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PROBLEMS OF SIMULATING TORNADO-LIKE HEAT TRANSFER IN TURBULENT FLOW PAST A DIMPLED RELIEF ON A NARROW CHANNEL WALL

S. A. Isaev[a] **and A. I. Leontiev**[b]

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This paper analyzes the state of the art of numerical and partly physical simulation of convective heat transfer in the vicinity of dimpled reliefs on one of the walls of narrow plane-parallel channels. We show that there is a mismatch and spread of the results of these investigations, their conclusions lack substantiation, and there are "white spots" in the problems under consideration and in the methods of their investigation. Several physical experiments have been analyzed, and the correlation between the calculated predictions and measurement data has been discussed. In conclusion, the thermohydraulic characteristics of various dimpled reliefs are compared, and the advantage of oval dimples over spherical ones is demonstrated.

Keywords: *tornado-like enhancement, heat transfer, hydraulic losses, turbulence, dimpled relief in a channel, Menter model.*

Introduction. Dimple technologies as a means for vortex intensification of heat transfer are of keen interest for thermal physicists, and the geography of their investigations is expanding steadily, which is explained by the great advantages of using such technologies compared to other mechanisms of heat transfer enhancement, as well as by their ability to provide a high thermohydraulic efficiency of the process [1]. At the same time, new spheres of using dimples open up, in particular, they are used in microchannels and for solving problems of cooling microelectronic devices [2]. The above facts stimulate the development of numerical and physical simulation of the detached flow and the heat transfer in the vicinity of dimpled reliefs aimed at refining and detailing forecasts of their local and integral characteristics. A characteristic feature of the current complex works on heat transfer enhancement is subjecting models to systematic laboratory tests including those with the use of current diagnostic techniques (PIV, thermocoats). The calculation models are also being improved and complicated, and the progress in this area is associated with a gradual change from solving Reynolds equations (RANS/URANS) to simulating large vortices (LES) [3, 4] and applying intermediate approaches (SAS) [5]. The central point here is the estimation of the role of nonstationary phenomena in the vortex mechanism of heat transfer enhancement, account of the influence on it of disturbances at the inflow boundaries of channels being of paramount importance.

Of enhanced interest is the estimation of hydraulic losses in channels with cavities [6]. However, the available literature estimates of these parameters turn out to be low and require careful check.

As mentioned above [1, 6], the thermohydraulic characteristics of spherical dimples are not the best in the case of turbulent flow conditions of the coolant, and their use under laminar conditions is practically unjustified.

In connection with the foregoing, the present paper considers a circle of problems connected with the numerical and partly physical simulation of tornado-like enhancement of the turbulent heat transfer near dimpled reliefs, the computational estimation of their limiting characteristics with the use of periodic boundary conditions at the flow boundaries of a periodic module with dimples, the verification of this estimation in comparison with physical experiments, and the application of the computational technology for comparing spherical and oval dimples in thermohydraulic parameters.

Simulation of the Vortex Dynamics and Heat Transfer near Dimpled Reliefs (brief analysis). In the analysis of dimple problems presented in a number of monographs of recent years, the opinion of thermophysicists prevails [7–10]. This concerns both the essence of the physical mechanism of heat transfer enhancement, the knowl-

[a]St. Petersburg University of Civil Aviation, 38 Pilotov Str., St. Petersburg, 196210, Russia; [b]N. É. Bauman Moscow State Technical University, 5 3rd Baumanskaya Str., Moscow, 107005, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 83, No. 4, pp. 733–742, July–August, 2010. Original article submitted November 28, 2009.

edge of which is considered by the authors of [8] to be a priority, and the comparison of dimples with other techniques of heat transfer enhancement (tenches, ribs, protrusions) [10]. At the same time, it appears to be obvious that dimples are kinds of cavities, with the difference that their depth (in considering spherical dimples) is limited, as a rule, to half of their characteristic size (spot diameter) and is relatively small. The aerohydrodynamics of detached flows in cavities is a branch of the hydromechanics of detached flows (see, e.g., [11]), and the mechanism of vortex formation in the regions of three-dimensional detachment of the flow have long been attracting the attention of researchers. For instance, in monograph [12] it is noted that in regions of different geometries one-type jet-vortex three-dimensional detached flows can be formed. In our report at the congress of mechanics in 2006, we proposed a concept of the generalized vortex cell [13] emphasizing the characteristic features of the flow in dimples, cavities, gaps between bodies, as well as in the near wake behind them.

Works [14, 15] present numerical and physical analogs of detached flows in circular and square cavities. The considered test problems were solved not only for the purpose of studying the control mechanisms of vortex formation in cavities, but also with the aim of developing and verifying multiblock computational technologies in combination with modifying the shear stress transfer model MSST taking into account the influence of the curvature of the streamlines. It has been established that the dimple acts as a vortex and fluid oscillator of a special type. Therefore, it seems obvious that the spherical dimple most often considered in the literature [16] is not an optimal means for the most effective control of the near-wall flow with low hydraulic losses.

In recent years, the state of vortex intensification of the heat transfer in flowing past dimpled reliefs has been subjected to repeated systematic analysis, especially in the field of numerical calculations [17–22]. In the present work, the above analysis is continued with special emphasis on the mismatch between the results of numerical and physical simulation.

One of the early prominent experimental works on the heat transfer enhancement on dimple ensembles was devoted to the case of flow past a flat plate with staggered spherical deep dimples [23]. The dimples are arranged with a longitudinal and a transverse interval between their centers equal to the diameter of the ball with which they were indented. The depth of each dimple is 1/4 of the characteristic size. At a characteristic size of the dimple of 3/4 in. (1.9 cm) the diagnosed surface of the plate has a length of 12 in. (30.48 cm) and a width of 3 in. (7.62 cm). On this surface, 3 and 4 rows of dimples in the transverse direction and 10 rows in the longitudinal direction alternate. The Reynolds number Re determined by the dimple diameter varies from 10^4 to $3{\cdot}10^4$. The corresponding Reynolds number constructed by the hydraulic diameter and the mass-mean velocity of the flow varies from 10^4 to $5.2{\cdot}10^4$. Note that in conventional notations, when for the characteristic size of the spherical dimple the diameter of its spot is taken, the relative depth of the dimple is 0.289, and the longitudinal and transverse intervals between dimples measure 1.155. An important quantity therewith is the density of dimples on the wall γ, and it is determined as 0.58 (close packing).

In total, the thermal load on the dimpled surface Nu_m is about 2.4–2.5 of the analogous load on a similar plane wall $Nu_{m,pl}$ and is practically independent of the Reynolds number in the investigated range. Such enhancement of the heat transfer is comparable to tape vortex generators. It should be noted that according to numerous experiments [9, 10] such a heat transfer enhancement factor is maximum.

Preliminary calculations of spherical dimpled reliefs [24, 25] corresponding to experimental analogs [23] have also made it possible to reveal, as in experiments, the periodic character of the longitudinal distribution of the relative Nusselt numbers averaged across the plate. In so doing, numerical forecasts change significantly depending on the bandwidth over which Nu/Nu_{pl} are averaged. Sharp peaks correspond to the projections of the windward edges of dimples on the longitudinal mean cross-section, with the peaks after odd rows of dimples (with a large number of them) being appreciably higher than the peaks after even rows. Valleys on the distribution are positioned on the projections of dimples, and the minima therewith turn out to be shifted to their leeward sides.

Comparison of experimental and calculated data [23, 24] points to their qualitative and quantitative mismatch, especially in the regions of valleys. While in the experiment the curves are close to periodic distributions with a slight decrease in the Nu/Nu_{pl} maxima with increasing number of rows, the numerical calculations point to an increase in the heat transfer enhancement with increasing number of dimple rows, i.e., the maxima and minima increase with increasing longitudinal coordinate. In dimple-containing bands, the heat transfer minima in numerical forecasts do not exceed 1, i.e., on the leeward sides of dimples heat removal is strongly impeded because of the weak vortex motion in the detached zone. In the experiment, this effect turns out to be weakened, most likely due to the difficulties of experimental recording of large gradients of Nu/Nu_{pl}. As a result, it may be expected that the integral heat transfer in the physical simulation will be overestimated.

The dimple problems are of scientific and practical interest largely due to the breaking (as the pioneers of these studies supposed) on dimpled reliefs of the Reynolds analogy in favor of the heat transfer enhancement compared to the rate of increase in hydraulic losses. However, the experimental (and computational) studies point to a considerable spread of data on hydraulic losses, also towards their excess over the heat transfer enhancement.

Below we give some conclusions drawn from this very brief analysis.

1. It is expedient to consider dimples as vortex generators, and spherical dimples therewith do not seem to be rational from the point of view of intensification of tornado-like vortex structures.

2. The accumulated databases on the flow parameters and turbulence and heat transfer characteristics near dimpled reliefs require critical revaluation. It is highly desirable to have reliable open databases that can be used for adjusting experiments being performed. It is imperative for experimentalists and calculators to join efforts.

3. Particular consideration should be given to the part of the work that would seem to have been accomplished long ago — analysis of hydraulic losses measured by total pressure drops. The difficulty of their experimental estimation is obvious since it requires measurements of the characteristics of velocity fields in flows with a complex jet-vortex structure.

Calculation of the Limiting Thermohydraulic Characteristics of Narrow Channels with Dimpled Reliefs on the Walls on the Basis of Periodic Boundary Conditions. Obviously, it is expedient to determine the thermal and thermohydraulic efficiency of dimpled reliefs at a large number of dimples. In this case, it may be expected that the initial portions on which the relative Nusselt numbers averaged in the transverse direction (see the previous paragraph) depend on the longitudinal coordinate, do not produce a significant effect on the integral indices of the relief on the whole. Of course, the question on the limiting number of (rows of) dimples remains open. However, the integral estimate of reliefs seems to be necessary in order to compare them with one another.

At the present time, in numerical calculations (see, e.g., [26]) the most popular approach is that connected with simulating a detached flow and heat transfer in a longitudinally oriented channel module whose lateral faces represent longitudinal plane sections of the dimpled relief passing through the centers of adjacent dimples. On these lateral boundaries, the symmetry conditions are set on the assumption that the flow past the relief is symmetric. However, such a formulation of the problem is unjustified because in deep spherical dimples an asymmetric vortex flow arises.

An alternative approach to the problem is associated with the use of periodic boundary conditions at the flow boundaries of the region. A channel with an unlimited number of dimples on one of the isothermal walls is considered. The wall with dimples is heated (373 K), and the opposite one is "cold" (293 K). Thus, a constant temperature difference between the walls is maintained. The method for calculating the turbulent flow and the heat transfer is described in detail in [1]. It is based on original procedures of correcting the pressure gradients and the mass-mean temperature. The method developed for calculating the heat transfer in tube banks was first substantiated in [27] by comparing the results for the periodic calculation modulus with the data for the channel with multiple-row tubes. In [28, 29], the proposed methodology was evaluated for calculating flows in channels and tubes with single-row dimples and cavities. It should be noted that an analogous approach was used to analyze the optimization of the form of the dimpled relief in [30] and to investigate the laminar flow in a channel with a staggered dimpled relief in [31].

In the present work, we continue the investigations on the dimple problems conducted in [28, 29] with the aim of justifying the calculation methodology and searching for rational forms and arrangement of dimples in plane-parallel channels. We chose air as a coolant.

Testing of the Calculation Methodology Using the Corridor Dimpled Relief of the TsKTI (M. A. Gotovskii's experiment) as the Example. At the TsKTI, experimental studies of the convective heat transfer in channels and tubes with dimples on their walls have been carried out for several decades. In one of the investigations [32], a test plane-parallel channel with a multiple-row dimpled relief on one of its sides was considered (Fig. 1). The corridor packet contains four shallow (Δ = 0.2 in fractions of the spot diameter), close to sharp-edged (the edge rounding radius is 0.01) dimples disposed across the channel (Fig. 2a).

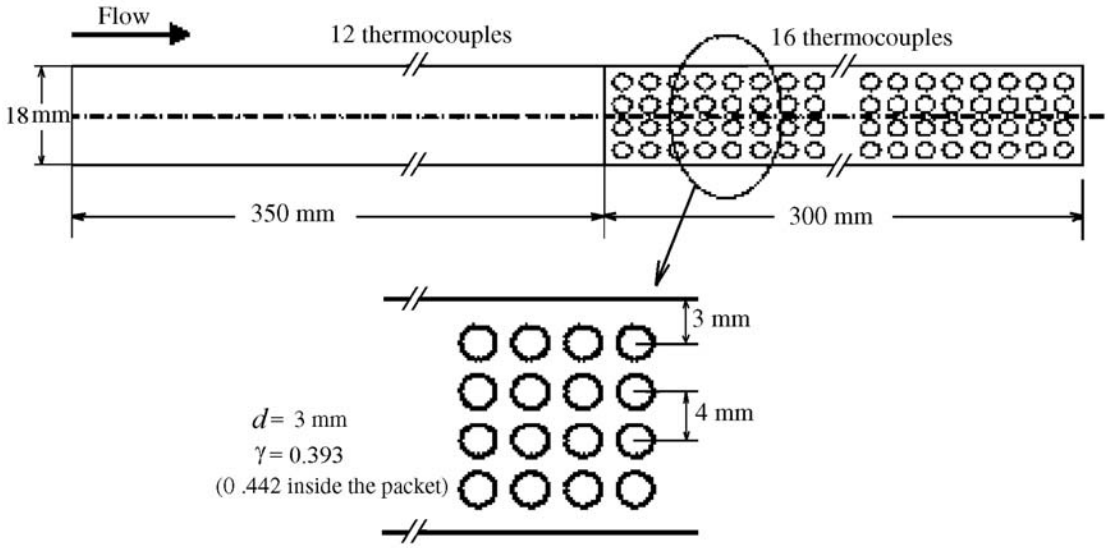

Fig. 1. Scheme of the tested plane-parallel channel with a corridor arrangement of spherical dimples on one of the walls.

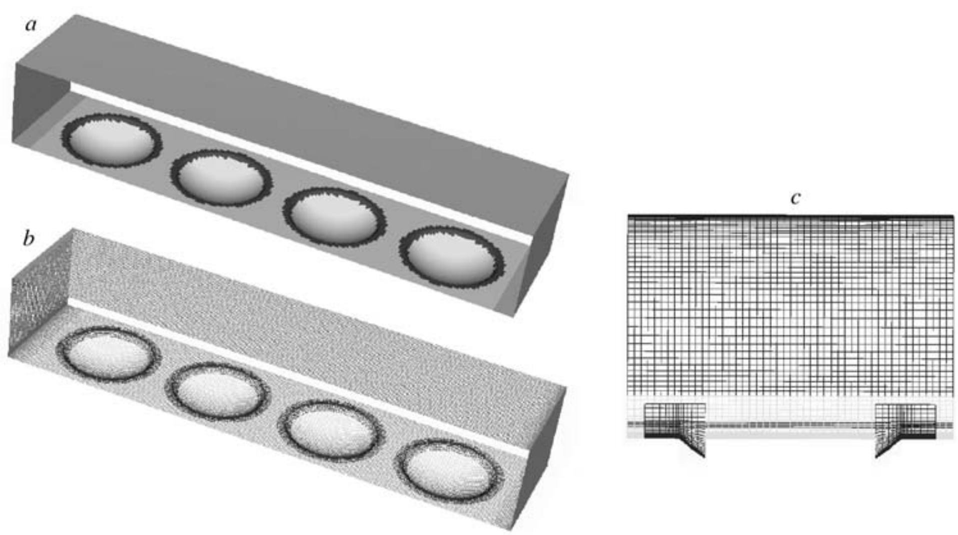

Fig. 2. Repeating calculation module with four dimples (a), multiblock mesh in the channel with dimples with the isolation of edges (b), and cross-section of the channel with an edged cylindrical mesh (c).

The height of the channel $H = 1$ and its width $L = 5.766$. The interval between the centers of the dimples in the longitudinal and transverse directions is 1.333, which corresponds to the dimple density $\gamma = 0.442$. The Reynolds number determined by the characteristic size and mass-mean velocity is $2 \cdot 10^4$.

The multiblock computational mesh (Fig. 2b) contains a fragmentary structured mesh covering the plane-parallel channel and containing $49 \times 69 \times 225$ cells, a near-wall curvilinear mesh with $49 \times 29 \times 181$ cells, and four edge cylindrical meshes containing $104 \times 27 \times 14$ cells. The total number of computational cells is about 1.1 million. The near-wall mesh width is $5 \cdot 10^{-4}$. The mesh widths in the longitudinal and transverse directions are equal to 0.03.

Figures 3, 4 and Table 1 present some of the obtained results. As in the case of the staggered dimpled relief [24, 25], the flow past the corridor packet of dimples turns out to be synchronized, i.e., in all dimples the coolant transfer is realized in the same manner from left to right (Fig. 3), and the spread patterns within the dimples are of the same type. More than one-half of the area of each dimple on the leeward side turns out to be in the zone of lowered thermal loads, i.e., $Nu/Nu_{pl} < 1$, with their maxima coinciding with special points of the focus type. The regions

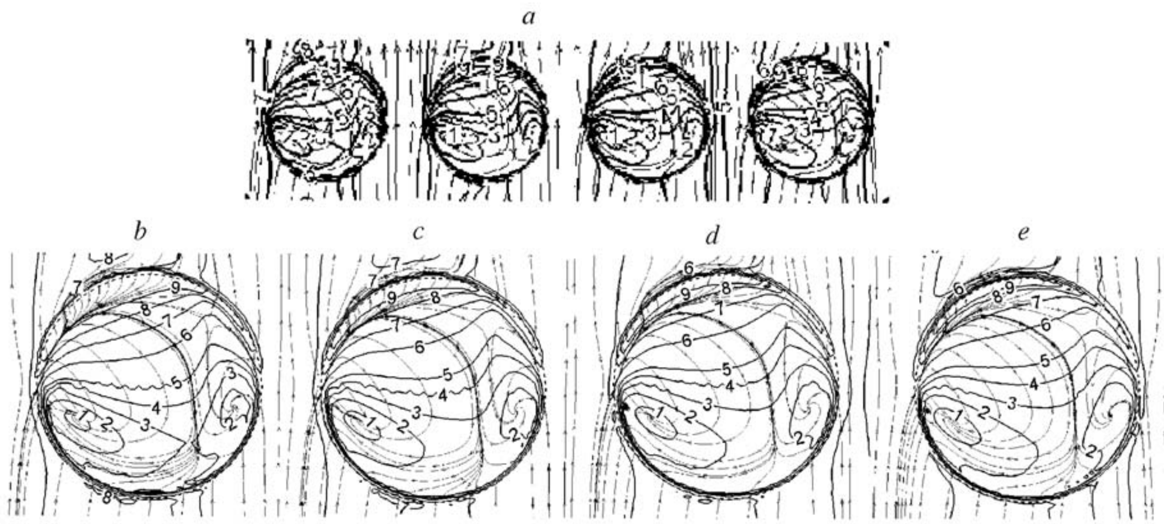

Fig. 3. Fields of relative Nusselt numbers in a dimple packet (a) and separately for each dimple from left to right (b–e) with spread patterns: 1) Nu/Nu_{pl} = 0.2; 2) 0.4; 3) 0.6; 4) 0.8; 5) 1; 6) 1.5; 7) 2; 8) 2.5; 9) 3.

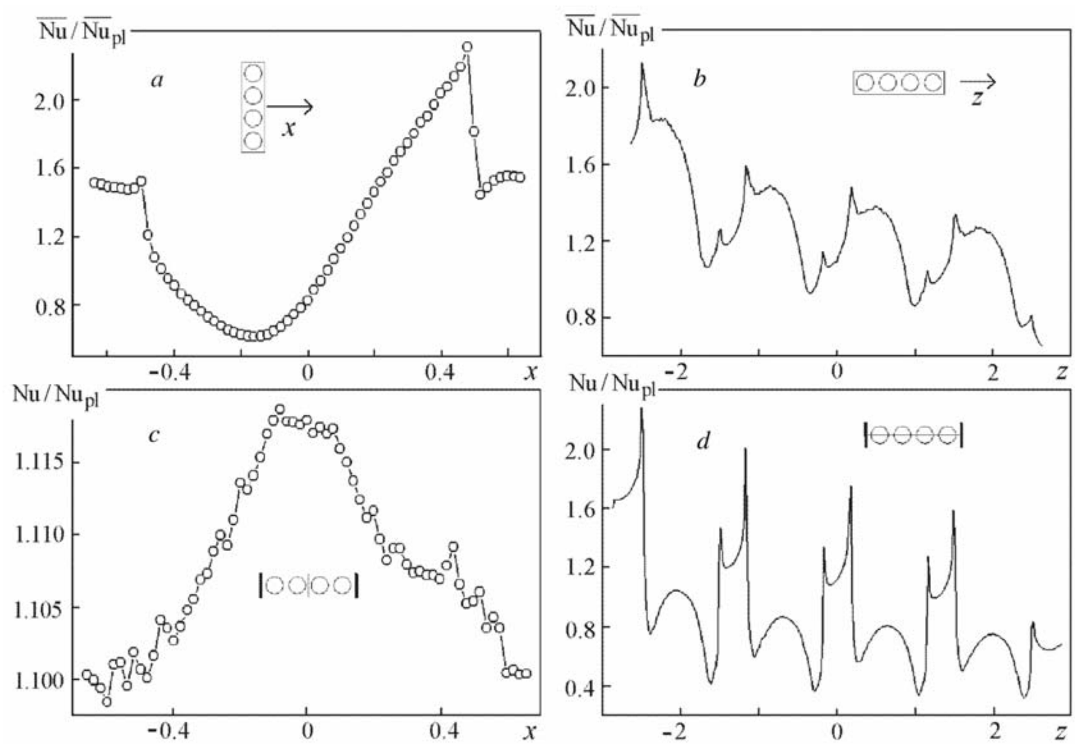

Fig. 4. Longitudinal (a, c) and transverse (b, d) distributions of the band-averaged (a, b) and local-in-average cross-sections (b, c) of moduli of relative Nusselt numbers.

of heat transfer enhancement are on the windward sides of the dimples in the regions of edges down the stream and in the near wake behind the dimples.

As follows from Figs. 3 and 4, the distribution of the relative Nusselt numbers across the channel with dimples is asymmetric, decreasing from left to right analogously to the turning direction of the flow inside the dimples and behind them. The local maxima of Nu/Nu_{pl} (Fig. 4d) in the average cross-section coincide with the lateral edges of the dimples, and the local minima of Nu/Nu_{pl} inside the dimples are located on the lateral slopes, the above min-

TABLE 1. Comparison of the Integral Characteristics of the Channel with Dimples for the Heat Transfer Enhancement in It

Integral characteristics of the channel with dimples	Calculation	Experiment
$Nu_m/Nu_{m,pl}$	1.38	1.40
ζ/ζ_{pl}	1.52	1.10
THE	0.91	1.27

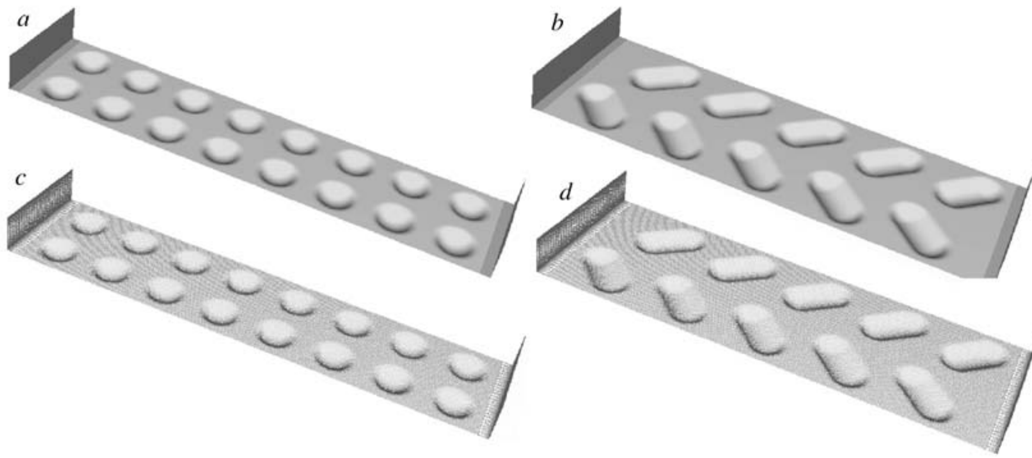

Fig. 5. Plane-parallel channels with spherical (a, c) and oval (b, d) dimples on one of the sides close in dimple density (0.49) and geometry and the multiblock mesh (*c*, *d*).

ima being much lower than 1. The averaging of the relative Nusselt numbers over the area of the band across (a) and along (b) illustrates the thermal efficiency of vortex intensification, especially the second distribution (Fig. 4b). Attention is attracted primarily by the dip of $\overline{Nu}/\overline{Nu}_{pl}$ in the band containing dimples with a minimum of the order of 0.6 (Fig. 4a). The $\overline{Nu}/\overline{Nu}_{pl}$ maximum falls on the projections of the dimple edges and has a value of 2.3. Before and after the dimples, the level of $\overline{Nu}/\overline{Nu}_{pl}$ has a value of the order of 1.5.

If the extreme left dimple is not considered, then for the other dimples the $\overline{Nu}/\overline{Nu}_{pl}$ maxima turn out to lie in the 1.3–1.4 range (Fig. 4b).

The calculated and experimental data on the integral characteristics of the channel with dimples presented in Table 1 show a very good agreement in thermal efficiency and a significant disagreement in hydraulic losses. As a consequence, the experimental and theoretical values of the thermohydraulic efficiency (THE) differ, and, in so doing, in the calculation this characteristic does not reach 1, and in the experimental estimate, on the contrary, it exceeds 1 (and very significantly). Apparently, the question on the hydrodynamical drag of the channel with dimples on the wall requires additional refining investigations; however, this follows also from the brief analysis of the available experimental and calculation information.

Analysis of the Obtained Results on the Limiting Thermohydraulic Characteristics of Channels with Oval and Spherical Dimples on the Walls. In conclusion of the given investigation, we present the analysis of the limiting characteristics of dimpled reliefs of the lower heated wall of a plane-parallel channel of height 0.8 and width of the order of 10. The upper wall is held at a constant temperature of 293 K adopted as a characteristic temperature, and the lower wall is held at a temperature of 373 K. The dimple density is registered to be at the level of 0.489.

We compare dimples of various forms — spherical ones of depth 0.2 (in fractions of the spot diameter) taken as a linear scale and oval ones composed of two halves of a spherical dimple connected by a cylindrical insert of length 0.8 (Fig. 5). The edges of the dimples are rounded off on a radius equal to 0.25. The oval dimples are inclined at an angle of 45° to the incident flow (towards the lateral walls of the channel). The choice of oval dimples was justified in [6].

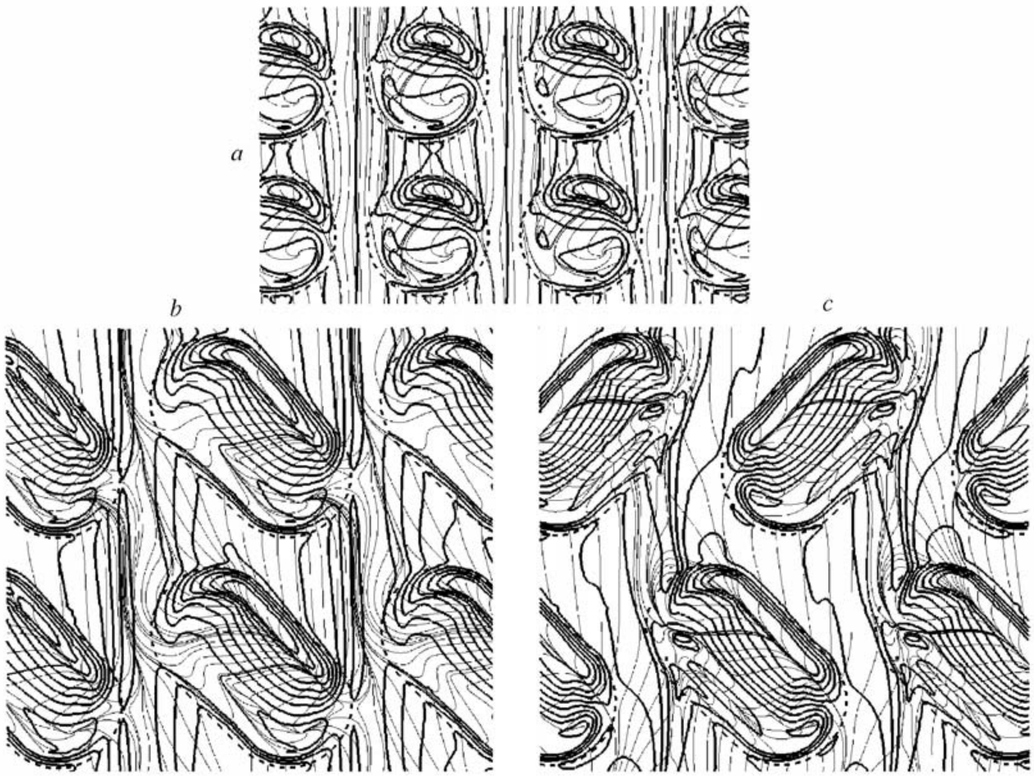

Fig. 6. Comparison of the distributions of the relative thermal loads in the central part of the channel for spherical (a) and oval (b — ladder, c — eccentricity zigzag) dimples in their corridor arrangement. Nu/Nu_{pl} isolines are plotted at a 0.5 step from 0.5 to 4.5.

At a constant density of dimples on the channel wall eight spherical and five oval dimples are positioned edgewise. We consider three packets of oval dimples: a zigzag packet, a ladder packet, and a zigzag packet with eccentricity. The eccentricity was formed by displacing the oval dimples by 0.3 to the left and to the right from the longitudinal cross-sections passing through the centers of the dimples (the first case).

The Reynolds number constructed by the mass-mean velocity and the characteristic size was assumed to be 10^4. The length of the calculation modulus for the spherical dimples is equal to 1.265, and for the oval ones, 1.8.

The multiblock mesh was introduced for calculating the turbulent flow and the heat transfer in the periodic modulus. It consists of a rectangular mesh partitioning into $41 \times 57 \times 195$ cells, the space of the plane-parallel channel and the curvilinear mesh consistent with a surface with dimples of height 0.1. The number of mesh cells is $93 \times 31 \times 241$. The total number of cells is about 1.1 million. The near-wall mesh width is $5 \cdot 10^{-4}$. The longitudinal and transverse widths of the crude channel mesh are 0.1 and 0.06, respectively, and for the fine near-wall mesh the above widths are equal and measure 0.4.

Figures 6 and 7 and Table 2 present some of the obtained results.

The patterns of the coolant spread over the curvilinear wall of the channel with dimples show that the flow in the vortex layer is ordered and the large-scale jet-vortex structures are synchronized. In the majority of spherical dimples, transfer occurs from right to left except for the first lateral row. In zigzag oval dimples the traververse flow corresponds to the orientation of the dimple, i.e., it changes direction periodically. The eccentricity does not affect the topological spread pattern. And in the case of ladder-arranged oval dimples, the motion in the wall layer resembles a nozzle set with parallel nozzles or a blade cascade in a turbomachine where all generated wall jets have the same sense of orientation consistent with the inclination of the dimples. It should be emphasized that the fields of relative Nusselt numbers are strongly dependent on the form of dimples and their orientation with respect to the flow in the channel flow core. Noteworthy (Table 2) is that the zigzag dimpled relief has the lowest thermal efficiency, comparing unfavorably with an ensemble of spehrical dimples. The other reliefs are more promising in terms of thermal efficiency.

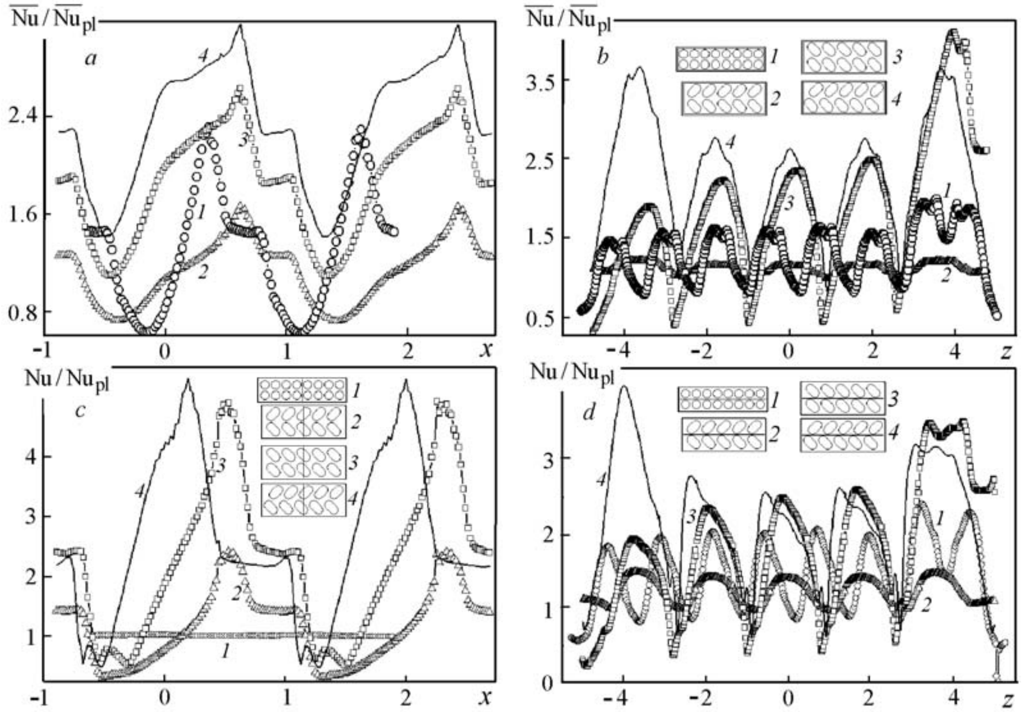

Fig. 7. Longitudinal (a, c) and transverse (b, d) distributions of the band-averaged (a, b) and local-in-average cross-sections (c, d) of moduli of Nusselt numbers. The numbers of bands and cross-sections correspond to the distribution numbers.

TABLE 2. Comparison the Thermohydraulic Integral Characteristics of the Channels with Spherical and Oval Dimples

Integral characteristics of the channel with dimples	Forms of dimples			
	spherical	oval		
	corridor arrangement	zigzag	ladder	eccentricity
$Nu_m/Nu_{m,pl}$	1.38	1.20	1.96	2.47
ζ/ζ_{pl}	1.42	1.24	2.00	2.22
THE	0.97	0.97	0.98	1.11

The detailed analysis of the patterns of relative Nusselt numbers for various dimpled reliefs (Fig. 6) performed on one scale shows that in the dimples and in the space between them zones of lower thermal loads $Nu/Nu_{pl} < 1$) are formed, with minima reaching values (Fig. 7) of the order of 0.2. As mentioned in the previous paragraph, zones of minimal relative loads arise mainly in the vicinity of special points in the pattern of liquid spread over the leeward sides of the dimples. The maximum relative thermal flows concentrate on the windward sides of the dimples and in the region of near wakes, with the maximal Nu/Nu_{pl} reaching values of the order of 5, and their level in the wake behind oval dimples turns out to be in the 2.2–2.5 range. It is interesting to note the rather low level of relative thermal loads in the zones between dimples with their corridor arrangement (Fig. 6a, b). For instance, for spherical dimples Nu/Nu_{pl} in these zones turns out to be of the order of 1. And only in the presence of an eccentricity analogous, to a certain extent, to the staggered dimpled relief in the region between dimples does the enhancement of the heat transfer prevail over its attenuation, i.e., the arms of low Nu/Nu_{pl} become noticeably narrower (Fig. 6c).

The distributions over the longitudinal and transverse coordinates of the relative Nusselt numbers averaged over the transverse and longitudinal bands, as well as of the local Nusselt numbers in the average cross-sections (Fig. 7), demonstrate a combination of peak thermal loads with thermal unloading zones that appear on the plot in the form of dips. The number of peaks and dips corresponds to the number of dimples. Peaks correspond to the windward edges of dimples, and dips correspond to their leeward portions. The central dimples on the channel wall reflect the attained level of thermal efficiency, since the extreme dimples differ from them rather widely. Across the channel with dimples the local relative Nusselt numbers do not exceed 2 for spherical dimples and 2.5 for oval ones, whereas the relative Nusselt numbers averaged over the longitudinal bands differ much more significantly, 1.5 for spherical dimples and 2.5 for oval ones.

As follows from Table 2, the thermal efficiency of spherical dimples is 1.38, as in M. A. Gotovskii's experiments with sharp-edge dimples. However, because of the high smoothness of edges, the hydraulic losses turn out to be much lower (1.42 as against 1.52 for the sharp-edge dimples). Oval dimples arranged as a ladder and zigzag dimples with an eccentricity display a much higher thermal efficiency at a fairly moderate density of dimples: 1.96 and 2.47, respectively. In these cases, however, the hydraulic losses also increase: 2 and 2.22. Thus, oval dimples having obvious advantages in thermal efficiency are also characterized by higher hydraulic losses. An estimate of the thermohydraulic efficiency of dimpled reliefs shows that it is almost equal to 1 for the majority of the analyzed reliefs and even exceeds 1 (1.11) for eccentricity zigzag oval dimples, which are preferable according to the results of the given investigation.

CONCLUSIONS

1. It is expedient to consider dimples as vortex generators, and spherical dimples thereby do not seem to be rational from the point of view of intensification of tornado-like vortex structures.

2. The accumulated databases on the flow parameters and characteristics of the turbulence and heat transfer near dimpled reliefs require critical revaluation. It is highly desirable to develop reliable open databases that can be used for adjusting experiments being performed. It is imperative to combine the efforts of experimentalists and calculators working on these lines.

3. Primary consideration should be given to the part of investigations that would seem to have been accomplished long ago — analysis of hydraulic losses measured by total pressure drops. The difficulty of their experimental estimation is obvious, since it requires measurements of the velocity field characteristics in flows with a complex jet-vortex structure.

4. We have verified the computing method based on the use of periodic boundary conditions for estimating the characteristics of dimpled reliefs with a corridor packet of four spherical dimples arranged across a plane-parallel channel used as the example in comparing M. A. Gotovskii's experimental data with the obtained numerical forecasts. The quite satisfactory agreement in thermal efficiency goes with the disagreement in hydraulic losses.

5. The comparison of several dimpled reliefs in thermohydraulic efficiency made in the concluding part of the investigation confirms the advantage of oval dimples over spherical ones, as well as substantiates their eccentricity zigzag arrangement.

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NOTATION

d, diameter of the spherical dimple spot, m; H, narrow channel height, in fractions of d; L, channel width, in fractions of d; THE = $(\mathrm{Nu}_m/\mathrm{Nu}_{m,pl})/(\zeta/\zeta_{pl})$, thermohydraulic efficiency of a part of the channel with a dimple; Nu, Nusselt number, Re = $\rho Ud/\mu$, Reynolds number; U, mass-mean velocity, m/s; x, z, longitudinal and transverse coordinates, in fractions of d; γ, density of dimples; Δ, spherical dimple depth, in fractions of d; ζ, hydraulic loss factor; μ, dynamic viscosity coefficient, kg/m^3. Subscripts: bar, values averaged over the chosen band; m, value averaged over the area of the chosen part with a dimple; pl, plane wall.

REFERENCES

1. Yu. A. Bystrov, S. A. Isaev, N. A. Kudryavtsev, and A. I. Leontiev, *Numerical Simulation of Vortex Intensification of Heat Transfer in Tube Banks* [in Russian], Sudostroenie, St. Petersburg (2005).
2. X. J. Wei, Y. K. Joshi, and P. M. Ligrani, Numerical simulation of laminar flow and heat transfer inside a microchannel with one dimpled surface, *J. Electron. Packag.*, **127**, 63–70 (2007).

3. M. A. Elyyan and D. K. Tafti, LES investigation of flow and heat transfer in a channel with dimples and protrusions, *Proc. GT2007. ASME Turbo Expo 2007: Power for Land, Sea, and Air*, 2007. No. GT2007-27811.
4. J. Turnow, N. Kornev, S. Isaev, and E. Hassel, Vortex-jet mechanism of heat transfer enhancement in a channel with spherical and oval dimples, *Proc. Int. Conf. on Jets, Wakes and Separated Flows*, Berlin (2008).
5. F. R. Menter and Y. Egorov, A scale-adaptive simulation model using two-equation models, *AIAA Paper* No. 2005–1095 (2005).
6. S. A. Isaev, A. I. Leont'ev, and P. A. Baranov, Simulation of tornado-like enhancement of heat transfer for low-velocity motion of air in a rectangular channel with cavities. Part 2: Results of parametric studies, *Therm. Eng.*, **54**, No. 8, 655–663 (2007).
7. A. V. Shchukin, A. P. Kozlov, R. S. Agachev, and Ya. P. Chudnovskii, *Heat Transfer Intensification by Spherical Cavities under the Action of Disturbing Factors* [in Russian], MGTU, Kazan' (2003).
8. G. I. Kiknadze, I. A. Gachechiladze, and V. V. Alekseev, *Self-Organization of Tornado Jets in Flows of Viscous Continuous Media and Heat and Mass Transfer Intensification Accompanying This Phenomenon* [in Russian], MÉI, Moscow (2005).
9. A. A. Khalatov, *Heat Transfer and Hydrodynamics Near Surface Recesses* (*Dimples*) [in Russian], ITTF NANU, Kiev (2005).
10. A. A. Khalatov, I. I. Borisov, and S. V. Shevtsov, *Heat Transfer and Hydrodynamics in the Fields of Centrifugal Mass Forces* [in Russian], Vol. 5. ITTF NANU, Kiev (2005).
11. P. K. Chang, *Control of Flow Separation* [Russian translation], Vols. 1–3, Mir, Moscow (1972).
12. A. V. Ermishin and S. A. Isaev (Eds.), *Control of the Flow around Bodies with Vortex Cells as Applied to Flying Vehicles of Integral Arrangement* (*Numerical and Physical Modeling*) [in Russian], MGU, Moscow (2003).
13. S. A. Isaev and A. I. Leontiev, Concept of the generalized vortex cell and its use in the aerodynamics of thick profiles and dimple technologies, in: *Abstracts of papers submitted to the 9th All-Russia Congress on Theoretical and Applied Mechanics*, Vol. 2, NNSU, Nizhnii Novgorog (2006), pp. 96–97.
14. P. A. Baranov, S. V. Guvernyuk, M. A. Zubin, and S. A. Isaev, Numerical and physical simulation of a circulatory flow in a vortex cell on the wall of a plane-parallel channel, *Izv. Ross. Akad. Nauk*, *Mekh. Zhidk. Gaza*, No. 5, 44–56 (2000).
15. V. B. Kharchenko, *Numerical Simulation of Detached Flows with Vortex and Jet Generators on the Basis of Multiblock Computational Technologies*, Author's Abstract of Doctoral Dissertation (in Engineering), St. Petersburg (2006).
16. I. A. Popov, *Thermohydraulic Efficiency of the Promising Methods of Heat Transfer Intensification in the Channels of Heat Exchangers in Forced and Free-Convective Motion of Coolants*, Author's Abstract of Doctoral Dissertation (in Engineering), Kazan' (2008).
17. S. A. Isaev, A. I. Leontiev, and I. A. Pyshnyi, Vortex intensification of heat transfer in flow past grooved and dimpled reliefs (numerical simulation), in: *Proc. 27th Siberian Thermophysical Seminar dedicated to the 90th Anniversary of Academician S. S. Kutateladze*, ITF SO RAN, Novosibirsk (2004).
18. S. A. Isaev, Numerical simulation of vortical heat transfer in sub- and supersonic flow past dimpled reliefs with the aid of multiblock computational technologies, in: *Problems of Gas Dynamics and Heat and Mass Transfer in Power Plants*, *Proc. 15th School-Seminar of Young Scientists and Specialists Guided by Academician A. I. Leontiev*, MÉI, Moscow (2005), Vol. 1, pp. 7–12.
19. S. A. Isaev and A. I. Leontiev, Modeling of tornado-like intensification of heat transfer: state-of-the-art and prospects, in: *Heat Transfer and Hydrodynamics in Twisted Flows*, *Proc. 2nd Russian Conf.*, MÉI, Moscow (2005), pp. 27–28.
20. S. A. Isaev, Modeling of tornado-like intensification of heat transfer near dimpled reliefs (state-of-the-art and prospects), in: *Proc. 4th Russian National Conf. on Heat Transfer*, Vol. 6, *Dispersed Flows and Porous Media. Heat Transfer Enhancement*, Izd. Dom MÉI, Moscow (2006), pp. 230–233.
21. S. A. Isaev, A. I. Leontiev, V. L. Zhdanov, N. V. Kornev, and E. Hassel, Whirlwind-like enhancement of heat transfer on dimpled reliefs, *Heat Transfer Res.*, 39, No. 1, 79–90 (2008).

22. S. A. Isaev, A. I. Leontiev, and N. V. Kornev, Numerical simulation of tornado heat transfer in flowing past dimpled surfaces (state-of-the-art and prospects), in: *Proc. 6th Minsk Int. Forum "Heat and Mass Transfer–MIF-2008"* [in Russian], May 19–23, 2008, Minsk (2008), Vol. 1, pp. 99–100.
23. M. K. Chyu, Y. Yu, H. Ding, J. P. Downs, and F. O. Soechting, Concavity enhanced heat transfer in an internal cooling passage, *ASME Paper*, 97-GT-437 (1997).
24. A. Isaev, A. I. Leontiev, P. A. Baranov, I. A. Pyshnyi, and A. E. Usachov, Numerical analysis of the vortex intensification of heat transfer in a channel with a set of deep spherical dimples on one of the walls, *Dokl. Ross. Akad. Nauk*, 386, No. 5, 621–623 (2002).
25. S. A. Isaev, A. I. Leontiev, and V. L. Zhdanov, Simulation of tornado-like heat transfer at the flow passing a relief with dimples, *Heat Transfer*, 2002, *Proc. Twelfth Int. Heat Transfer Conf.*, Grenoble, 2002, Vol. 2, pp. 735–738.
26. Ph. Grenard, V. Quintilla-Larroya, and E. Laroche, Numerical study of heat transfer on a dimpled surface with CEDRE code, *Proc. 2nd European Conf. Aerospace Science* (2007).
27. S. A. Isaev, P. A. Baranov, T. V. Baranova, and N. A. Kudryavtsev, Numerical simulation of vortical heat transfer in tube banks, *Heat Transfer Research*, Issue 7, 593–605 (2006).
28. P. A. Baranov, S. A. Isaev, O. G. Klyueva, and L. E. Sternin, Numerical simulation of the heat transfer enhancement in the channels of power units with one longitudinal row of spherical and groove dimples on the walls, in: *Proc. 4th Russian Nat. Conf. on Heat Transfer*, Vol. 4, *Disperse Flows and Porous Media. Heat Transfer Intensification*, Izd. Dom MÉI, Moscow (2006), pp. 162–165.
29. S. A. Isaev, Modeling of cyclic and periodic vortex flows and temperature fields with the aid of multiblock computational technologies, in: *Proc. 16th School-Seminar of Young Scientists and Specialists guided by Academician A. I. Leontiev "Problems of Gas Dynamics and Heat and Mass Transfer in Power Plants,"* Izd. Dom MÉI, Moscow (2007), Vol. 1, pp. 57–61.
30. K.-Y. Kim and J.-Y. Choi, Shape optimization of a dimpled channel to enhance turbulent heat transfer, *Numer. Heat Transfer*, **48**, Part A, 901–915 (2005).
31. W. V. Patrick, Computation of flow structures and heat transfer in a dimpled channel at low and moderate Reynolds number: *Master's Thesis in Mechanical Engineering* (2005).
32. R. Banker, M. Ya. Belen'kii, M. A. Gotovskii, S. A. Isaev, and B. S. Fokin, Experimental and computational investigation of the hydrodynamics and heat transfer in a plane, variable-width channel for the cases of a smooth and intensified surface, in: *Proc. 3rd Nat. Conf. on Heat Transfer,* Vol. 6, *Heat Transfer Enhancement. Radiative and Complex Heat Transfer*, MÉI, Moscow (2002), pp. 37–40.