As follows from (10), with an increase in the thickness of the deposition the diffusion flow to the rough surface diminishes, and this may lead to a decrease in the concentration of particles at the surface and to a reduction in the migration component of the rate of deposition.

NOTATION

a, particle dimension; d, tube diameter; D, diffusion factor; C, particle concentration; g, acceleration of free fall; \(j_D\), diffusion flow at the surface; R, \(R_1\), inside and outside radii of the tube; \(U_\star\), dynamic velocity; \(v\), particle volume; \(y\), coordinate; \(\alpha_1, \alpha_2\), coefficients of heat transfer from the internal and external media; \(B = 1 - 6/R\), choking factor; \(\Delta\), roughness height; \(\delta\), thickness of deposition; \(\epsilon_{re}\), resistance; \(\epsilon_R\), specific dissipation energy; \(\nu\), kinematic viscosity; \(\Delta \rho = \rho_{re} - \rho_{re}, \rho\), density of particles and the carrier phase; \(\eta\), dynamic viscosity; \(\tau\), stay time; \(\tau_r\), relaxation time; \(\tau_w\), tangential friction; \(\varphi\), volumetric particle fraction. Subscript: 0, for a clean tube.

LITERATURE CITED


CHANGES IN THE STRUCTURE OF TURBULENT FLOWS
SUBJECTED TO THE ACTION OF FLOW ACCELERATION

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We examine the effects resulting from the laminarization of turbulent flows subjected to the action of flow acceleration. We describe the factors and conditions for the appearance of this phenomenon. As a theoretical base for this investigation we employ a mathematical model of a boundary layer for a broad range of turbulent Reynolds numbers, based on a modified \(\varepsilon-\varepsilon\) turbulence model.

The theory of hydrodynamic stability [1] rejects the possibility of a reverse transition from turbulent flow to laminar. However, in a number of experimental studies into turbulent flows [2, 3] a significant deviation was noted in the integral characteristics of heat exchange and friction, as well as in the profiles of the average velocity and temperature from those universal relationships applicable to a turbulent flow regime in the direction of relationships that are more in line with the laminar regime. This phenomenon has been designated as the laminarization of turbulent flows.

In their effort to generalize and systematize questions related to the phenomenon of turbulent-flow laminarization, the authors of [4], on the basis of studies that they carried out, came to the conclusion that it is possible to isolate certain external factors which, under these conditions, lead to a change in the mechanism of turbulent exchange:

- flow acceleration which strives to reduce the extent to which the turbulent frictional stresses affect the average flow characteristics [3, 5];
- the curvature of the streamlined surface, resulting in transverse flows through the channel [6];
- the cooling of the boundary layer, which results in a tendency to stabilize the vortex structure of the boundary layer [7].
It is obvious that it is impossible to draw a clearly delineated boundary between the influence of these factors on the structure of turbulent flows, since they are interrelated with one another. For example, any increase in the curvature of the streamlined profile or an increase in the nonuniformity of the temperature field along and across the flow will lead to an increase in flow acceleration. Moreover, in real designs these factors may make themselves felt simultaneously. Therefore, the division of external factors affecting the laminarization of turbulent flows is conditional in nature, but useful from a methodological standpoint, enhancing the detailed study of individual aspects of the phenomenon.

In experimental studies into the flow of a gas in tubes with heated walls [8] note was also taken of the phenomenon of laminarization. It may be assumed that as the temperature rises there is an increase in the viscosity of the gas and, consequently, turbulent vortices are subjected to increasingly viscous damping as the gas makes its way through the tube. In this case, any turbulent gas flow will finally change over into laminar flow, provided that the walls are sufficiently heated over an adequate length. This may indeed be valid; however, it is obvious that just as in the case of boundary-layer cooling, we are dealing here with a nonuniformity in the temperature field, resulting in increased acceleration of the flow.

Bearing in mind the above-presented data, there is some point to examining in greater detail the conditions under which flow acceleration influences the structure of turbulent flows. Although the explanation for the laminarization of turbulent flows demands profound study into the very nature of the formation and disruption of turbulence, some of the quantitative relationships for this process can be predicted, relying on the integral momentum equation for the case of a plane stationary boundary layer within a compressible fluid, in the absence of any body-force effect [9]:

\[
\frac{d\delta_p}{dx} + \frac{\delta_p}{U_m} \frac{dU_m}{dx} \left(2 + \frac{\delta_p}{\delta_b} - M^2\right) = \frac{\tau_w}{\rho U_m^2}.
\]

(1)

If the velocity profile in the turbulent boundary layer corresponds to the 1/7 rule, the formula for the local coefficient of friction can be obtained in the form

\[
\frac{\tau_w}{\rho U_m^2} = 0.0128 \left(\frac{U_m \delta_p}{v}\right)^{-1/4}.
\]

(2)

Having substituted into (1) the value of \(\tau_w\) from (2) and the ratio of the conditional boundary-layer thicknesses, equal to 1.29, after introduction of the momentum-loss thickness into the Reynolds number we derive the following equation:

\[
\frac{v}{(2.29 - M^2)} \frac{d \text{Re}_{\delta_p}}{dx} = \frac{0.0128}{(2.29 - M^2) \text{Re}_{\delta_p}^{1/2}} - \left(\frac{v}{U_m^2} \frac{dU_m}{dx}\right).
\]

(3)

With large accelerations of the flow, the last of the terms in Eq. (3) increases. The gradient in the Reynolds number may then become negative, which leads to a reduction in \(\text{Re}_{\delta_p}\). If we draw the entirely logical, even if quite coarse, conclusion to the effect that laminarization of turbulent flows begins at the same Reynolds numbers as in the direct transition \([\text{Re}_{\delta_p}]^*_w = 360\), in the case of flows with \(M \ll 1\) we can obtain the dimensionless acceleration parameter which defines the onset of laminarization:

\[
K = \frac{v}{U_m^2} \frac{dU_m}{dx} > 3.5 \cdot 10^{-6}.
\]

(4)

It has been established experimentally [2, 4, 5] that a reduction in the characteristics of heat exchange begins to make itself evident in flows with \(K \sim 2\cdot 4\cdot 10^{-6}\). However, this criterion does not allow for a quantitative evaluation of the effects of laminarization in turbulent flows.

Experimental and theoretical data [3, 10] have demonstrated that the so-called reverse transition of the turbulent flow regime into a laminar regime under the action of flow acceleration. For any levels of acceleration, even with \(K > 10^{-6}\), a high level of pulsations in velocity and temperature is maintained, i.e., the flow cannot be regarded as laminar. It is assumed that laminarization is a special specific form of the turbulent flow regime and physical and mathematical models of turbulent transport may serve as its theoretical basis.

Theoretical studies of turbulent boundary layers in accelerating flows [10] have demonstrated the possibility of describing the effects of laminarization by means of a mathematical model of a boundary layer for a broad range of turbulent Reynolds numbers [11], based on the modified two-parameter e-e turbulence model. The utilization of this model allows in greater detail to examine the processes of heat and momentum transfer in accelerated flows, to determine the features and conditions for the phenomena of laminarization, and to describe the nature of the changes occurring within the structure of turbulent flows, ascribed to the effect of a negative pressure gradient. Moreover, the carrying out of a numerical