

Validation of RANS 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

© S.A. Isaev^{1,2}, A.Yu. Chulyunin³, D.V. Nikushchenko¹, A.G. Sudakov²

¹ State Marine Technical University, St. Petersburg, Russia

² Novikov St. Petersburg State University of Civil Aviation, St. Petersburg, Russia

³ Institute of Mechanics of Lomonosov Moscow State University, Moscow, Russia

E-mail: isaev3612@yandex.ru

Received August 4, 2025

Revised August 28, 2025

Accepted August 29, 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 using the RANS and IDDES approaches, 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 reasonable 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.2026.01.62811.20461

The problem of reducing viscous friction during flow around bodies and reducing hydraulic losses during fluid motion in pipes and channels has long attracted research attention in various fields of aerohydrodynamics and single- and multiphase thermal physics [1]. A reduction in resistance and hydraulic losses is related directly to the energy efficiency of technical projects of various purpose (specifically, to the construction of efficient heat exchange surfaces). One way to reduce resistance is to structure the streamlined surface with grooves [2] and dimples [3]. The results of numerical calculations of turbulent stabilized flow in a channel with height H revealed that its resistance with flat walls may potentially be reduced by 5% through the use of a surface structured with grooves with depth $0.03H$ [2]. The resistance and heat transfer for various proposed shallow dimple geometries (circular, elliptical, diamond-shaped, and teardrop-shaped with the apex pointing upstream and downstream) was analyzed in [3]. Structured surfaces are characterized by a high density of dimples, which approaches 100%. The heat transfer on walls with dimples of all geometries was found to be enhanced by as much as 16%. This was accompanied by an overall reduction in resistance of about 8% for all geometries (with the exception of round dimples, which increased the resistance by roughly 5%). Intensifiers of heat exchange on energy-efficient structured surfaces in the form of inclined oval-trench and oval-arched dimples were examined in [4]. They generate intense helical near-wall vortices. Such structured surfaces have preferable characteristics in terms of hydraulic losses and differ significantly from their

counterparts in [3]. These are the reasons why they were used in the present study. The calculation procedure was taken from [5], where the flow in a periodic module of a channel with an inclined oval-trench dimple was calculated within the RANS approach using a modified SST turbulence model. To reduce hydraulic losses in the channel, a significant edge radius of dimples was chosen, and their depth was varied from 0 to 0.425 (in fractions of the channel height).

Following [3], we examined a section of stabilized air flow and heat exchange in a channel with height H with multi-row inclined oval-arched dimples on a section of an isothermal wall. Symmetry conditions corresponding to the mirror arrangement of dimples in a multi-row package were set on the lateral boundaries of this section, and periodicity conditions were set on the flow inlet and outlet boundaries. All linear dimensions were normalized to H . The calculated periodic section of the channel had a height of 1, a length of 3.5, and a width of 2. A dimple of variable depth with an edge radius of 2 was positioned at the center of the lower isothermal wall (Fig. 1). The oval-arched dimple combines two hemispherical fragments connected by an arc cylindrical trench with an inclination of 45° at the inlet section and orientation along the flow at the outlet. In the case of very shallow dimples, the width of the trench section was 1, and the length of dimples was 3.5. The flat upper wall of the channel was maintained at temperature $T_{ref} = 293$ K, and 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 $2 \cdot 10^5$. Cartesian coordinate system x, y, z was tied to the middle of the

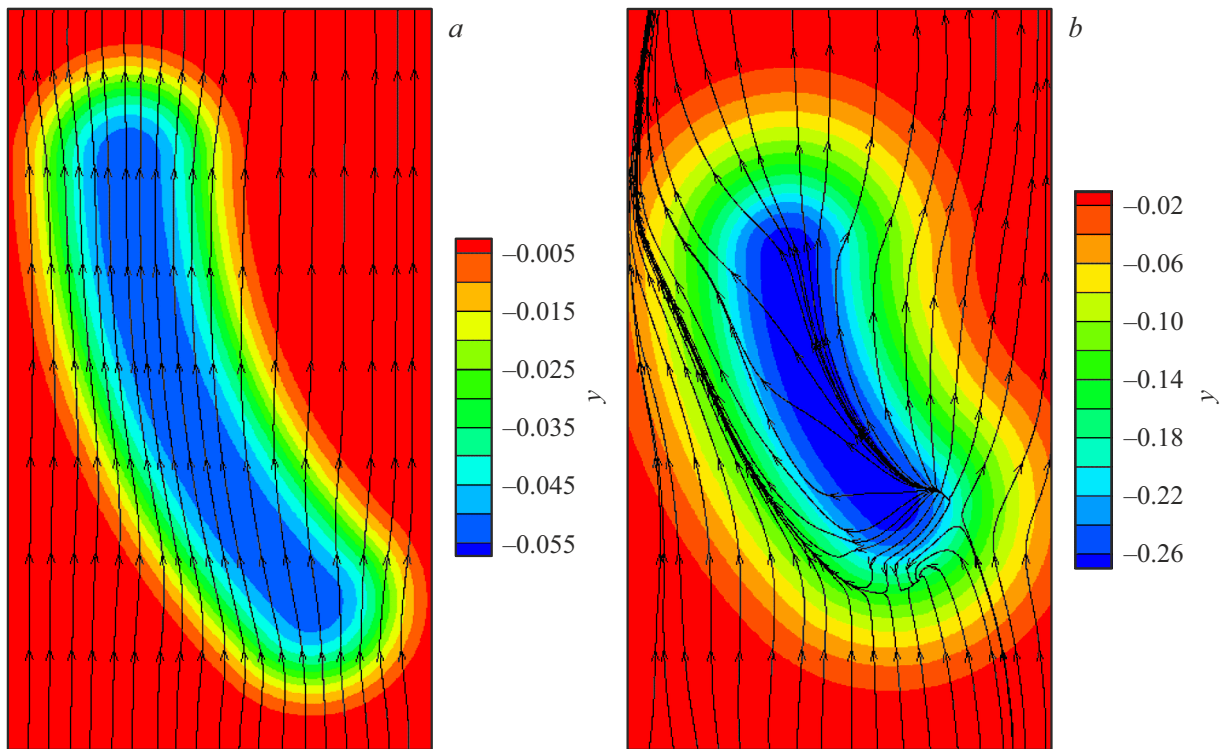


Figure 1. Surface profiles of oval-arched dimples with depth $\Delta = 0.055$ (a) and 0.275 (b) in single-row packets on stabilized hydrodynamic sections of the channel with air spreading lines indicated on walls (trajectories of fluid particles in the near-wall layer at a distance of $5 \cdot 10^{-6}$). A color version of the figure is provided in the online version of the paper.

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. Characteristics with index pl are representative of points of a plane-parallel channel corresponding to projections of the curved structured wall of the channel. At moderate and large dimple depths Δ and a significant edge radius (set to 2), the footprint area of a dimple on the wall of the periodic module increases considerably (Fig. 1). In the case of shallow dimples, the dimple density is close to 65%, which is significantly lower than in [3].

Numerical modeling of convective heat transfer in a channel with turbulent air flow and single-row oval-arched dimples was carried out based on of the Reynolds-averaged Navier–Stokes and energy equations written for an incompressible fluid [6]. 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 [6]. The initial 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 dimple surface) were introduced. The total number of grid cells was on the order of $1.7 \cdot 10^6$. The longitudinal and transverse grid spacing on the structured wall was 0.025. The near-wall spacing was 10^{-5} . The calculation model was validated by applying it to similar test problems of anomalous intensification of separated flow and heat transfer on structured surfaces (see, e.g., [7]).

Figures 1–3 present some of the obtained results, and the extreme values of flow characteristics in the channel with multi-row dimples are listed in the table. With an increase in Δ , turbulent flow in the periodic module of the channel changes from unseparated (Fig. 1, a) to separated (Fig. 1, b); the transition is observed at Δ on the order of 0.14. The key figure in the numerical study is Fig. 2, which shows the dependences of relative hydraulic losses between the inlet (A) and outlet (B) sections and thermal and thermal-hydraulic efficiency of the control regions of surfaces of the lower wall of the module and the curved region of a dimple with a width of 1 and a length of 3.5 on Δ . To analyze the distributions of characteristics at different scales, two ranges of Δ variation were distinguished: from 0 to 0.425 and from 0 to 0.14. First of all, it should be noted that ξ/ξ_{pl} reaches its minimum of approximately 0.96

Influence of the depth of an oval-arched dimple on the extreme parameters of stabilized turbulent flow in a channel with a structured wall

Δ	U_{\max}	U_{\min}	W_{\max}	W_{\min}	$K_{\max} \cdot 10^2$	$\mu_{t \max} \cdot 10^3$
0	1.082	0	0	0	0.5791	3.103
0.025	1.083	0	0.0399	-0.0347	0.614	3.11
0.045	1.089	0	0.0558	-0.06558	0.663	3.188
0.055	1.095	0	0.0599	-0.08115	0.6994	3.249
0.075	1.106	0	0.0692	-0.1133	0.782	3.408
0.085	1.109	0	0.0731	-0.1289	0.822	3.476
0.105	1.116	0	0.0892	-0.1565	0.906	3.545
0.125	1.125	0	0.1012	-0.1873	1.006	3.536
0.135	1.130	0	0.1064	-0.1998	1.065	3.538
0.145	1.135	-0.0015	0.1103	-0.2139	1.129	3.537
0.165	1.145	-0.0122	0.1162	-0.2477	1.162	3.557
0.185	1.153	-0.0290	0.1207	-0.2853	1.455	3.613
0.205	1.160	-0.0512	0.124	-0.3299	1.663	3.680
0.225	1.164	-0.0778	0.1272	-0.3764	1.829	3.752
0.25	1.168	-0.1206	0.1318	-0.4278	1.987	3.843
0.275	1.169	-0.1622	0.1345	-0.4637	2.076	3.996
0.3	1.169	-0.2015	0.1357	-0.4833	2.134	4.223
0.325	1.168	-0.2323	0.1403	-0.4899	2.198	4.466
0.35	1.167	-0.2593	0.1527	-0.5214	2.266	4.711
0.375	1.165	-0.2752	0.1670	-0.5543	2.402	4.949
0.4	1.169	-0.2921	0.1909	-0.5824	2.548	5.279
0.425	1.167	-0.2975	0.2058	-0.6157	2.829	5.515

at $\delta = 0.055$. It is also noteworthy that when the relative hydraulic losses are reduced to a level of 0.98, the thermal efficiency in the structured channel increases approximately to 1.1. The thermal efficiency grows rapidly with Δ , reaching 1.56 at $\Delta = 0.425$. The maximum of thermal-hydraulic

efficiency (THE = 1.33) is found at $\Delta = 0.275$. It should be emphasized that, starting with $\Delta = 0.08$, the increase in thermal efficiency of the region inside the oval-arched dimple outpaces the increase in thermal efficiency of the lower wall of the periodic module.

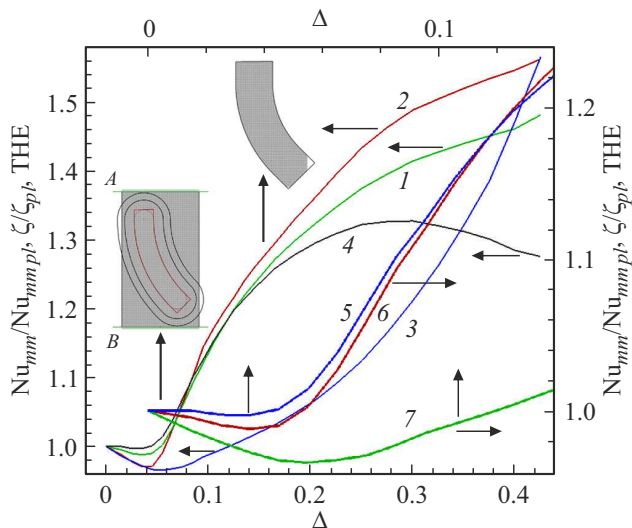


Figure 2. Comparison of thermal efficiency $Nu_{\min}/Nu_{\min,pl}$ of the wall of the periodic channel module with an arched dimple (1, 5) and a curved region enclosing the outline of a dimple (2, 6) with the dependence of relative hydraulic losses ξ/ξ_{pl} between sections A and B of the module (3, 7) and thermal-hydraulic efficiency of the module $THE = Nu_{\min}/Nu_{\min,pl}/(\xi/\xi_{pl})^{-1/3}$ (4) on dimple depth Δ with two ranges of its variation: from 0 to 0.425 (1–4) and from 0 to 0.14 (5–7).

The fields of relative values of surface friction f/f_{pl} and Nusselt number Nu/Nu_{pl} in Fig. 3 illustrate the configurations of dimpled walls that correspond to extreme thermal-hydraulic characteristics. The reduction in hydraulic losses, which are specified by the total pressure difference, in the structured channel is similar to the reduction in flow resistance in [1–3] and is attributable to a reduction in integral relative friction for $\Delta = 0.055$ (Fig. 3, a). The local minimum of $f/f_{pl} = 0.55$ is located in the inlet region of a dimple, while zones of increased relative friction with maximum $f/f_{pl} = 1.35$ remain at the module inlet and the dimple outlet. The increase in hydraulic losses in the dimpled channel with increasing Δ is associated with an increase in (predominant) contribution of pressure resistance to the total resistance.

It is of interest to compare the Nu/Nu_{pl} fields for channel configurations corresponding to minimum hydraulic losses at $\Delta = 0.055$ and the optimum thermal-hydraulic efficiency at $\Delta = 0.275$ (Figs. 3, b, c). The maximum of relative heat transfer Nu/Nu_{pl} increases from 1.4 to 2.2 and shifts from the back slope of a dimple to its end part.

Turbulent air flow in the periodic module with an inclined oval-arched dimple develops as Δ increases (see the table). Unseparated flow is typically seen around shallow dimples (Δ less than 0.14); at the same time, a helical vortex with a swirling flow intensity of approximately 20% of U_0

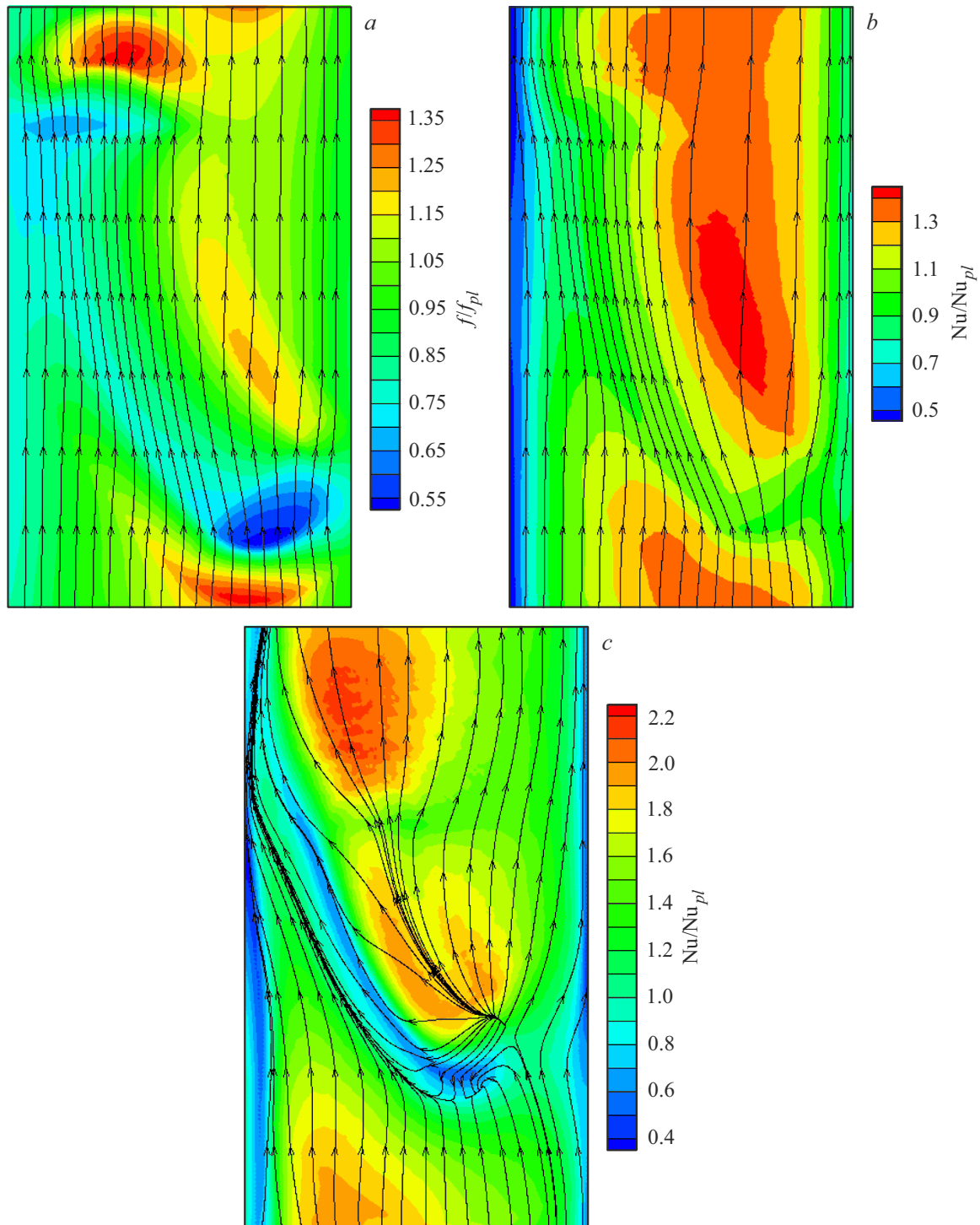


Figure 3. Fields of relative friction values f/f_{pl} (a) and Nusselt number Nu/Nu_{pl} (b, c) with superimposed patterns of air spreading along the walls of the periodic module with arched dimples with a depth of 0.055 (a, b) and 0.275 (c). A color version of the figure is provided in the online version of the paper.

is formed and spreads in the near-wall layer within the boundaries of a dimple. Turbulence energy K_{max} increases by a factor of approximately 1.8, while the maximum turbulent viscosity changes only slightly by a factor of 1.13, and its value within the Δ range of 0.1–0.2 is frozen at the level of 0.0035.

With a transition to deep dimples, separated flow intensifies with an increase in maximum velocities of reverse and swirling flow to 0.3 and 0.6, respectively.

The flow becomes turbulent fairly quickly. K_{max} increases by a factor of 5, and $\mu_{t,max}$ increases by a factor of almost 1.8 at $\Delta = 0.425$.

The acceleration of turbulent flow in the channel core is low (approximately 8%). The results of numerical modeling of turbulent flow and heat transfer in a channel with multi-row inclined oval-arched dimples with varying depth at high Reynolds numbers on the order of $2 \cdot 10^5$ in a stabilized hydrodynamic section confirmed that it is possible to achieve a significant (almost 4%) reduction in relative hydraulic losses in the case of shallow dimples with a depth of 0.055 and an edge radius of 2. It was also established that a 10% increase in thermal efficiency at a dimple depth on the order of 0.09 is achieved with a moderate (approximately 2%) reduction in relative losses. It was found that the thermal-hydraulic efficiency is maximized (33%) at a dimple depth of 0.275.

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.

References

- [1] *Viscous flow drag reduction*, ed. by H.R. Hough. Progress in Astronautics and Aeronautics (American Institute of Aeronautics and Astronautics, 1980), vol. 72.
- [2] S.A. Isaev, A.D. Chornyi, Yu.V. Zhukova, A.A. Vysotskaya, V.B. Kharchenko, *J. Eng. Phys. Thermophys.*, **92** (6), 1509 (2019). DOI: 10.1007/s10891-019-02070-x
- [3] M.A. Nasr, C.M. Tay, B.C. Khoo, *J. Enhanced Heat Transfer*, **29** (4), 81 (2022). DOI: 10.1615/JEnhHeatTransf.2022041456
- [4] A. Mironov, S. Isaev, A. Skrypnik, I. Popov, *Energies*, **13**, 5243 (2020). DOI: 10.3390/en13205243
- [5] S.A. Isaev, A.B. Mazo, D.V. Nikushchenko, I.A. Popov, A.G. Sudakov, *Tech. Phys. Lett.*, **46** (11), 1064 (2020). DOI: 10.1134/S1063785020110073.
- [6] S.A. Isaev, P.A. Baranov, A.E. Usachov, *Multiblock computational technologies in the VP2/3 package on aerothermodynamics* (LAP LAMBERT Academic Publ., 2013).
- [7] S.A. Isaev, A.G. Sudakov, D.V. Nikushchenko, A.E. Usachov, M.A. Zubin, A.A. Sinyavin, A.Yu. Chulyunin, E.B. Dubko, *Fluid Dyn.*, **58** (5), 894 (2023). DOI: 10.1134/S001546282360133X.

Translated by D.Safin