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Validation Test of Parallelized Codes in the Study of Flow and Heat Transfer Anomalous Enhancement in a Single Inclined Groove on a Plate

***Sergey A. Isaev*[1,2], *Alina A. Klyus*[2], *Alexandr G. Sudakov*[2], *Dmitry V. Nikushchenko*[1], *Alexandr E. Usachov*[3], *Vladimir V. Seroshtanov*[4], *Alexei Yu. Chulyunin*[5]**

A validation test is presented based on the study of the phenomenon of separated turbulent air flow and anomalous enhancement of heat transfer in an inclined groove on a heated plate. The groove is made up of two halves of a spherical dimple with a spot diameter of 0.25, and it is connected by a trench insert that is 5 long. The generation of tornadoes in grooves associated with extraordinary static pressure differences contributes to the formation of fields of ultra-high velocities, high gradients of relative friction, and heat transfer coefficients inside the inclined groove. Databases of heat flux measurements in a groove on the isothermal section of the plate when varying the inclination angle from 0° to 90° were obtained on the SPbPU thermophysical setup. Parametric numerical and physical studies of heat transfer on a plate with a single groove were performed at $Re = 3\times10^4$. Using the parallelized package VP2/3 has resulted in a satisfactory agreement between experimental data and numerical predictions made within the RANS-SST framework. Abnormal heat transfer enhancement in grooves occurs at angles of inclination from 30° to 75°, which correlates with conclusions on analysis of pressure distributions in grooves on the plate. The vortex structure in the groove on the plate at an inclination angle of 45° is illustrated. It is shown that the focused pressure difference between the adjacent stagnation zone on the windward slope and the reduced pressure region at the entrance to the groove initiates a tornado-like vortex and the developing intense swirling flow.

Keywords: heat transfer enhancement, tornado-like vortex, inclined groove, plate, turbulence, parallelized VP2/3 package.

Introduction

Validation tests, which are considered as analogues of experimental problems, serve to configure and verify mathematical models of control processes, in particular, turbulent transport [1], as well as assess the accuracy and efficiency of developed program codes [3]. Recently [7], original validation tests have been proposed based on a study of separated flow enhancement in inclined grooves on structured surfaces of a plate and channel wall. The grooves are two halves of a spherical dimple connected by a long trench cylindrical insert [5]. The entrance spherical segments that are oriented towards the free-stream flow create tornado-like structures that developed into high-intensity flows in separation zones inside the groove and create zones of decreased pressure. Ultra-high velocities of reverse-direction and secondary flow in the grooves turn out to be on the order of the characteristic velocity of the free-stream flow and sometimes exceed it. As a consequence, the generated intense vortex flows inside the grooves form zones of parameter gradients that are anomalously high for separated flows. These zones are characterized by multiple superiorities of the absolute values of negative friction and heat transfer coefficient compared

[1]Saint Petersburg State Marine Technical University, Saint Petersburg, Russian Federation
[2]A. Novikov Saint-Petersburg State University of Civil Aviation, Saint Petersburg, Russian Federation
[3]Moscow Research Complex Central Aerohydrodynamic Institute, Moscow, Russian Federation
[4]Peter the Great St.Petersburg Polytechnic University, Saint Petersburg, Russian Federation
[5]Institute of Mechanics, Lomonosov Moscow State University, Moscow, Russian Federation

to the flat walls. A connection has been established between the separated flow and anomalous enhancement of the heat transfer in inclined grooves with extraordinary pressure drops between the regions of deceleration of flow entering the grooves and rarefaction in places where tornado-like vortices are generated [6]. This paper examines tests concerning the anomalous enhancement of heat transfer in the separation zone in the inlet part of an inclined groove on an isothermal heated section in a thermally insulated plate. The experiments were carried out using gradient heatmetry at the thermophysical setup of Peter the Great St. Petersburg Polytechnic University. [14]. Parametric calculations are carried out by multi-block computing technology parallelized code VP2/3 (Velocity-Pressure, 2D/3D) [8] using 24-core Xeon Gold 6562 processor.

The article is organized as follows. Section 1 is devoted to methods of numerical simulation and physical study. The research results and their detailed description are presented in Section 2. Conclusion summarizes the study.

1. Methodology. Calculations and Experimental Justification

In a thermophysical setup, a thermally insulated plate with an inclined groove in a heated isothermal region is placed in the subsonic wind tunnel test section (Fig. 1a). The closed-circuit wind tunnel is equipped with a cooling system for the air-flow connected to a cold water supply system, which makes it possible to maintain the temperature of air almost constant (±0.2 K) during long-term experiments.

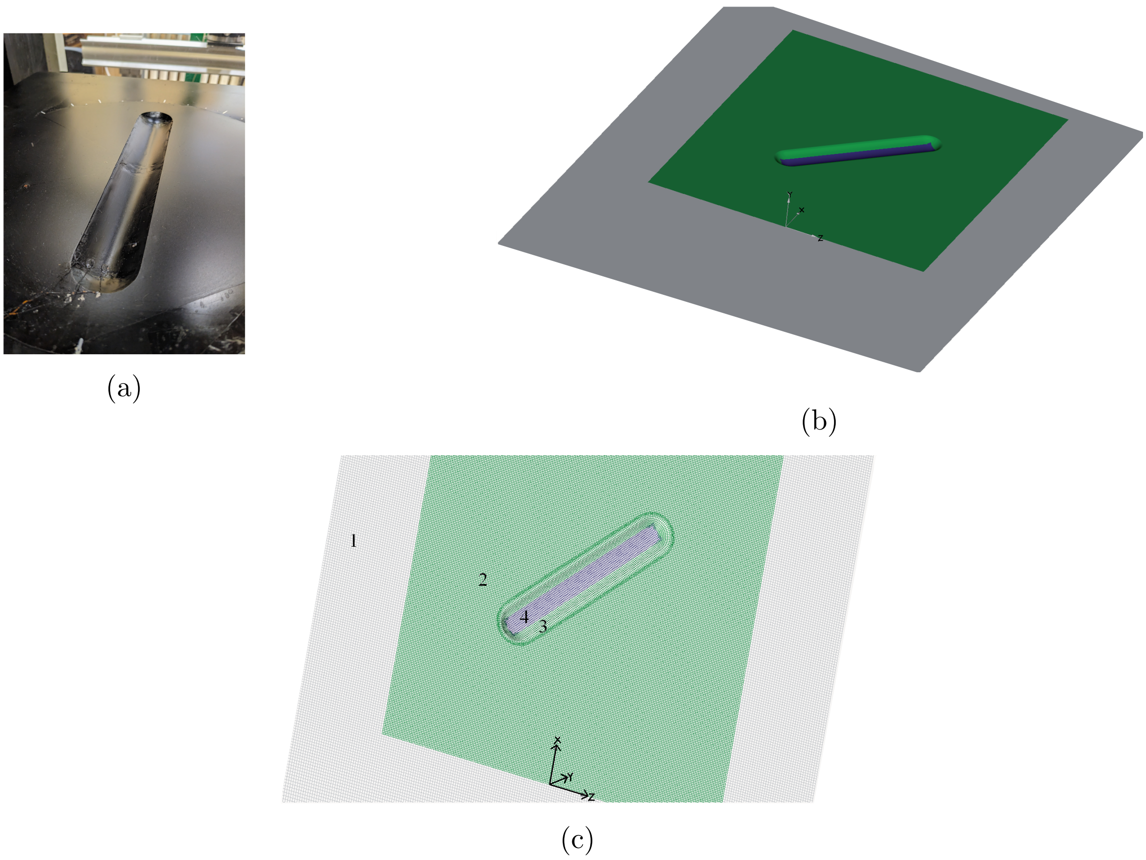


Figure 1. Thermophysical setup with a heated plate and an inclined groove (a), a setup digital twin (b) and a multi-block wall with a Cartesian x, y, z coordinate system (c)

To align the flow, guide vanes are installed in the turns of the tunnel, and a honeycomb is installed in front of the confuser. The experimental models are made in the form of a rotating round plate with a diameter of 0.3 m with a groove under study. The groove consists of two halves of a spherical dimple connected by a trench cylindrical insert. Its width is $D = 0.04$ m, depth is $h = 0.25D$ and the length of the trench insert is $L = 5D$.

The groove is made of a copper sheet 0.002 m thick and soldered into a steel plate 0.001 m thick. From below, a cylindrical box is attached to the plate with groove. The box is equipped with connecting legs for supplying steam and draining condensate. The model is heated using saturated steam supplied from an electric steam generator. The excess pressure in the steam generator does not exceed 200 mm of water and the temperature at the heat transfer surface is kept constant and close to 100 °C. The cylindrical box is installed in a heated rectangular part (with dimensions of 0.475×0.415 m), located on a thermal insulated flat plate with dimensions of 0.71×0.6 m. The temperature of the heated surface T_w was monitored using a testo-875 thermal imager. The heated isothermal section is 0.25 m away from the leading edge of the plate, and the center of the groove is located in its middle longitudinal section at a distance of 0.5075 m from its beginning. This approach enabled the stabilization of the hydrodynamic and thermal boundary layers in front of the groove.

A cylindrical box-shaped structure with a groove can be rotated around an axis passing through the center of the groove, which made it possible to change the inclination angle θ from 0 to 90° to the free-stream velocity vector U. The experiments were carried out for the Reynolds number $Re = UD/\nu = 3 \times 10^4$, where ν is coefficient of kinematic viscosity of air. In studies [6, 7], the Reynolds number is twice as high, but in a separate series of PIV-experiments it was shown that a turbulent flow develops in front of the groove. To determine the relative local heat transfer coefficient in characteristic cross-sections of the groove gradient heat flux sensors (GHFS) were installed [14]. In this study, we used battery-type GHFSs based on ATE made of single-crystal bismuth with a purity of 0.9999. In the experiments, the dimensions of the sensors were $(2.5 \times 2.5 \times 0.2) \times 10^{-3}$ m, and the volt-watt sensitivity was 5 mV/W. GHFSs signals were recorded and archived using an NI 9216 ADC by National Instruments. The GHFSs are installed uniformly in the middle longitudinal cross-section and in the character section of the transition from the input spherical segment to the cylindrical trench. The measurement uncertainty was examined and it was determined that the total standard relative measurement uncertainty of the local heat transfer coefficient is less than 10%.

For the digital twin of the experimental setup, convective heat transfer is considered during stationary turbulent air-flow around a single groove at an inclination angle θ from 0° to 90° on a heated section of the plate (shown in solid color in Fig. 1b). The heated isothermal section is mounted in a thermally insulated plate, at the entrance to which a uniform flow is set. The turbulence number is set close to the experimental one (1%), and the turbulence scale is taken to be of the order of the characteristic dimensionless size D. The relative radius of the edge rounding is 0.025. The Prandtl number Pr is taken to be 0.71.

The computer solution of the stationary Reynolds-averaged Navier–Stokes (RANS) equations for describing turbulent flow around a plate, as well as the energy equation for predicting heat transfer characteristics, is based on the concept of splitting into physical processes [8] using the consistent pressure correction procedure SIMPLEC [15] and multi-block structured grids with their partial overlap. The semi-empirical shear stress transport (SST) model proposed by Menter [10] is utilized to solve the equations of motion. The generalized transport equation is written in increments of dependent variables. In the explicit part of the equation, the discretization of the convective terms of the equations is carried out using a hybrid scheme of variable order of approximation for the equations of momentum and the TVD scheme [9] for the equations of turbulence characteristics. The central finite-difference scheme is used to represent the diffusion terms. The implicit part of the generalized equation uses an upwind scheme with one-sided differences. The hybrid HS scheme combines a second-order approximation upstream scheme with Leonard quadratic interpolation [16] with a blending factor R and a first-order approximation upwind scheme with one-way differences with a weight number (1-R).

By using centered computational grids, where dependent variables are determined at the cell centers, the pressure field needs to be monotonized by introducing the Rhee-Chow correction [11, 12]. The algebraic equations solution is carried out by the preconditioned BiCGSTAB method [13] with an algebraic multigrid accelerator from the Demidov library (amgcl) [2] for pressure correction and ILU0 factorization algorithm for other variables. The original VP2/3 pack (Velocity-Pressure, 2D/3D) was developed on the basis of multi-block computing technologies (MCT) described in [8]. MCT is based on a set of multi-scale, multi-tiered, and intersecting structured grids, consistent with the multi-scale structural elements of a physical problem [4]. In two rows of boundary cells of each of the intersecting or overlapping grids, the parameters are found using linear interpolation [8].

A rectangular section of a flat plate with a length of 19.625 and a width of 15.675 is being used to evaluate the flow and heat transfer. The center of the groove is located at a distance of 12.688 from the inlet section, in which a uniform flow is formed. The computational domain is built on a rectangular section of the plate and has a vertical size of 8.8. The wall flow region is displayed on the external Cartesian grid MG, condensing towards the wall (Fig. 1c; the numbers indicate: 1 – Cartesian grid for describing the flow along the plate; 2 – small-scale Cartesian grid in the near-wall layer of the heated section of the plate; 3 – curvilinear O-type grid, consistent with the groove surface; 4 – curvilinear grid “patch” in the groove central area). Inside the computational region, a rectangular zone adjacent to the wall is distinguished in the vicinity of an inclined groove with a length of 11.875, a width of 10.375 and a height of 0.7. The temperature of the wall of the selected zone is fixed at 373 K, as in the experiment. The remaining surface of the plate is assumed to be thermally insulated. In the selected rectangular area, an oblique MR mesh is constructed. In the vicinity of the groove for the basic version of mesh A, the cells of the MG and MR meshes are specified as square with a pitch of 0.07 and 0.05 in the longitudinal and transverse directions. In the direction of the inlet, outlet and lateral boundaries, the sizes of the MG grid cells increase. Curvilinear elliptical meshes Ring and Rec are introduced to represent the spatially separated flow inside the groove. The central zone is served by Rec as a patch for Ring, which is an O-type mesh. Thus, the calculation of flow and heat transfer in the computational domain is carried out on a multi-block grid of four fragmentary multi-scale grids with partial overlap. The size of the wall-mesh step is 10^{-5}.

To examine mesh independence numerical predictions of the integral characteristics of flow and heat transfer on grids with different number of computational cells are compared. Basic grid A contains 8.8 million cells, grid B – 6.25 million cells, grid C – 4.18 million cells, grid D – 3 million cells.

The center of the Cartesian coordinate system (x, y, z) is located in the middle cross-section of the channel at a distance of 6.25 from the inlet. The lateral and upper boundaries of the computational domain have sliding conditions set. In the outlet section, “soft” boundary conditions are specified – conditions for the continuation of the solution to the boundary, and no-slip conditions are set on the plates wetted surface. In the groove, a coordinated system of s, y, t is put in place that is aligned in the middle longitudinal section, vertical direction, and transverse characteristic section of the transition from the input spherical segment to the cylindrical trench.

Temperature T_{ref} represents the nondimensionalization scale (293 K) for the isothermal upper boundary. At the inlet the temperature T is set constant and equal to T_{ref}, and at the outlet from the computational domain, soft boundary conditions are set for temperature T. The dimensionless temperature at the isothermal section of the wall is taken to be 1.273.

The solving a problem is iterative. At each iteration step, the pressure correction equation is solved and the fields of the Cartesian components of velocity, pressure, and turbulence characteristics are calculated. The computational process ends when the maximum errors of the dependent variables reach the level of 10^{-5} and stabilize the extreme local and integral parameters, including the drag force and the total heat transfer coefficient in the test area with an inclined groove. In this paper, the local flow and heat transfer characteristics of a grooved plate are presented. These include longitudinal and transverse distributions of the static pressure drop $P - P_{pl}$, relative heat transfer coefficient Nu/Nu_{pl} in characteristic cross-sections of a flowing around plate with a groove. The index pl refers to the parameters on the flat (smooth) plate.

Table 1. Justification of mesh independence

N, mln	Nu_{mm}	$10^2 \times C_x$	Nu_{mmd}	$10^2 \times C_{xd}$
8.8	28.32	0.6978	27.64	1.596
6.25	28.35	0.6980	27.71	1.597
4.18	28.34	0.6985	27.74	1.603
3	28.36	0.6961	27.81	1.606

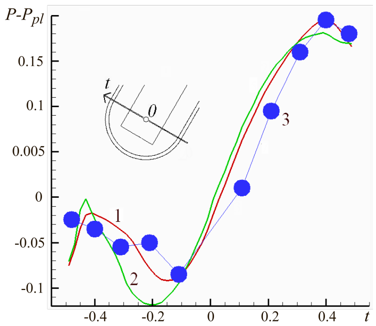
Table 1 compares numerical predictions of heat transfer coefficient Nu_{mm} and drag coefficient C_x for a test area with an inclined groove of size 7×7, and Nu_{mmd} and C_{xd} for an area limiting the groove contour with a size of 6×1, on multi-block meshes of the same topology and different number of the computational cells N at $Re = 10^4$.

The mesh independence of the results obtained when using the convective terms of the Leonard scheme ($R = 1$) for discretization is demonstrated, and the integral indicators change little within the range of varying the number of cells from 3 to 9 million.

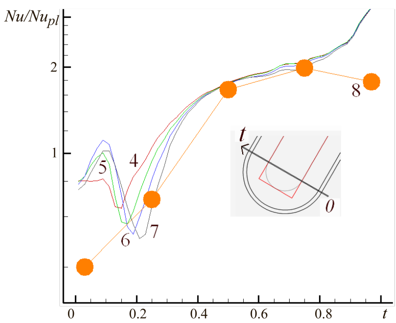
2. Results Analysis

Figures 2, 3 and 4, show comparisons between numerical predictions and experimental data [7] and this study. Parametric calculations of heat transfer on a plate with a single groove are made at $Re = 3 \times 10^4$. The turbulent boundary layer on the plate before the groove was analyzed by PIV.

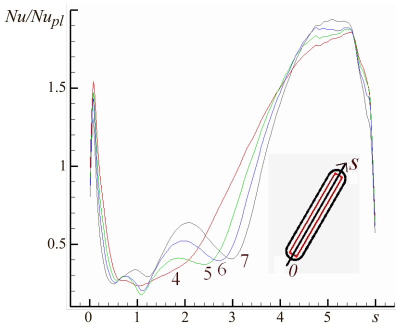
The extraordinary pressure drops measured on the setup of the Institute of Mechanics of Lomonosov Moscow State University [7] in the characteristic cross-section of the inlet part of a groove on the plate with a similar configuration, obtained at $Re = 6.7 \times 10^4$, are in good agreement with the RANS numerical solutions closed using the SST turbulence model (Fig. 2a; numbers indicate: 2 – forecasts based on the Fluent and 1, 4. . . 7 – forecasts obtained using the VP2/3 package; 4 – $R = 0.5$; 5 – $R = 0.7$; 6 – $R = 0.8$; 7 – $R = 0.9$. 1, 3 – [7]; 2, 8 – this study).



(a)

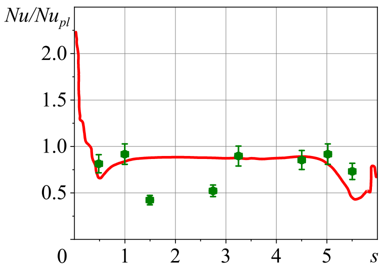


(b)

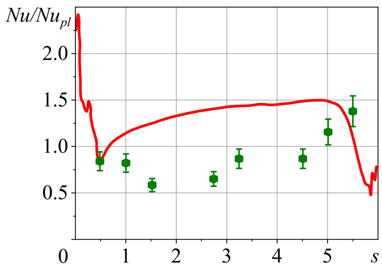


(c)

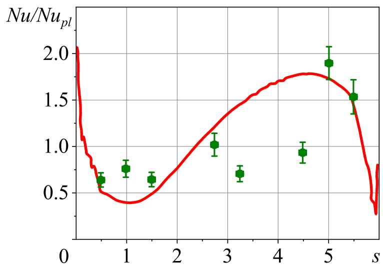
Figure 2. Comparison of calculated (1, 2, 4–7) and experimental (3, 8) distributions of $P - P_{pl}(t)$ (a) and $Nu/Nu_{pl}(t)$ (b) in the transverse inlet section of a groove inclined at an angle of 45° passing through the center of the transition of the spherical segment and the trench, and the distributions of $Nu/Nu_{pl}(s)$ in the longitudinal middle section of the groove (c)



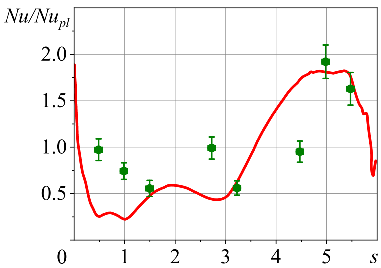
(a) $\theta = 0°$



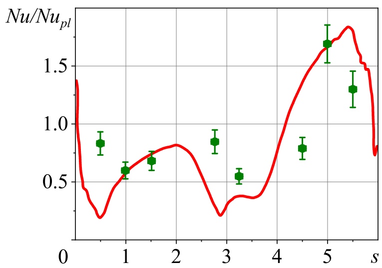
(b) $\theta = 15°$



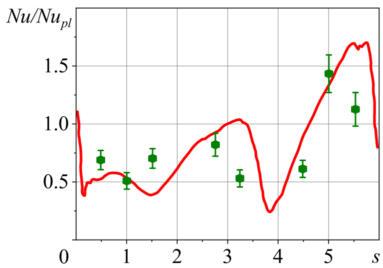
(c) $\theta = 30°$



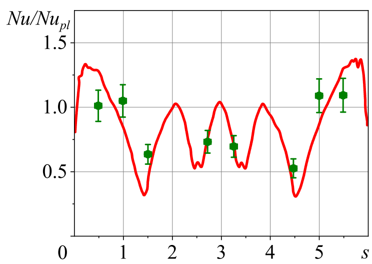
(d) $\theta = 45°$



(e) $\theta = 60°$



(f) $\theta = 75°$



(g) $\theta = 90°$

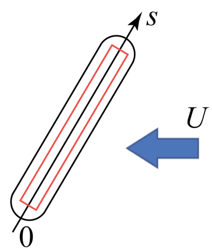
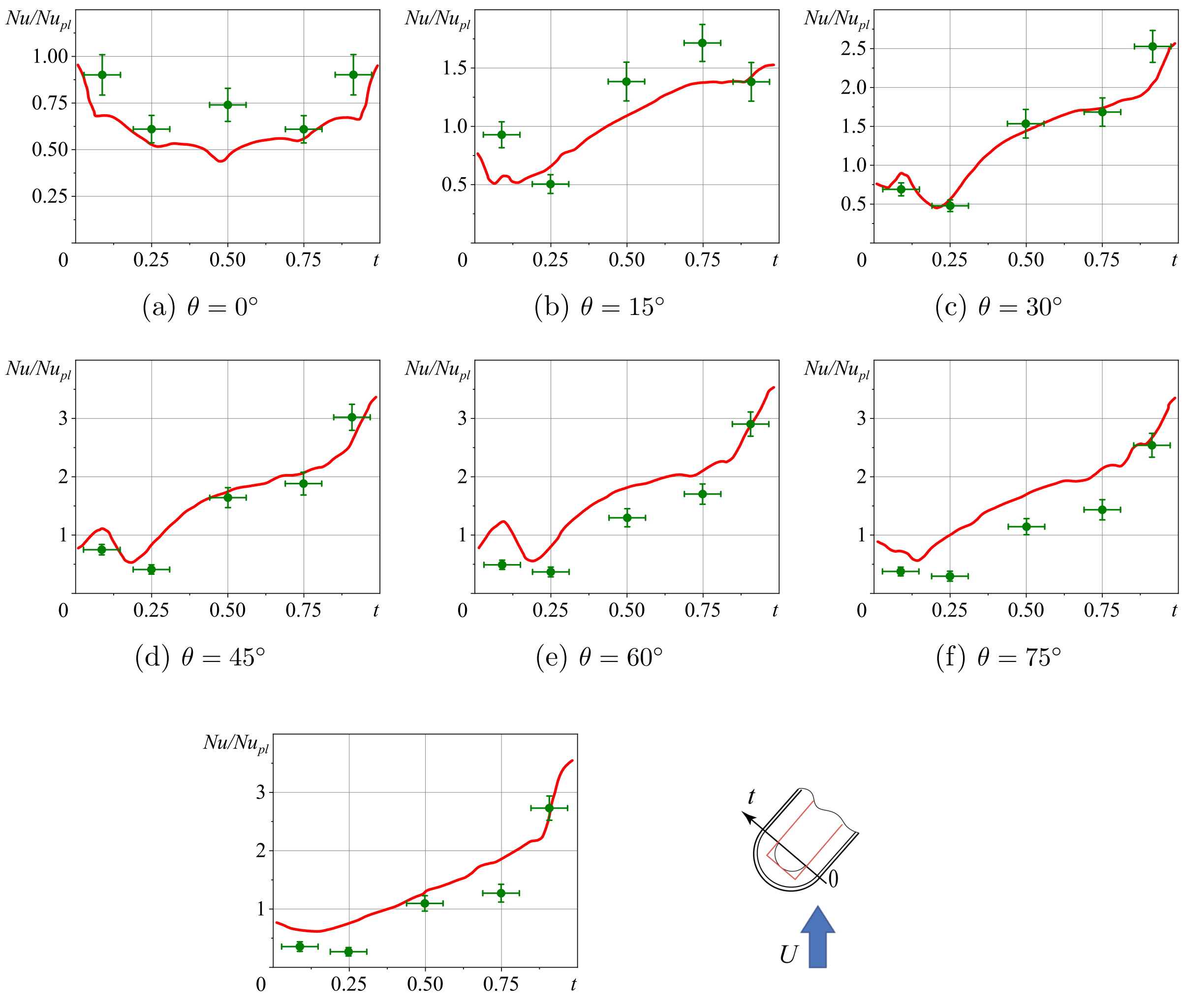


Figure 3. Comparison of calculated curves and experimental Nu/Nu_{pl} points in the middle longitudinal cross-section of a groove on a heated plate with varying inclination angle θ

On the windward slope, in the braking zone of the external flow entering the groove inclined at an angle θ of 45°, a pressure level of about 0.2 is reached, related to the double dynamic pressure (ρU^2). An extraordinary pressure difference between the stagnation zone and the rarefaction region at the bottom of the groove is created by the development of a tornado-like structure generated in the spherical segment of the groove. Without the formation of a tornado and a swirling high-intensity flow, a zone of reduced pressure would not have arisen at the bottom of the groove with a minimum pressure of the order of -0.1. The velocities of return flows and secondary swirling flow in the inlet part of the groove are close to the free-stream flow velocity [6].

The influence of the coefficient R in the hybrid scheme for approximating the convective terms of the momentum equations on the distributions Nu/Nu_{pl} in the characteristic transverse and longitudinal cross-sections of the groove is considered in Fig. 2 b, c, and a comparison is made with GHFS-measurement data.



(a) $\theta = 0°$ (b) $\theta = 15°$ (c) $\theta = 30°$

(d) $\theta = 45°$ (e) $\theta = 60°$ (f) $\theta = 75°$

(g) $\theta = 90°$

Figure 4. Comparison of calculated curves and experimental Nu/Nu_{pl} points in the in grooves cross-section passing through the center of the transition of the inlet spherical segment and the trench insert with varying inclination angle θ

It is obvious that an increase in numerical diffusion with a decrease in R “smooths” out the Nu/Nu_{pl} distributions and has a slight effect on the maximum relative thermal loads. The R coefficient in the parametric study is chosen to be 0.9. A good agreement has been achieved between the calculated Nu/Nu_{pl} distributions and the experimental data, and a twofold increase in the relative heat transfer at the bottom of the groove in the zone of formation of intense return flow has been established.

Figures 3 and 4 present comparisons of the Nu/Nu_{pl} databases obtained during experiments in the longitudinal and transverse characteristic sections of the groove when varying the inclination angle θ from 0° to 90° and numerical predictions based on RANS solutions using parallelized VP2/3 codes.

Overall, there is a satisfactory agreement between numerical simulation and experiment taking into account the turbulence modeling approach. However, the results obtained for $\theta = 15°$ require further study. It should be noted that an anomalous heat transfer enhancement in the grooves occurs at angles θ from 30° to 75°, which correlates with the conclusions from the analysis of pressure distributions in the grooves on the plate [6].

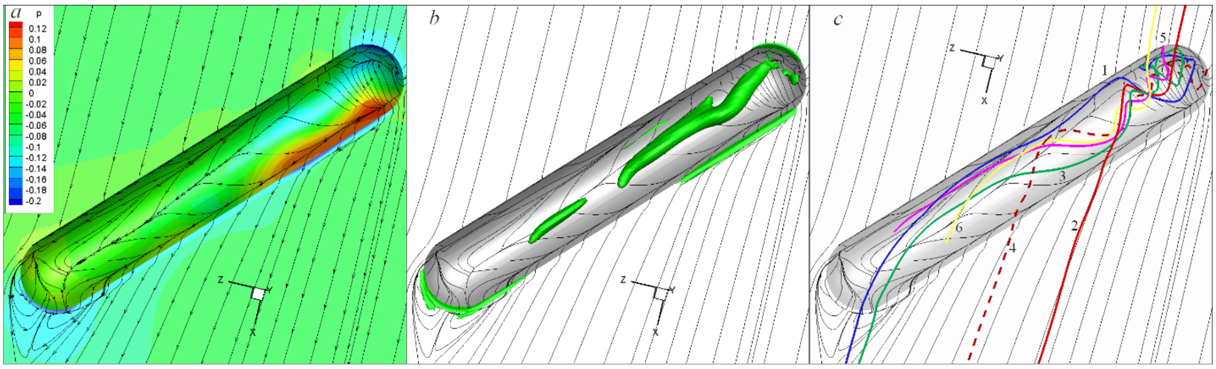


Figure 5. Pressure field (a), isosurface Q2 = -1.12 (b) and trajectories of liquid particles, passing through a point with coordinates $x = 4.4$; $z = -1.5$ (c), with printed patterns air spreading over the surface of the groove on the plate at an inclination angle of 45°. $1 - y = -0.24$; $2 - y = -0.2$; $3 - y = -0.15$; $4 - y = -0.1$; $5 - y = -0.05$; $6 - y = 0$

Figure 5 illustrates the vortex structure in a groove on the plate at an angle $\theta = 45°$. Air spreading over the wall is shown superimposed on the pictures distribution of surface pressure related to twice the velocity pressure, isosurface of criterion Q2 equal to -1.12, and trajectories of liquid particles passing through a fixed point in the center of the joining section of the input spherical segment and a cylindrical trench. Focused pressure difference between adjacent zones braking on a windward slope and an area of reduced pressure at the entrance to the groove is initiated by a tornado-like vortex and a developing intense swirling flow, shown by isosurfaces of Q2. The flow in the groove carries complex nature, demonstrated in Fig. 5.

Conclusion

To test software for parallel computing systems, a validation test is presented, based on a study of the phenomenon of separated turbulent air flow and heat transfer anomalous enhancement in an inclined groove on a heated plate. Its peculiarity is the generation of tornadoes in grooves, associated with extraordinary differences in static pressure, the formation of fields of ultra-high velocities, high gradients of relative friction and heat transfer coefficient inside the inclined groove. Databases of heat flux measurements in a groove on the isothermal section of the plate were created when the inclination angle varied from 0° to 90°, obtained at the SPbPU thermophysical stetup using gradient heatmetry. There is quite a satisfactory agreement between experimental data and numerical predictions made within the framework of RANS-SST using the parallelized package VP2/3.

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