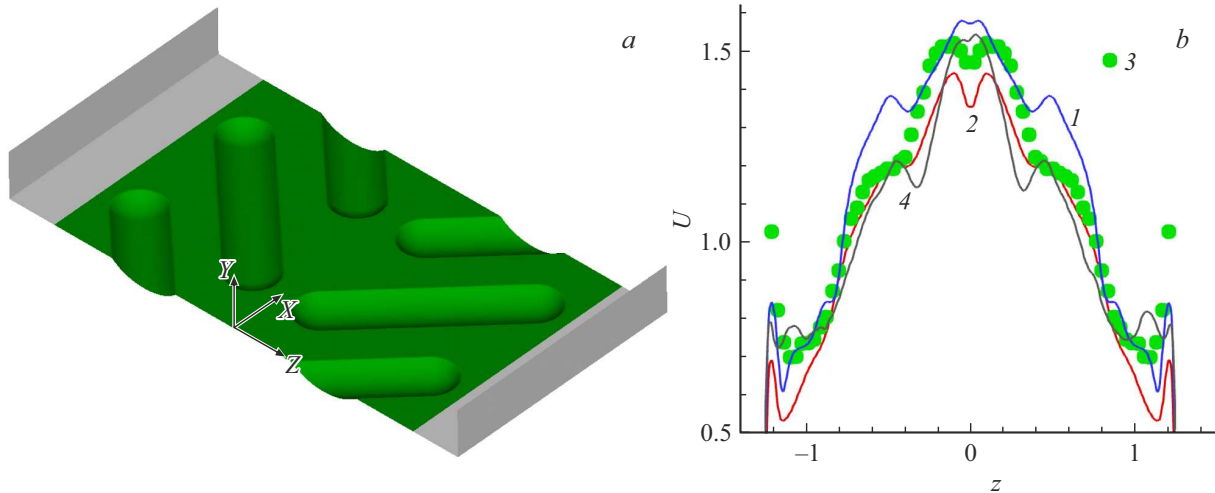


Figure 1. Periodic module in a narrow structured channel with two-row inclined grooves (*a*) and comparison of transverse profiles of longitudinal Cartesian velocity component $U(z)$ in the mid-section of the module at height $y = 0.23$ relative to the lower wall of the channel (*b*). 1 — RANS calculations in the periodic module, 2 — RANS calculations in a long channel in the central section of the 22nd groove, 3 — experiments at KazSC RAS in a long channel in the central section of the 22nd groove, and 4 — IDDES calculations in the periodic module.

experimental data [4]. Cartesian coordinate system x, y, z was tied to the middle of the lower wall of the channel in the inlet section, and the axes were oriented along the channel in the vertical and transverse directions. Cartesian velocity components $U, V,$ and W were normalized to characteristic velocity U_0 ; turbulence energy K , to U_0^2 ; and turbulent viscosity, to $U_0 H$. The no-slip condition was imposed on walls. Nusselt number Nu was determined by the temperature gradient on the wall and the difference between the wall temperature and the mass-average temperature in the corresponding cross section of the channel. Nusselt number Nu_m was integrated over a control section of the wall with grooves with a length of 5.06 and a width of 8. Hydraulic loss coefficient ξ was determined in accordance with the procedure outlined in [6] between the input and output sections of the periodic module. Characteristics with subscript pl are representative of points of a plane-parallel channel corresponding to projections of the curved structured wall of the channel.

As in [3,4], numerical modeling of turbulent air flow and heat transfer in the periodic channel module with two-row grooves was carried out by solving the Reynolds-averaged Navier–Stokes equations and energy equations [7] written for an incompressible fluid. The system of equations was closed using a shear stress transfer model, which was modified to take into account the curvature of flow lines in accordance with the Rody–Leshtsiner–Isaev approach [7]. Stationary equations in linearized form were solved using multi-block computational algorithms and partially overlapping multi-scale structured grids. A Cartesian grid in the periodic section of the channel and a curvilinear oblique grid in the near-wall layer (consistent with the groove surface) were introduced. The total number of grid cells varied from approximately 1 to 7 million. The longitudinal

and transverse grid pitches on the structured wall varied from 0.04 to 0.1. Near-wall grid pitches were set to $(1-2.5) \cdot 10^{-4}$, where the size of $2.5 \cdot 10^{-4}$ corresponds to $y^+ = 1$. The procedures for correcting the pressure gradient and the mass-average temperature implemented in the VP2/3 (Velocity–Pressure, 2D/3D) package were applied [7].

The eddy-resolving Improved Delayed Detached Eddy Simulation (IDDES) approach [8] was also used to simulate periodic turbulent fluid flow in the module with $R = 0$ (Fig. 1, *a*). The near-wall flow was calculated within the SST turbulence model [9]. Periodic boundary conditions with the mass flow rate maintained were set at the inlet and outlet of the module, and the no-slip condition was imposed on the channel walls and groove surfaces. The calculation domain was divided into control volumes using hexagonal cells. The cell size was 0.0185 in the flow core and 0.00938 in the vicinity of grooves. A prismatic layer of cells was used to characterize the flow near solid walls correctly; the height of the first cell was chosen so that dimensionless parameter $y^+ < 1$. The grid model contained approximately 10.4 million elements in total. An implicit second-order scheme was used for time discretization in an unsteady solution. Time step τ was 0.005, which ensures that the condition for Courant number $Co < 1$ is satisfied. The bounded central differencing (BCD) scheme with a mixing coefficient of 0.5 was used to discretize convective terms. To perform a correct comparison with the results of RANS calculations, the solution averaging procedure was initiated at time point $t = 150$ and kept going until $t = 300$.

Figures 1–3 present some of the results obtained. Table 1 substantiates the grid convergence of RANS solutions for $R = 0.02$ and 0.1 through a comparison of the results of calculations of thermal-hydraulic characteristics Nu_m and

ξ for grids of different densities. The extreme values of Cartesian velocity components U , V , and W in the periodic module of the channel with two-row grooves determined within the RANS and IDDES approaches are compared in Table 2. The presented characteristics agree quite well; notably, the closest agreement was observed for the hydraulic loss coefficients. It should be noted that the thermal efficiency in the stabilized section of the structured channel is 2.85 with a twofold increase in relative hydraulic losses ξ/ξ_{pl} . The value of U_{max} in the plane-parallel channel is 1.23. In the core of turbulent flow in the structured channel, U_{max} increases by a factor of 1.3 compared to its value in the plane-parallel channel; the velocity of return flows approaches 0.7, and the velocities of swirling flows in inclined grooves exceed 1. The maximum velocities of upward and downward flows within the grooves approach 0.6 and 0.4, respectively. Thus, both numerical simulation methods demonstrate that ultra-high velocities of return and secondary swirling flow characteristic of AISFHT are achieved in an inclined groove.

It can be seen from Fig. 1, *b* that RANS predictions of transverse velocity profile $U(z)$ at the center of the 22nd groove in the long channel [4] agree closely with RANS predictions of $U(z)$ at the center of the periodic module and the experimental measurement data, which is indicative of flow stabilization in the considered section of the channel. The obtained IDDES results are in

Table 1. Results of RANS calculations of thermal-hydraulic characteristics of structured channels with grids of different densities

$N \cdot 10^{-6}$	R	Nu_m	ξ
1.08	0.1	34.3	0.0414
2.2	0.1	34.5	0.0424
6.6	0.02	37.4	0.0426
Plane-parallel channel fragment	–	13.1	0.0205

Table 2. Comparison of extreme characteristics of separated flow in the structured channel

Approach	U_{max}	U_{min}	V_{max}	V_{min}	W_{max}	W_{min}
RANS	1.61	–0.701	0.563	–0.426	1.046	–1.046
IDDES	1.59	–0.645	0.622	–0.393	1.061	–1.056

reasonable agreement with the experimental data and RANS predictions, representing the $U(z)$ profile well in the central region of the channel and in the vicinity of its walls.

A comparison of RANS- and IDDES-calculated $U(y)$ velocity profiles at three characteristic points of an inclined groove in the inlet, middle, and outlet sections of the periodic module also reveals their satisfactory agreement. It demonstrates the restructuring of profiles within the groove and weakening of the flow intensity in the core observed when one approaches the side wall (Fig. 2, *a*). In the inlet part of the inclined groove, the minimum velocity of return flows decreases to -0.6 , while the maximum flow velocity in the core reaches 1.47. It should be emphasized that the longitudinal component of flow velocity at the wall level is significantly higher than the mass-average velocity and assumes the value of 1.24; i.e., the near-wall layer becomes significantly thinner above the groove. The secondary flow lines in the central section of the module plotted on velocity field $U(z, y)$ reveal the formation of helical vortex structures in the central region of the channel (Fig. 2, *b*).

A comparison of RANS- and IDDES-calculated pressure coefficient fields C_p on the structured wall of the stabilized section of the channel demonstrates that they agree satisfactorily in terms of maximum and minimum (negative) values (Fig. 3). The patterns of flow lines in the near-wall layer at distance $y = 0.00005$ from the wall in Fig. 3, *a* reveal the formation of regions of return flows and extraordinary pressure differences between the regions of stagnation on the windward slopes of grooves and rarefaction at the sites of generation of tornado-shaped structures (with a negative excess pressure).

A reasonable agreement between the results of RANS-SST and IDDES calculations for a periodic module and their alignment with the data from experiments performed at KazSC RAS for a stabilized section of

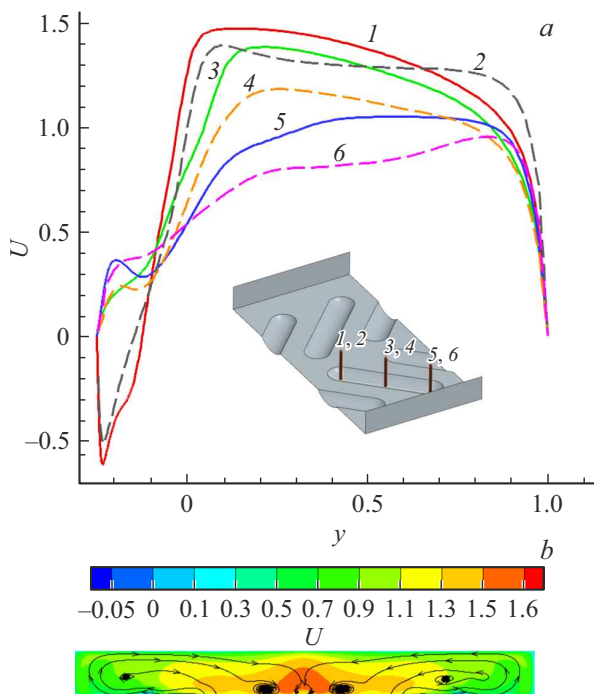


Figure 2. Comparison of calculated using RANS (1, 3, 5) and IDDES (2, 4, 6) $U(y)$ profiles at the centers of sections of the transition from end spherical segments to the trench part and at the center of an inclined groove of the periodic module of the structured channel (*a*) and RANS-calculated field $U(y, z)$ in the mid-section of the module with secondary flow lines indicated (*b*).

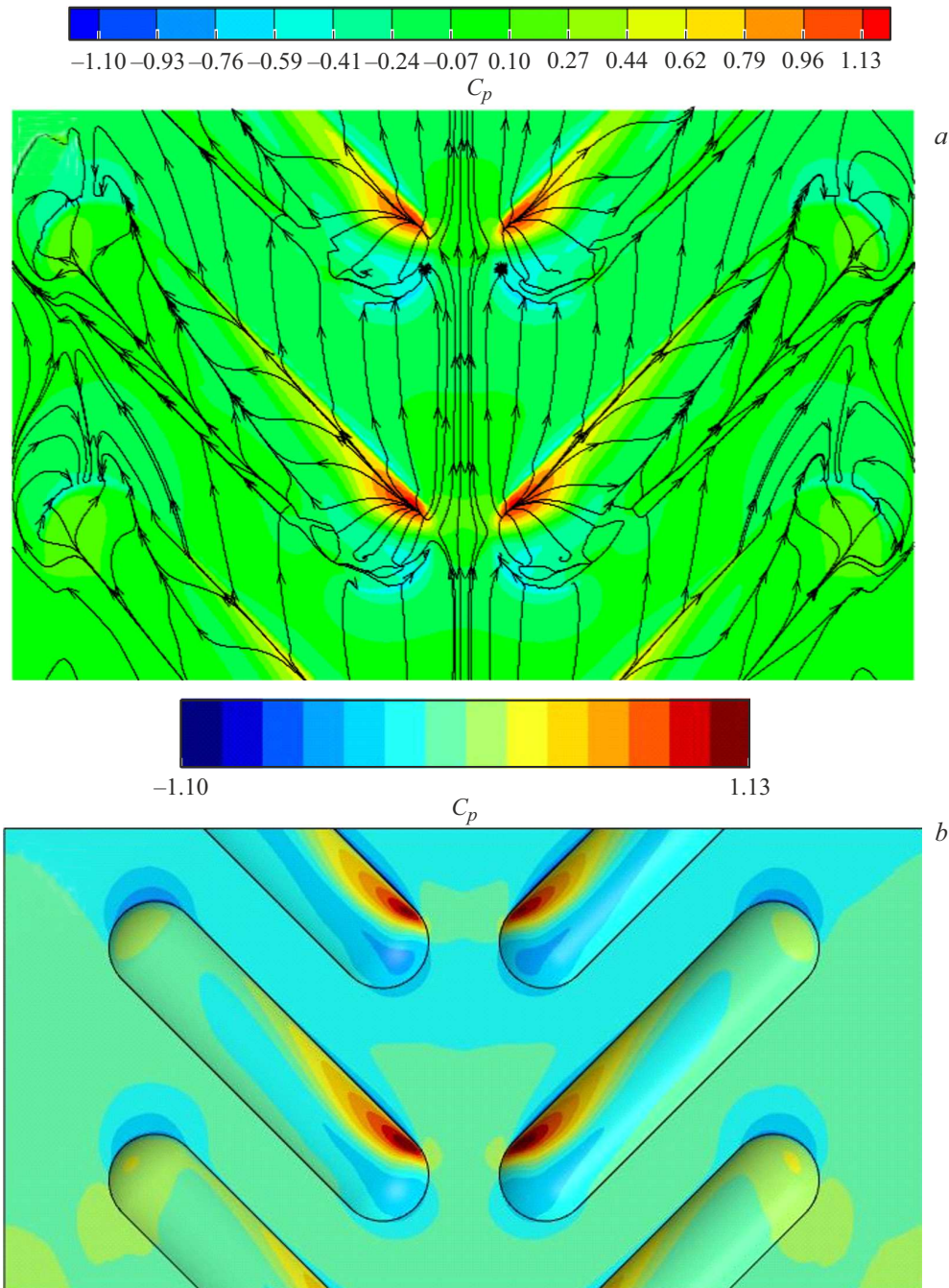


Figure 3. Comparison of RANS- (*a*) and IDDES-calculated (*b*) fields of the pressure coefficient on the structured wall of the periodic channel module. Flow lines in the near-wall layer are indicated in panel *a*.

a long channel with 26 inclined grooves in a two-row package on the wall confirms the veracity of the effect of anomalous intensification of separated flow in grooves and flow acceleration in the core of a structured channel.

Funding

This study was performed under state assignment 075-03-2025-584 dated January 27, 2025.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin