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ENHANCEMENT OF VORTEX HEAT TRANSFER IN A BUNDLE OF TRANSVERSE TUBES WITH ORDERED TRENCHES

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Enhancement of vortex heat transfer in laminar and turbulent transverse flows past a remote circular cylinder in a bundle, with trenches periodically arranged on the cylinder surface, is analyzed numerically on the basis of multiblock computational technologies.

Introduction. Numerical simulation of convective heat transfer in ordered bundles of circular tubes is usually conducted on an individual circular cylinder in the distinguished remote module on the flow-through boundaries of which the periodic boundary conditions reflecting the effect of the neighboring cylinders in the bundle are specified [1, 2]. This approach is based on the assumption of the repetitiveness of the velocity fields near the remote cylinders and, in general, near the ordered elements, including periodic protrusions on the channel walls [3]. In many respects, its wide use during the last four decades is related to the economy of computation resources in choosing compact computational domains, especially in solution of Navier–Stokes equations written in the transformed variables vorticity–stream function. In contrast to most papers, where curvilinear nets adapted to the cylinder surface and the rectangular boundaries of the distinguished module are used (see, e.g., [4]), in [1, 2], the traditional cylindrical nets with partial overlapping are introduced. This approach based on orthogonal nets turns out to be free of the errors due to skewness of net lines, which substantially improves the accuracy of calculation of detached flows. It should be noted that the superimposed nets of simple topology served as the basis for development of multiblock computational technologies (MCT) [5, 6].

The concept of MCT arose, first of all, from the consideration of flows near multiply connected objects as applied to the problem of monitoring of flow past bodies by using vortex cells imbedded in the loop [6]. It should be noted that this concept has much in common with the algorithms based on intersecting multiblock nets, which were suggested at the beginning of the 1980s but did not then (or even now) gain wide acceptance in the practice of computation [7]. In the zones of intersection of nets, the flow parameters and turbulence characteristics are determined by interpolation, most often linear. A characteristic feature of MCT is the purposeful use of different-scale nets intended for catching structural special features of flow, viz., boundary and shear layers, separation zones, vortex sheets, etc. In many respects, thanks to MCT, jet-vortex structures of spatial detached flows have been identified, and characteristic features of the governing physical mechanism of the tornado-like enhancement of heat transfer in flow past a spherical lune on a plane wall (including a narrow channel) have been revealed to a certain extent [8, 9].

MCT developed during the last decade have been realized within the package VP2/3 (velocity–pressure, two- and three-dimensional versions) and possess all the main features of the well-known software, such as FLUENT, CFX, StarCD: a modular structure that combines the generator of nets, solver, and interpreter of results and an interactive friendly interface. It is obvious that a great role in improvement of the intellectual level of developments is played by the object-oriented programming systems (the Delphi system in the present case), which strongly distinguishes them from the FORTRAN-based working programs of the 1970–80s.

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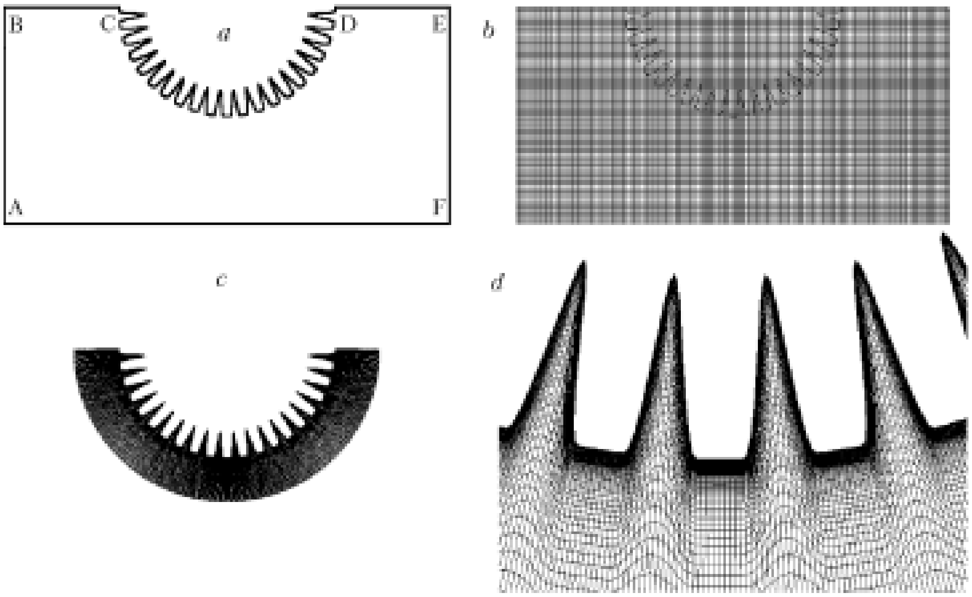

Fig. 1. Schematic of the computational domain around the cylinder with fins (a), rectangular (b) and circular (c) multiblock nets, and the fragment of the circular net in the vicinity of the roughness elements (d).

The content of the VP2/3 package is more limited than that of the above-mentioned universal packages. It involves the library of the hydrodynamic and thermophysical problems to be solved, among which, in addition to traditional test ones (flow in the cavity, flow past a cylinder), are a number of special formulations. It is important to note that, in reference to calculation, all the problems belong to different types as regards complexity and the number of governing equations to be solved. In this case, nonstationary two-dimensional and spatial problems and problems using moving nets (mixing of a medium in a cylindrical cup in impeller rotation, oscillation of a cylindrical pendulum in a rectangular cavity filled by a viscous incompressible fluid [10]) are considered. Much attention is paid to composition of the catalog of semi-empirical models of turbulence, among which are both standard widely used versions of the two-parameter dissipative model and modern (of the 1990s) models. The tests conducted allow one to recommend the model of shear-stress transfer suggested by Menter (see, e.g., [11, 12]) and the Spalart–Allmaras model of eddy viscosity [13] as the most appropriate for engineering calculations.

A series of numerical studies [14–16] has adapted MCT for solution of two-dimensional problems of the dynamics of viscous fluid and heat transfer with periodic boundary conditions. The procedures of correction of the pressure gradient and mass-mean temperature are discussed in detail. Convective heat transfer in an in-line bundle of round tubes under laminar and turbulent conditions of flow is analyzed within a wide range of variation of geometric and operating parameters. An important study was presented in [17], where the assumption of periodic boundary conditions is substantiated on the basis of consideration of an eight-row bundle of cylinders.

Another approach is oriented toward investigation of the effect of concavity on the plane wall on the vortex dynamics and heat transfer; here, transverse trenches are considered along with lunes of different geometry [18]. Enhancement of turbulent heat transfer in the vicinity of the bundle of ordered trenches is analyzed in [19].

In the present work, we study enhancement of convective heat transfer in laminar and turbulent flows past a remote cylinder in an in-line bundle of tubes with trenches being applied on the cylinder surface at a constant pitch.

Problem Formulation. Solution of dynamic and thermal problems of stationary convective heat transfer in an in-line tube bundle, which are described by the Navier–Stokes equations in the laminar mode and the Reynolds equations in the turbulent mode as well as by the energy equation, is determined in the computational domain ABCDEF shown in Fig. 1a. The Reynolds equations are closed by the two-parameter model of shear-stress transfer (MSST) suggested by Menter. The assumption on incompressibility of the working medium (air) allows separate solution of the dynamic and thermal problems, with the calculated fields of velocity and turbulent characteristics being used in the latter.

The object of investigation is a circular cylinder with an applied relief — ordered trenches — i.e., it has N equal curvilinear periods. The cylinder diameter D is taken as a characteristic size. The periodic disturbance of the shape of the body consists of two fragments: the base circular arc of the outer cylinder and the contour of the trench, the bottom of which also is a circular arc — the generatrix of the inner cylindrical surface. The configuration of the side walls of the trench is represented by curvilinear wavy lines that are specified numerically by trigonometric functions on the basis of a smooth conjugation with the base and bottom parts. The determining parameters are the amplitude of the disturbance — the trench depth and the dimensions of the base and bottom cylindrical surfaces. In this study, the integral geometric characteristic is the ratio of the length of the contour of a streamlined body to the length of the contour of a smooth cylinder without the shape disturbance ξ. The approach applied to the construction of the body shape allows one to consider a wide range of its geometric configurations: from traditional wavy to finned cylinders. In Fig. 1, the body has the shape of a gear wheel.

The mass-mean velocity U is taken as the characteristic velocity. A series of calculations in the laminar mode of flow past a remote cylinder in the bundle is made at Re = 40, 10^2, $2.5{\cdot}10^2$, $5{\cdot}10^2$, and 10^3 and in the turbulent mode — at $3{\cdot}10^3$, 10^4, and $3{\cdot}10^4$. The laminar and turbulent Prandtl numbers are taken equal to 0.7 and 0.9, respectively.

As in [14–16], periodic boundary conditions are set on the flow-through boundaries AB and EF and the sticking conditions are set on the washed wall CD. The geometric dimensions of the computation module are taken to be 2×1. The cylinder wall is assumed to be isothermal and hot (equal to 1.27 in dimensionless units). As the characteristic temperature we take the mass-mean temperature at the inlet section (in dimensional form it is equal to 293 K, then superheating of the washed wall is 100 K).

The two-block structurized nets used consist of different-scale fragments of different types. Similarly to [14–16], a polar curvilinear net (with nonuniform pitches along the circular and radial coordinates) that agrees with the body shape and stretches to a distance of 0.15 from the cylinder surface (Fig. 1c), is applied to the base Cartesian net (with square meshes with a pitch 0.015), which covers the entire computational domain (Fig. 1b). The Cartesian net does not change in the calculations and the polar net adapts to the chosen geometry of the relief. Thus, for the cylinder configuration shown in Fig. 1, there are 61 meshes in the radial direction of the polar net with the near-wall pitch equal to 0.0001 and 481 meshes in the circular direction of the polar net (Fig. 1d).

Calculation Technique. The use of MCT in solution of the problem posed is stipulated by the fact that it is characterized by the presence of different-scale structural special features, including a separated flow past a cylinder and small-size (by an order smaller) trenches on its surface. As has already been mentioned, in [13–18] convective heat transfer from a remote cylinder in the in-line tube bundle has been modeled numerically by the developed multiblock factorized implicit methods of solution of the Navier–Stokes and Reynolds equations [6]. The same works give a thorough description of the computational algorithm on the basis of structurized superimposed grids and specially developed procedures of correction of pressure β_p and mass-mean temperature β_T. The same algorithm is used in the present paper. As in [16–19], to calculate turbulent heat transfer in detached flows we use the model of shear-stress transfer that has been recently modified by Menter [20]. It should be noted that the developed multiblock algorithm and the selected model of turbulence have been verified in numerous problems that have experimental analogs.

Analysis of Calculated Results. Figures 2–8 and Table 1 give some of the results obtained. A part of them, the table included, is devoted to a comparative analysis of the effect of the Reynolds number on the flow pattern and heat transfer near a smooth and a finned cylinder, with the shape of the latter being distinguished by the highest enhancement of heat transfer of all considered reliefs. Another part of the results relates to the estimation of the effect of different configurations of cylinders, which differ in their number and in the shape of the trenches and, as a whole, in the quantity ξ, on a turbulent flow past a body and vortex heat transfer at a fixed number, Re = $3{\cdot}10^4$.

The in-line tube bundle with a distance between the centers of the cylinders equal to 2 refers to the class of dense arrangements of tube bundles that are characterized by the mode of flow blocking, i.e., formation of separation zones between successively positioned cylinders. Similarly to a smooth cylinder [14, 15], an increase in Re in a laminar flow past a finned cylinder (Figs. 2 and 3a and Table 1) is accompanied by substantial deformations of the structure of the detached flow and temperature fields. A high rate of variation is most typical of low velocities of flow, when in transition from Re = 40 to Re = 10^2 the separation zones between the cylinders become noticeably larger. In this case, the position of the separation point on the back side of the body turns out to be rather close to the asymp-

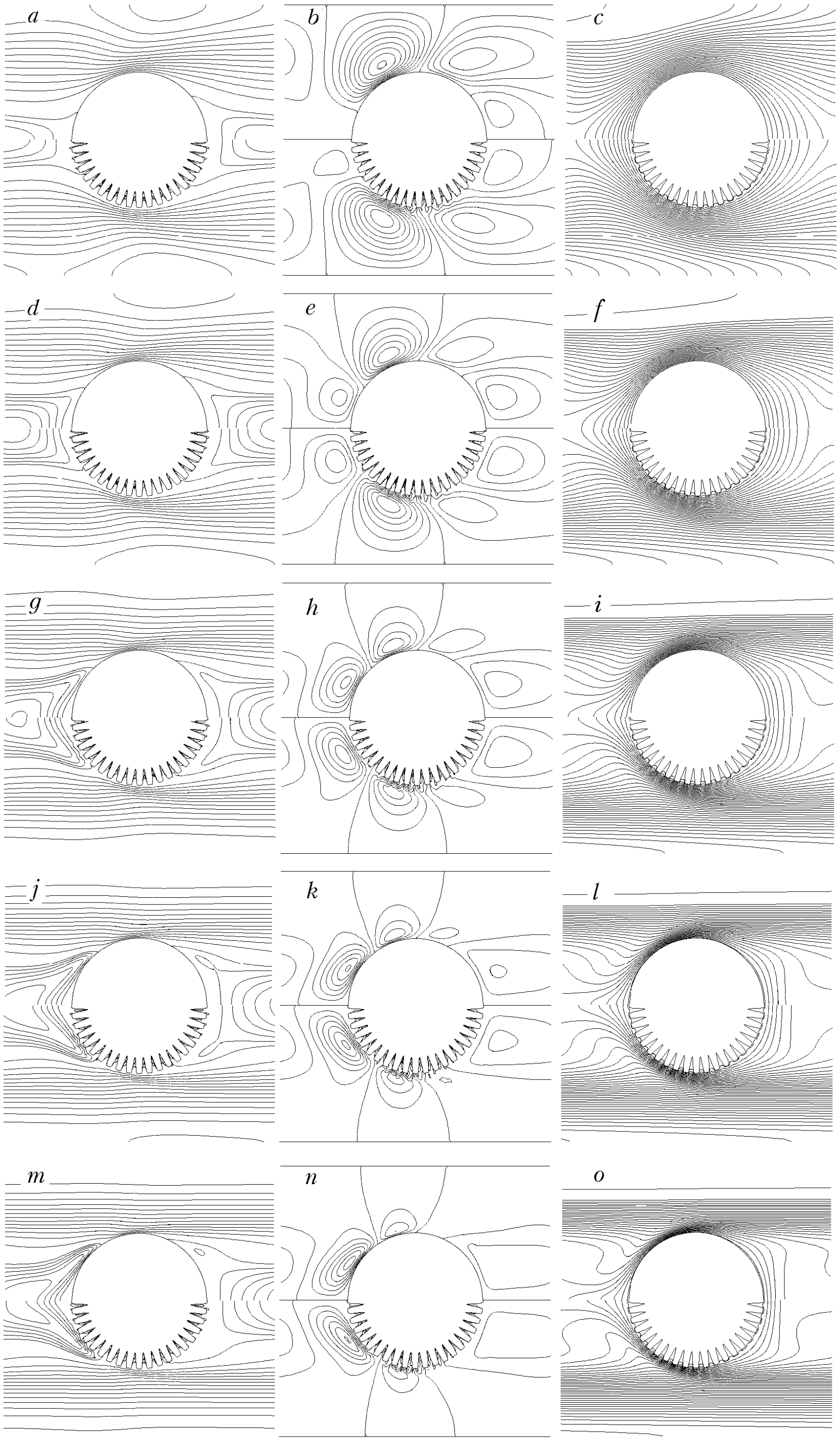

Fig. 2. Comparative analysis of patterns of isolines of the horizontal *u* (a, d, g, j, m) and vertical υ (b, e, h, k, n) components of velocity and isotherms *T* (c, f, i, l, o) in a laminar flow past circular (upper halves) and finned (lower halves) cylinders at different Reynolds numbers: Re = 40 (a, b, c); 100 (d, e, f); 250 (g, h, i); 500 (j, k, l); 1000 (m, n, o). Isolines *u* are drawn with a pitch 0.02 for $u < 0$ and 0.1 for $u > 0$, υ with a pitch 0.02, and *T* with a pitch 0.01.

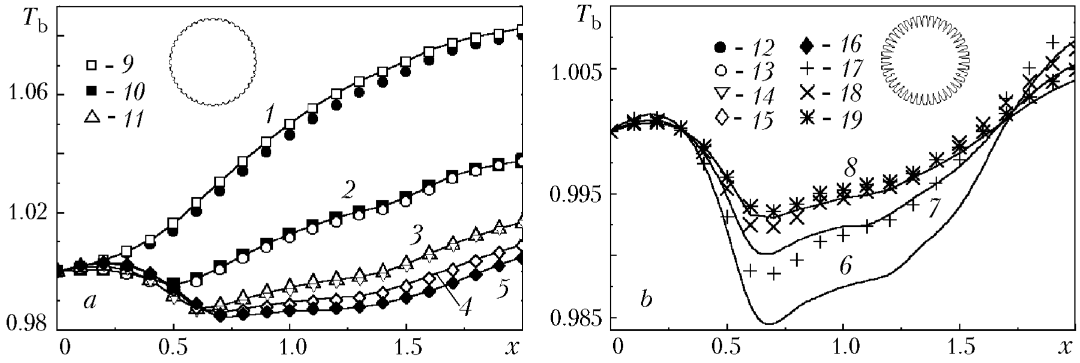

Fig. 3. Dependence of the distribution of the mass-mean temperature T_b on the longitudinal coordinate x for smooth (1–8) and finned (9–19) cylinders at different Reynolds numbers in the laminar (a) and turbulent (b) modes: 1, 9, 12) Re = 40; 2, 10, 13) 10^2; 3, 11, 14) 250; 4, 15) $5 \cdot 10^2$; 5, 16) 10^3; 6, 17) $3 \cdot 10^3$; 7, 18) 10^4; 8, 19) $3 \cdot 10^4$.

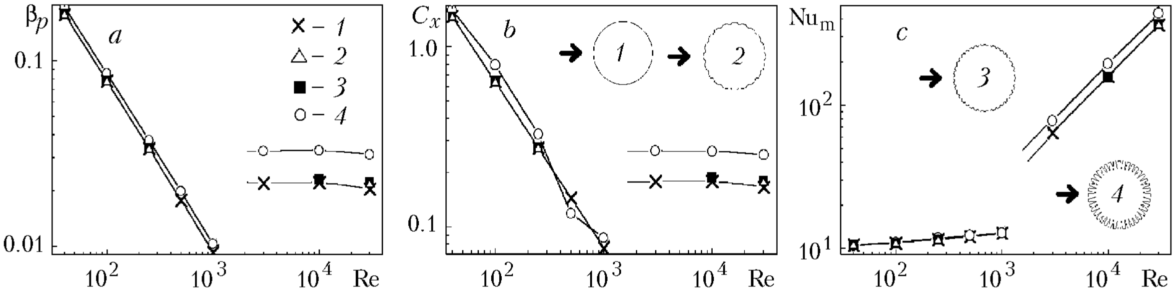

Fig. 4. Influence of the Re number on the coefficient of hydraulic losses (a) and the drag coefficient (b) and the Nusselt number summed up around the washed contour (c) at different lengths of the contour of finned cylinders ξ normalized along the length of a smooth cylinder: 1) ξ = 1; 2) 1.059; 3) 1.224; 4) 3.517 [2) N = 10; 3, 4) 20].

totic one that is observed at high Re. Low intensity and small dimensions of large-scale vortices between the cylinders at small mass-mean velocities predetermine a large difference between the local velocities of flow in the vicinity of the body and in the flow core in the flow-through part between the tubes, i.e., in the median cross section the flow accelerates noticeably and then decelerates. Sluggishness of the velocity field as a whole leads to a considerable increase in the mass-mean temperature along the computation module.

Intensification of the back flow and some increase in the size of the separation zone between the cylinders are observed with further increase in Re. In this case, the position and contours of a large-scale vortex remain virtually constant for Re > 250. As has already been mentioned in [15], the temperature in the flow core has a tendency toward leveling as Re increases.

As follows from Fig. 2, the effect of finning on the pattern of the detached flow past a cylinder turns out to be slight. However, an analysis of the highest values of the back flow, given in Table 1, allows one to note some increase in the intensity of motion of a large-scale vortex at low mass-mean velocities in the bundle for the finned cylinder compared with a smooth cylinder and an intense tendency toward flow attenuation in the vortex at high Re numbers. At the same time, changes in the velocity field virtually do not affect heat transfer (Fig. 3a). It should also be mentioned that the shape of finning exerts the same weak effect on heat transfer.

An analysis of integral characteristics of flow and heat transfer (see Fig. 4) allows one to draw the conclusion that the effect of finning on the pressure drop in the module β_p, the drag coefficient C_x, and the total heat transfer $\mathrm{Nu_m}$ in a laminar flow past a remote cylinder is very slight. In logarithmic coordinates, we note a linear regressive

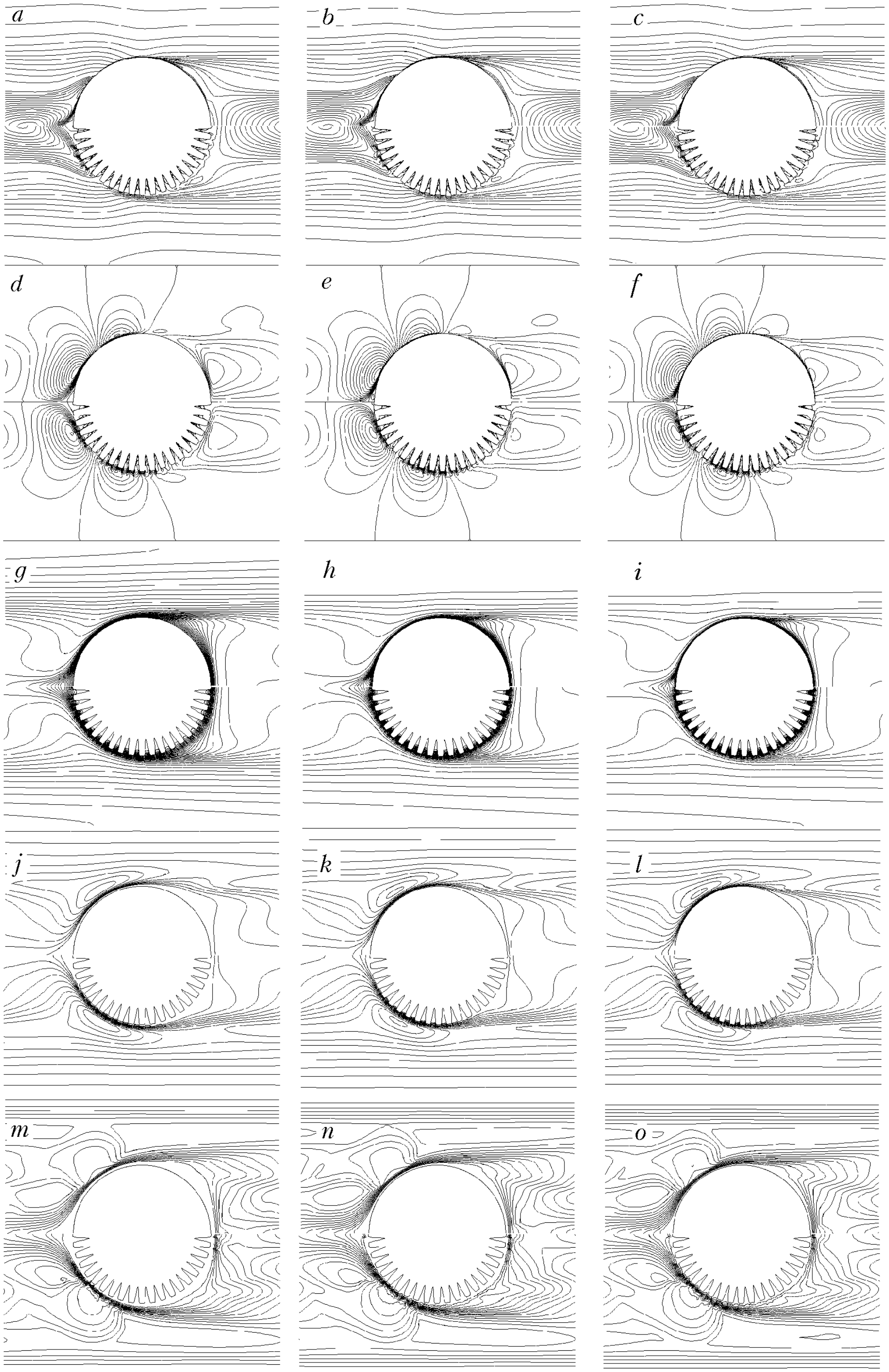

Fig. 5. Comparative analysis of the isolines of the horizontal u (a, b, c) and vertical υ (d, e, f) components of velocity, temperature T (g, h, i), turbulence energy k (j, k, l), and eddy viscosity ν_t (m, n, o). Isolines u are drawn with a pitch 0.02 for $u < 0$ and 0.1 for $u > 0$, υ with a pitch 0.02, T with a pitch 0.01, k with a pitch 0.005 from the 0.005 level, and ν_t with a pitch 0.0005 from the 0.0005 level.

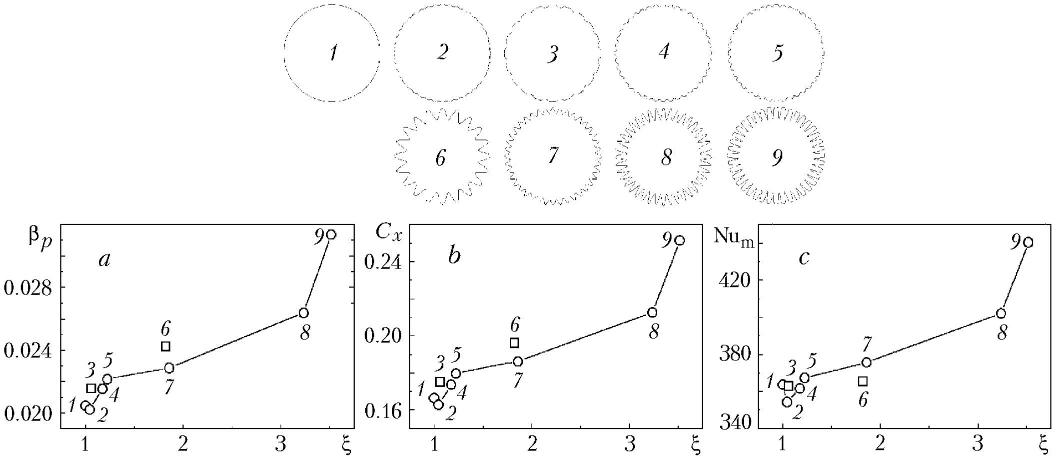

Fig. 6. Influence of ξ on the coefficient of hydraulic losses (a), the drag coefficient (b), and the Nusselt number summed up around the washed contour of the finned cylinder (c) at Re = $3 \cdot 10^4$: 1) ξ = 1; 2) 1.045 (N = 20); 3) 1.059 (10); 4) 1.174 (20); 5) 1.224 (20); 6)1.823 (10); 7) 1.860 (20); 8) 3.235 (20); 9) 3.517 (20).

character of the dependences β_p(Re) and C_x(Re) and also a very slow rate of increase of the dependence $\mathrm{Nu_m}$(Re), which is very close to linear.

In the present paper, we make the assumption, which is typical of such studies (see, e.g., [16]), that the turbulent mode of a stationary flow past a remote cylinder is realized at Re of the order of several thousand. In our work, we *a priori* set Re equal to $3 \cdot 10^3$.

Variation of the Reynolds number from $3 \cdot 10^3$ to $3 \cdot 10^4$, as has been found earlier for a smooth cylinder [16], does not lead to considerable changes in the flow patterns, fields of temperature and turbulence characteristics (Fig. 5), longitudinal distribution of the mass-mean temperature (Fig. 3b), and integral force and thermal characteristics (Fig. 4). As compared to the case of a laminar flow past a body, here we observe enhancement of the detached flow, with a threefold increase in the maximum velocity of the back flow, which reaches 32% of the mass-mean velocity. The large-scale vortex that forms in the gap between two successive cylinders possesses characteristic features of two different types of detached flows in the near wake behind an individual cylinder (the right-hand side of the flow patterns in Fig. 5) and in the leading stalling zone in front of the cylinder, which forms, in particular, in interaction between the body and the flow with a periphery maximum of the velocity of the type of the profile in the far wake (the left-hand side of the flow patterns in Fig. 5) [21]. A shear layer, where the turbulence rate and eddy viscosity increase with distance from the separation point, develops on the boundary of the circulation zone on the back side of the cylinder. In the bottom part of the body, the longitudinal component of the velocity of the back flow is rather low (Fig. 5a–c) and the velocity of transverse flows is very high (Fig. 5d–f). As a result, the isotherms on the back side of the cylinder are practically parallel to the body contour. At the same time, interaction between the shear layer and the curvilinear body is accompanied, as is known, by a sharp increase in pressure in the vicinity of the reattachment point and intense spreading of fluid (air, in our case) over the surface. As a consequence, the intensity of transverse flows in the front part of the body is much higher than in the bottom zone. Here, the values of the longitudinal component of the velocity of the back flow are higher with the maximum of the velocity being shifted to the front stagnation point on the body (relative to the median cross section between the centers of the neighboring cylinders). The appearance of a small-size, low-intensity secondary separation zone in the vicinity of this point is noted. As a result, a stratified temperature field (decreasing with distance from the cylinder) in the flow core in the high-intensity part of the separation zone in front of the body is transformed to a temperature spot that is close to the isothermal one.

In contrast to the laminar mode, the effect of finning on vortex heat transfer in a turbulent flow past the remote cylinder in the tube bundle turns out to be rather strong. As follows from Fig. 5 and Table 1, finning leads to a decrease in the intensity of the back flow in a large-scale vortex and simultaneously to a considerable increase in the generated maximum energy of turbulent fluctuations. This indicates that the fins on the body surface serve as tur-

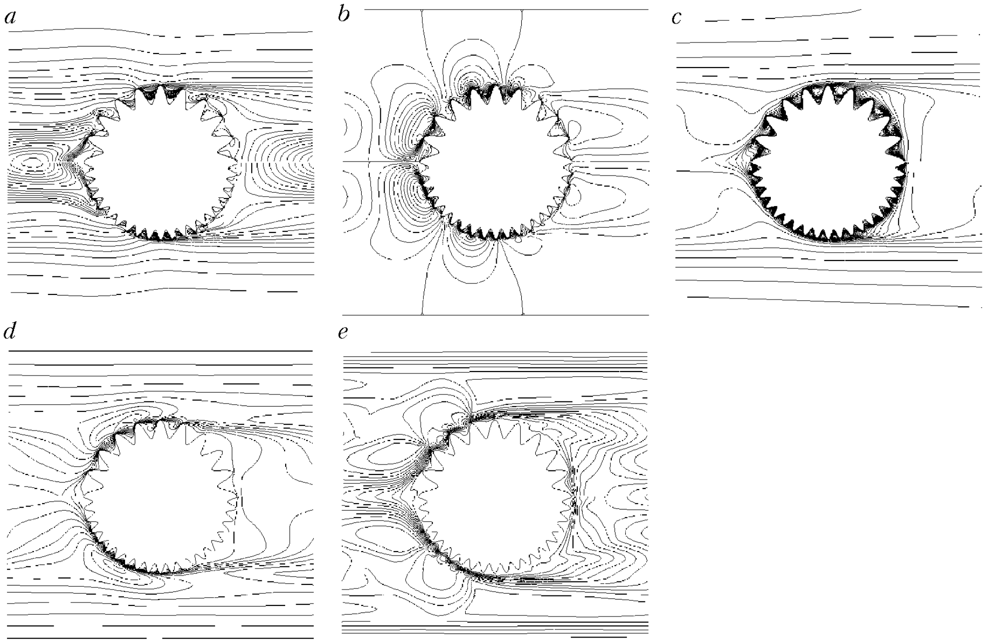

Fig. 7. Comparative analysis of the patterns of isolines of the horizontal u (a) and vertical υ (b) velocity components, isotherms T (c), isolines of the turbulence energy k (d), and eddy viscosity (e) for finned cylinders with close ξ (of order 1.8) and a different number of trenches (10 — patterns in the upper halfplane and 20 — patterns in the lower halfplane) on the contour at Re = $3{\cdot}10^4$. Isolines are drawn similarly to those in Fig. 5.

TABLE 1. Influence of the Reynolds Number on the Critical Characteristics of the Back Flow in the Vicinity of Smooth and Finned (ξ = 3.517) Cylinders

Mode	Re	Circular cylinder		Finned cylinder	
		$u_{\min}$	$k_{\max}$	$u_{\min}$	$k_{\max}$
Laminar	40	—0.0584	—	—0.0736	—
	100	—0.111	—	—0.114	—
	250	—0.123	—	—0.125	—
	500	—0.115	—	—0.113	—
	10^3	—0.118	—	—0.110	—
Turbulent	$3{\cdot}10^3$	—0.323	0.0439	—0.283	0.0597
	10^4	—0.323	0.0513	—0.264	0.0611
	$3{\cdot}10^4$	—0.312	0.0511	—0.271	0.0592

bulizers. As a result (Fig. 4), finning can lead to substantial (by 25%) enhancement of heat transfer, however, in this case, hydraulic resistance increases twofold.

A parametric analysis of the influence of the shape of finning on convective heat transfer in the bundle of cylinders is made at a fixed Reynolds number, equal to $3{\cdot}10^4$. In Fig. 6, the results of the calculations of the integral characteristics of flow and heat transfer as a function of the parameter ξ are summarized. It is obvious that the ratio of the length of the washed surface of the cylinder to the base length of the contour of the smooth cylinder without trenches is not the only determining geometric parameter. As has already been mentioned, trenches can have various geometric configurations and the density of their location on the cylinder is related to the number of them, N. The curves in Fig. 6 correspond to N = 20. The results for N = 10 are marked by individual points (3, 6). It is seen that

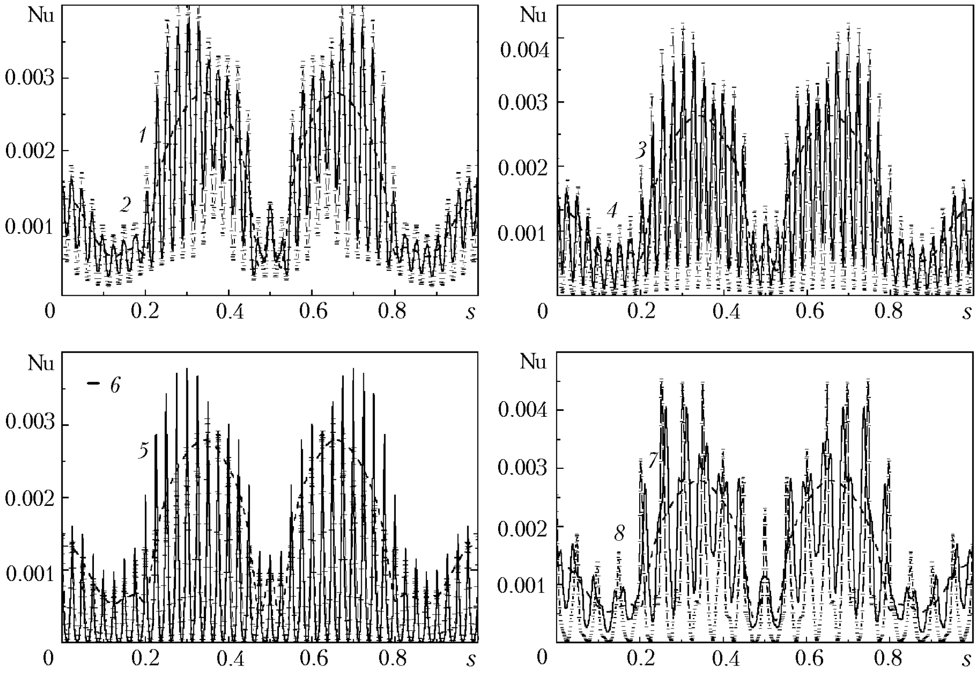

Fig. 8. Comparison of the profiles of the local Nusselt numbers along the contour of the finned cylinder at different ξ and N for Re = $3 \cdot 10^4$: 1) ξ = 1.045, N = 20; 2) 1.174 and 20; 3) 1.224 and 20; 4) 1.86 and 20; 5) 3.325 and 20; 6) 3.517 and 20; 7) 1.059 and 10; 8) 1.823 and 10. The dashed line corresponds to a smooth cylinder.

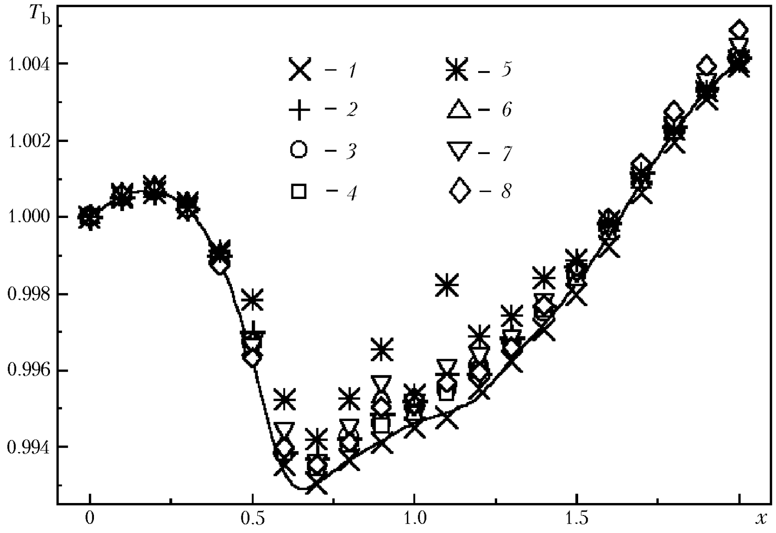

Fig. 9. Influence of ξ and N on the longitudinal distribution of the mass-mean temperature T_b at Re = $3 \cdot 10^4$: 1) ξ = 1.045, N = 20; 2) 1.059 and 10; 3) 1.174 and 20; 4) 1.224 and 20; 5) 1.823 and 10; 6) 1.86 and 20; 7) 3.235 and 20; 8) 3.517 and 20. The solid line corresponds to a smooth cylinder.

the high values of ξ are directly related to great amplitudes of disturbances of the shape of the circular cylinder. As should be expected, the trench configuration also greatly affects the characteristics of flow and heat transfer. For a finned cylinder (9), the total heat transfer, as well as hydraulic losses, is much higher than for a wavy cylinder (8). It is of interest to note that despite the tendency toward an increase in heat transfer with an increase in ξ, for most of the considered shapes of cylinders (1–7) that fall within the range of ξ from 1 to 1.9, the relative increase in $\mathrm{Nu_m}$ is not high (~5%).

The estimation of the effect of the number of trenches N at close ξ is illustrated in Figs. 4 and 7. The washed surface is wavy. As is seen, the condition that is imposed on ξ leads to a great difference in the amplitudes of disturbances of the shape of the circular cylinder, with small N, naturally, the amplitude being larger (6) than with a double number of trenches (7). It could be expected that for larger values of the amplitudes the effect of heat-transfer enhancement would be more considerable, but this does not happen. On the contrary, for smaller values of the amplitude but with a larger number of trenches the increment of heat transfer turns out to be larger (7). An analysis of the isolines of turbulence energy given in Fig. 7d allows one to explain the situation of enhanced turbulization in the shear layer, which is caused by an increase in the number of roughness elements on the cylinder surface.

Comparison of the profiles of local heat fluxes around the contour of the washed surface (Fig. 8) shows that the character of averaged distributions of the local Nu number for cylinders with different finning on the whole corresponds to the dashed curve of the respective dependence for the circular cylinder. The oscillating behavior of the curves presented is related, as has been found in [18], to the increase in local heat transfer on protrusions and its decrease on the recesses of the washed contour. As ξ increases, the difference between maximum and minimum values of Nu increases, with the lowest values of local heat transfer being zero for high ξ.

Estimation of the influence of finning of the remote cylinder in the tube bundle on longitudinal distribution of the mass-mean temperature in the computation module (Fig. 9) shows that for a wide scatter of the considered shapes of trenches within the range of ξ from 1 to 3.5 virtually all results gather near one curve. It appears that only the points for a wavy cylinder with $N = 10$ differ from it somewhat more greatly. Such similarity in the behavior of the data on T_b suggests that finning in the form of trenches on the surface of the circular cylinder affects mainly the near-wall flow, the surface characteristics, and the detached shear layers; it does not influence the core of the flow between vertical cylinders.

CONCLUSIONS

Using the developed multiblock computational technologies, which are realized in the VP2/3 package, and the approach on the basis of periodic boundary conditions, we carried out numerical calculation of vortex heat transfer in a bundle of tubes with ordered trenches in laminar and turbulent modes of flow within a wide range of variation of the Reynolds number, $40–3 \cdot 10^4$, for various shapes and a different number of trenches.

An analysis of the isolines of the characteristics of flow, turbulence, and isotherms and also longitudinal distributions of the mass-mean temperature shows that the effect of the disturbance of the shape of the circular cylinder from wavy to finned contours is bounded by the zone near the wall and the detached shear layer. The trenches on the washed surface in the turbulent mode of flow past the body are similar to the roughness elements that generate near-wall turbulence and cause heat-transfer enhancement. The increment of the total heat transfer reaches 25% with an advanced (twofold) increase in hydraulic losses. Finning in the laminar mode of streamlining is ineffective since it practically does not exert any influence on enhancement of heat transfer.

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NOTATION

C_x, drag coefficient; D, cylinder diameter, m; k, energy of turbulent fluctuations, in fractions of U^2; N, number of trenches on the cylinder surface; Nu, Nusselt number determined as $d\theta/dn$; x, axial coordinate, m; Re, Reynolds number, $\mathrm{Re} = \rho UD/\mu$; s and n, coordinates reckoned along the washed contour of the body and along the normal to it, m; T, dimensionless temperature; U, mass-mean velocity, m/sec; u and υ, Cartesian components of velocity, in fractions of U; β_p, pressure gradient; β_T, gradient of the mass-mean temperature; μ, viscosity, Pa·sec; θ, dimensionless temperature, $\theta = (T - T_\mathrm{w})/(T_\mathrm{b} - T_\mathrm{w})$; $\nu = \mu/\rho$, kinematic viscosity; ξ, ratio of the length of the washed contour with the trenches to the length of the circular cylinder; ρ, density, kg/m^3. Indices: b, mass-mean characteristic; m, value averaged over the perimeter; max and min, maximum and minimum values; t, turbulence parameter; w, parameters on the wall.

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