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Effect of periodic macroroughness on development of turbulent free convection near a suddenly-heated vertical plate

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The results of numerical simulation of unsteady free convection developing near a suddenly heated plate, on which protrusions in the form of adiabatic cylinders of double height with respect to the diameter are arranged in a staggered order, are presented. The calculations were performed according to the Reynolds equations using a differential model of turbulent stresses. The range of variation of the Grashof number (plotted according to the thickness of the free convective flow), in which a significant intensification of heat transfer can be achieved, has been determined. It is shown that the best conditions for intensification are created if the longitudinal pitch in the array of protrusions is approximately twenty times the diameter of the latter.

Keywords: unsteady free convection, vertical-plate boundary layer, heat transfer intensification, numerical modeling, Reynolds stress model.

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The issue of cooling of heated surfaces and, consequently, intensification of the heat exchange is highly relevant to the design and usage of various buildings and technical devices. The traditional approach to intensification of near-wall heat transfer processes involves the use of protrusions and fins of different shapes [1]. The alternative to protrusions is the use of surfaces with depressions in the form of round, oval, or oval-trench dimples that have been studied extensively over the recent years (see, e.g., [2,3]). The effect of protrusions and depressions is normally examined in the regime of forced convection. However, passive cooling of structures in many practical applications proceeds in the regime of free convection [4] with the free-convection boundary layer on the surfaces of life-size industrial installations and residential properties being in a turbulent state.

The specifics of heat exchange in a free-convection boundary layer are largely attributable to the nonmonotonicity of the longitudinal velocity profile that has two distinct parts: 1) internal, which extends from the wall to the point of maximum velocity; (2) external, which is significantly more extensive and stretches from the maximum to the outer boundary with the environment [5]. It has been demonstrated earlier that a significant intensification of heat transfer may be achieved only when both internal and external parts of the boundary layer are disturbed [6]. This may be implemented, e.g., by setting up large-scale obstacles on the heated surface.

The influence of an isolated obstacle in the form of a circular cylinder of various heights on the local intensification of heat exchange in a quasi-steady turbulent boundary layer on an isothermal vertical plate has been examined in [7] with the use of Reynolds-averaged Navier−Stokes equations closed with the $k-\omega$ SST turbulence model. However, the case of multiple large-scale obstacles distributed (e.g., periodically) over a significant part of the cooled surface is more practically relevant. The flow of a free-convection boundary layer past a single transverse row of periodically arranged cylinders has been examined numerically in [8] based on the formulation and the computational technique applied earlier in [7]. The intensification of heat transfer in a free-convection boundary layer on a vertical surface by an array of V-shaped plates has been studied experimentally in [9–11] (although only in the case of laminar flow in the disturbed layer).

In the present study, the intensifying effect of cylindrical protrusions arranged in a staggered manner on the surface of a vertical unbounded plate, which is heated suddenly relative to the environment, is examined numerically. The formulation of this three-dimensional model problem wherein the development of dynamic and heat-exchange processes along the longitudinal (vertical) coordinate is „substituted" with their development in time provides an opportunity to reduce dramatically the resource intensiveness of studies due to the possibility of allocation of a compact computational domain with periodicity conditions applied in the longitudinal direction. Note that this approach was proven fairly effective in direct numerical simulations of turbulence in a free-convection boundary layer on a smooth plate [12,13]. The solution of a statistically one-dimensional unsteady problem of the development of a free-convection turbulent boundary layer on a suddenly heated smooth plate was derived in [14] based on the Reynolds equations closed with the Reynolds stress model. Notably, it was demonstrated that the results of calculations at the stage of fully developed turbulence agree closely with direct numerical simulation data.

Thus, free-convection flow of air (Prandtl number $\mathrm{Pr} = 0.7$) in the vicinity of a vertical plate is considered

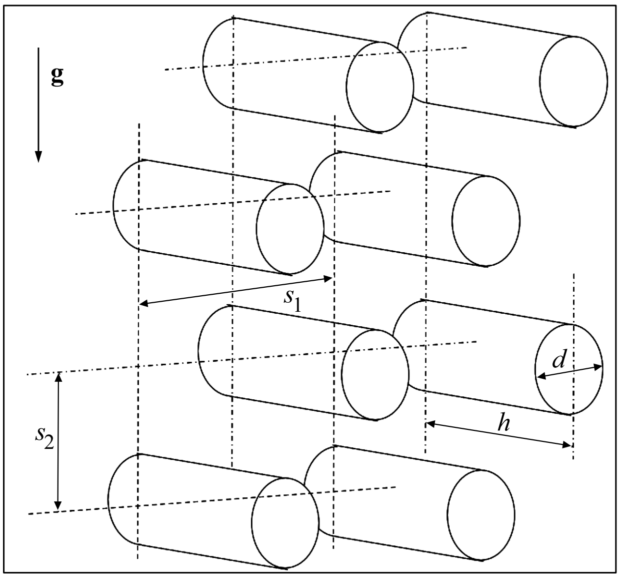

Figure 1. Diagram illustrating the formulation of the problem.

in the present study. Temperature T_w of the plate is raised suddenly at the initial instant relative to temperature T_a of the environment filled with a stationary medium. Cylindrical protrusions with diameter d are arranged in a staggered order on the plate. Their surface is assumed to be adiabatic. Protrusions with height $h = 2d$ form relatively dense rows in the transverse direction with pitch $s_1 = 2d$ (Fig. 1). Longitudinal pitch s_2 (distance between the rows of protrusions in the vertical direction) varies from $6d$ to $24d$.

The chosen rectangular computational domain is $0.5s_1 \times 2s_2 \times H$ in size, where $H = 50d$ is the extent of the domain normally to the plate that is sufficient for the outer boundary of the heated liquid layer to remain out of contact with the boundary of the computational domain throughout the entire time interval of development of convection. Periodicity conditions are established at the upper and lower boundaries of the computational domain. Symmetry conditions are imposed at the side boundaries passing through the centers of protrusions. No-slip conditions are established at the surfaces of the plate and protrusions.

Using the buoyancy velocity (introduced as $V_b = [g\beta(T_w - T_a)\nu]^{1/3}$ [5]) as a velocity scale, we define the time scale of the problem as $t_s = d/V_b$. The process of development of convection is calculated within a time interval of $32t_s$. Note that the characteristic Grashof number in the case of a smooth plate $\mathrm{Gr}_\delta = g\beta(T_w - T_a)\delta^3/\nu^2$ [8] assumes a value of 10^9 at the end of this interval. Here, g is the gravitational acceleration, β is the thermal expansion coefficient, ν is the kinematic viscosity coefficient, and δ is the integral boundary layer thickness calculated by integrating the vertical velocity profile [12] (it is close in magnitude to the half-width of the external part of the layer).

Unsteady three-dimensional Reynolds and energy equations are used to obtain a numerical solution; buoyancy effects are modeled in the Boussinesq approximation. The equations are closed with the BSL Reynolds stress model. According to it, the time scale of turbulence needed to close the system of transport equations of Reynolds stresses is calculated using the (similarly named) version of the $k-\omega$ Menter turbulence model [15]. Finite-volume calculations were performed using the ANSYS Fluent 18.2 general-purpose code on quasi-structured grids with approximately two million cells. The number of cells and the topology of computational grids were chosen based on the results of examination of the grid dependence in the numerical study into the problem of perturbation of a free-convection boundary layer by an isolated cylinder [7]. Grids were refined toward the solid walls in such a way that the average value of y^+ for the calculation points closest to the walls did not exceed unity within the entire studied time interval. Second-order schemes were used for discretization over time and space for all transport equations. A non-iterative solver was used to advance in time; the dimensionless time step was 0.004.

Two-color filling is used in Fig. 2 to represent the isolines of the instantaneous dimensionless vertical velocity field calculated at $s_2 = 6d$ and $18d$ in the symmetry plane and the distributions of the coefficient of heat transfer at the plate at a certain time point ($t = 14.6t_s$) corresponding to fully developed turbulence in the simulated free-convection flow (coefficient of heat transfer α is normalized to the value calculated at the same time point for the case of a smooth plate; the calculated α distribution is duplicated with mirroring in the image). It can be seen that detached flow regions and large-scale vortex structures (both horseshoe structures at the base of protrusions and „trailing“ structures) form at the junctions between protrusions and the plate. The presence of horseshoe vortices translates into a significant nonuniformity of the local heat transfer in the vicinity of cylinders. Regions of an enhanced heat transfer form in the trail behind protrusions (at distances exceeding $2d$ from the rear edge). The extent of these regions and their contribution to the intensification of heat transfer increase with the longitudinal pitch of the grid. At s_2/d lower than 10 (specifically, at $s_2 = 6d$), the interaction of the flow with protrusions of the next row interferes with the formation of an extended trailing region. Combined with the overall inhibiting effect of protrusions that becomes more pronounced as the pitch decreases, this negates the intensification effect.

Significant changes in the flow pattern occurring as the thickness of the heated layer grows predetermine the complex temporal behavior of the integral heat transfer. In order to extend the obtained results to the practically relevant case of a quasi-steady boundary layer along a vertical plate with a system of protrusions, one needs to consider the variation of the integral heat transfer with characteristic Grashof number $\mathrm{Gr}_\delta(t)$. The dependences of coefficient of heat transfer $\alpha_m(\mathrm{Gr}_\delta)$ averaged over the

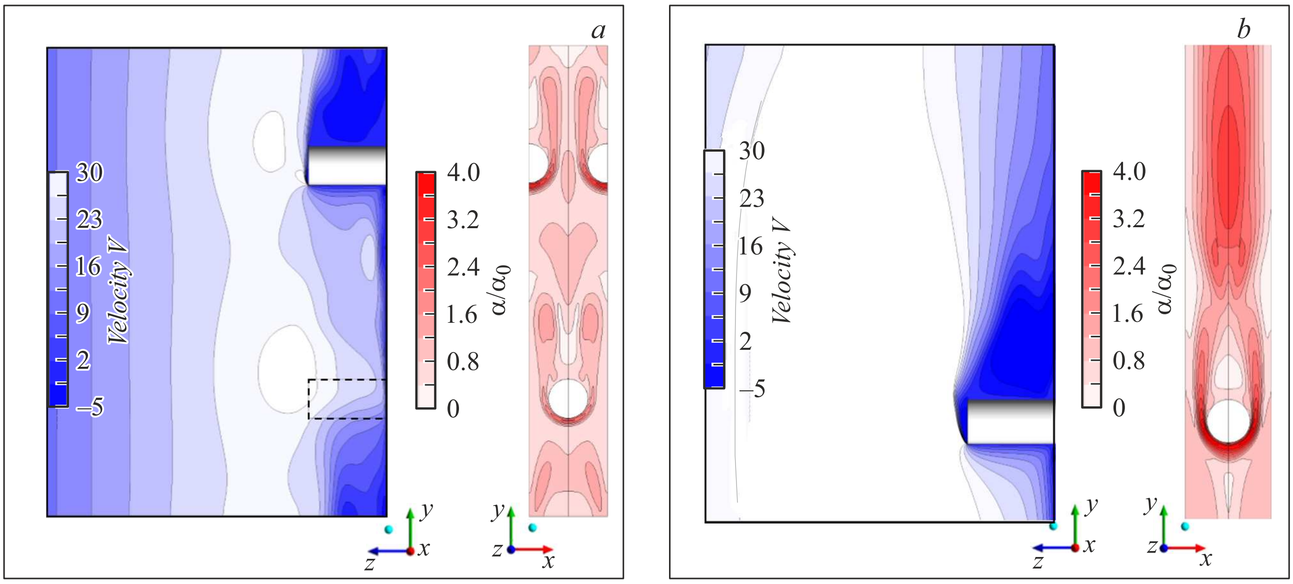

Figure 2. Vertical velocity field and normalized coefficient of heat transfer at the plate at time $t = 14.6t_s$. $s_2 = 6d$ (a) and $18d$ (b).

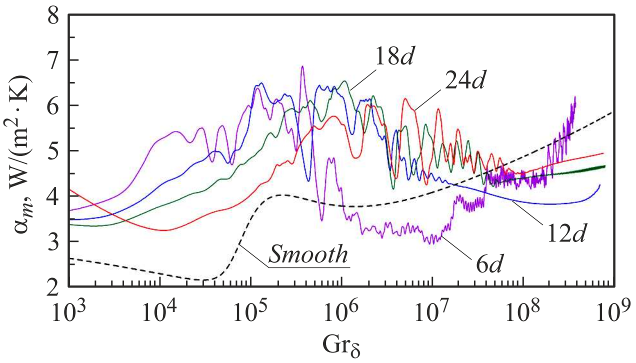

Figure 3. Effect of the longitudinal pitch of protrusions on the dependence of the integral coefficient of heat transfer on the characteristic Grashof number (solid curves) in comparison with the data for a smooth plate (dashed curve).

plate surface and calculated at different values of s_2 are compared in Fig. 3 with the data for a smooth plate obtained using the same verified method that was applied in [14]. It should be noted here that the data obtained at $\mathrm{Gr}_\delta < 10^6$ should be treated with caution, since the applied turbulence model is not meant to characterize adequately the laminar-turbulent transition phenomena. The $\alpha_m(\mathrm{Gr}_\delta)$ dependences obtained in our calculations for the plate with protrusions at the stage of sufficiently developed turbulence ($\mathrm{Gr}_\delta > 10^6$) are significantly nonmonotonic. This is indicative of the presence of low-frequency fluctuations. It follows from the results of analysis of temporal variations of the calculated flow patterns that these fluctuations are induced by the intrinsic instability of large-scale vortex structures forming in the trail behind each obstacle. Intriguingly, the hydrodynamic instability of these large structures is predicted in the used model of Reynolds stresses even if symmetry conditions, which restrict considerably the transverse motion of liquid particles, are applied. The performed averaging of the heat flux over a bounded computational domain within the heated plate does only partially smooth out the influence of the predicted instabilities on the temporal evolution of the integral heat transfer. Taken as a whole, the data presented in Fig. 3 suggest that turbulent heat transfer within the interval of Grashof numbers from 10^6 to $2 \cdot 10^7$ from a plate with protrusions arranged with a large vertical pitch is considerably more intense than the heat transfer from a smooth plate. An array of protrusions yields the maximum gain in heat transfer (approximately 80%) at the beginning of the stage of fully developed turbulence at $s_2 \approx 20d$.

Conflict of interest

The authors declare that they have no conflict of interest.

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