BOUNDARY-LAYER SUSCEPTIBILITY AND HEAT-TRANSFER INTENSIFICATION

N. F. Yurchenko, A. A. Pyadishyus, and
G. P. Zigmantas

UDC 532.526.4:536.24

Certain physical aspects of heat-transfer processes are examined on the basis of an investigation of boundary-layer susceptibility to perturbations of a different kind.

Examination of a laminar boundary layer as a linear oscillator permitted introduction of the concept of susceptibility [1] which can be used to describe the excitation process of natural vibrations in a boundary layer because of the action of external perturbations, sound fields, surface roughness, etc. In conformity with such a treatment, the problem of susceptibility was until recently the goal of investigations themselves or was the instrument for an experimental study of linear boundary layer stability. Excited Tollmien–Schlichting waves, dampled or growing in amplitude [2], were the criterion for susceptibility here. In the most general sense, susceptibility is boundary layer reaction to stimulated action governed by the nature and intensity of its appearance [3, 4]. This formulation and approach to the problem are due to the presence of a broad circle of physical and practical problems associated with boundary layer perturbation by some method for any flow mode therein, laminar, transitional, or turbulent. In the general case the boundary layer reaction is reflected in a change in a whole set of parameters characterizing its state, including the thermal characteristics also.

In this connection, the problem can be examined of the possibilities of boundary layer control in order to intensify heat transfer processes on the basis of methods and results of studying susceptibility.

From the viewpoint of controlling the boundary layer structure to intensify heat transfer it is expedient to apply measures directed, depending on the Prandtl number, to either the organization of stable large-scale motions of the medium or to regulation of the processes in a viscous sublayer and its parameters. Utilization of the susceptibility concept affords the possibility, firstly, of representing the heat transfer mechanisms with greater depth, and secondarly, of planning purposefully and with a predictable result the application of some facilities as a function of the problem being solved.

One of the traditional means for raising the heat elimination is based on using the flow nonuniformity (particularly separation phenomena) because of local boundary layer perturbation. The flow around a single obstacle is a specific realization of such a method referring to the first group. An experimental investigation of the influence of a two-dimensional obstacle on heat transport regularities was performed in a turbulent boundary layer of a flat lower wall of a wind tunnel with 0.3 × 0.3 × 2.5 m working section for U_∞ = 20 and 40 m/sec and $\varepsilon \approx 0.1\%$. The dimensionless height of the obstacle was H/δ_0 = 0.1-0.67 for a relationship b/H = 0.6-1.2. The measurement technique and the method of determining the local heat elimination, kinematic and dynamic boundary layer parameters are described in [5, 6]. The change in the kind of flow in the boundary layer is expressed in the formation of three zones downstream of the obstacle (recirculation, attachment, and relaxation). The flow configuration and extent of each of the zones depend on the height and shape of the obstacle as well as on the stream velocity and the turbulence conditions [5]. The intensity of the boundary layer reaction is determined by the degree of change in the hydrodynamic and thermal characteristics. An abrupt increase in the heat elimination is observed in the first zone where large-scale vortex configurations are formed because of flow separation. The heat elimination reaches a maximum in the flow attachment domain (x/H = 6-12) while it diminishes gradually in the relaxation domain because of restoration of the boundary layer structure. The energy redistribution between the spectrum components of the longitudinal fluctuation

Institute of Physicotechnical Problems of Power, Academy of Sciences of the Lithuanian SSR, Kaunas. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 6, pp. 916-924, June, 1989. Original article submitted January 6, 1988.

0022-0841/89/5606-0631$12.50

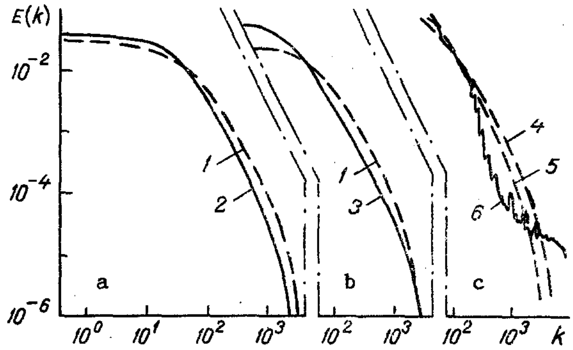

Fig. 1. Power spectral density of longitudinal velocity fluctuations in a turbulent boundary layer behind a two-dimensional obstacle (a and b) and cascade of vortex generators (c): a) curve 1 is measurements in an unperturbed boundary layer (without an obstacle, H = 0), U_∞ = 24.7 m/sec, x = 1.89 m, y/δ_0 = 0.01, 0.04 and 0.19; curve 2 is measurements in the attachment zone (H = 10 mm): x/H = 12, y = 0.4 mm; b) curve 1 is measurements in the unperturbed boundary layer and in the relaxation zone for y = 0.4 mm (H = 10 mm, x/H = 120), curve 3 is measurements in the relaxation zone for y = 10 and 20 mm (H = 10 mm, x/H = 120); c) curves 4 and 5 are for the unperturbed boundary layer and y/δ = 0.05 and 0.2; curve 6 is for a turbulent boundary layer perturbed by a cascade of vortex generators U_∞ = 0.56 m/sec; x = 2.4 m; y/δ = 0.17; λ_z = 12 mm; z = 0. E, m; k, m^{-1}.

velocity for the attachment (x/H = 12) and relaxation (x/H = 120) zones is displayed in Figs. la and b. It should be noted that in the case of an unperturbed boundary layer the spectrum curves 1 obtained for three values of y in the near-wall domain are in practically mutual agreement. The same effect is observed also for measurements in the attachment zone (curve 2), however at considerably greater distances from the wall, which indicates a sufficiently homogeneous turbulence structure in the normal direction. The perturbed motion is characterized in its spectrum comopsition here by predominance of low-frequency components as compared with curves 1 and also by diminution of the relative energy of components of the spectrum inertial subdomain, where curve 2 follows the law $k^{-5/3}$ in a large range of wave numbers. Homogeneity of the turbulence holds in the relaxation zone only upon removal from the wall: the spectrum curves 3 agree for y = 10 and 20 mm reflecting the same feature was curve 2. Therefore, starting with the attachment zone upon formation of a new boundary layer, the perturbed flow domain is forced back from the streamlined surface. The fact that the turbulence spectrum in the near wall domain is here (curve 4) not different from the unperturbed boundary layer spectrum indicates this. In other words, boundary layer reaction to the perturbation introduced by the obstacle appears most intensively and stably for the external flow domains; the boundary layer in the near-wall domain restores the initial properties sufficiently rapidly, which is one of the reasons for diminution of the heat elimination in the relaxation zone.

The restoration process follows well the velocity profiles measured at different sections x downstream of the obstacle (Fig. 2). The characteristic feature of the profiles of the average longitudinal velocity component in the relaxation zone is the appearance of inflection points on the obstacle height. If this is treated from the susceptibility aspect then the boundary layer state and development can be determined by starting from the principle of superposition of inviscid unstable flows on turbulent flow. The inviscid instability is characterized by the presence of perturbations undamped as the Reynolds number grows in the domain of small wave numbers. One the one hand this can explain the form of the spectrum curves with the ascent into the low-frequency part (see Fig. 1), and on the other, the excess of the heat elimination coefficient over its magnitude for the unperturbed boundary layer at significant distances downstream [6].

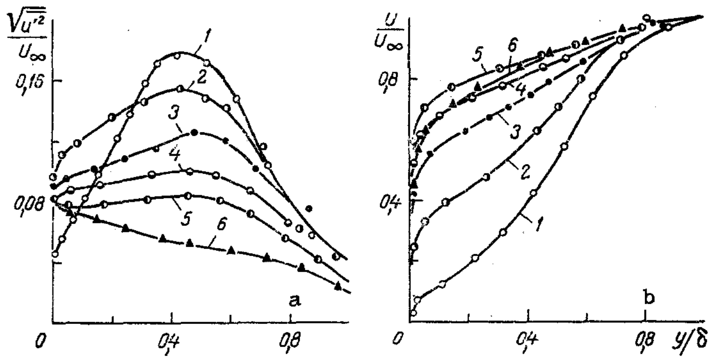

Fig. 2. Profiles of the fluctuation (a) and average (b) longitudinal velocity components measured at a different distance x/H downstream of the two-dimensional obstacle for $h/\delta_0 = 0.35$, $Re = 8.56 \cdot 10^5$: 1) x/H = 10; 2) 20; 3) 40; 4) 60; 5) 88; 6) H = 0, $Re = 2.7 \cdot 10^6$.

Measurements of the fluctuation velocity u' profiles (Fig. 2a) showed that at the beginning of the relaxations zone as the general fluctuation level is raised, their maximum is approximately at the height of the upper edge of the obstacle. Downstream this maximum is displaced from the wall, the total fluctuation level drops, and a second maximum appears near the surface. It becomes dominant with distance from the obstacle and the profiles are reproduced in a form characteristic for the unperturbed boundary layer.

Formal criteria for flow nonequiilbrium in the boundary layer (inflections of the mean velocity profiles, modification of the fluctuation and spectrum characteristics) appear even upon boundary layer excitation by methods, underlying which is production of a perturbation of a definite kind [3, 7, 8]. In contrast to the case considered, the type, intensity, and scale of the perturbations being generated can be given beforehand and controlled and also the boundary layer reaction can be predicted by using results of studying the susceptibility. Hence, investigations of the boundary layer reaction to the introduced plane waves and three-dimensional perturbations in the form of a system of longitudinal vortices. The technical facilities for the generation of such perturbations (a vibrating plate [3, 7] and a vortex generator cascade [4-8]) can be considered as modified two-dimensional obstacles: mobile and discrete. Depending on the plate width in the first case, the amplitudes and frequencies of its vibrations, realization is possible of both nonvortical and vortical flow in the boundary layer in the form of a nonsymmetric vortex street. In the second case, the magnitude of the vortex generators governs the intensity while the distance between adjacent vortex generators λ_z is the perturbation scale (the transverse dimensions of a pair of oppositely rotating longitudinal vortices). Vortex generators in the form of thin plates whose upper part was split forming a swept wing directed upstream in planform. The wing had a rounding off to give a spin-off to vortices shedding from the trailing edge. The vortex generator profiles (II and III) are shown in Fig. 3. The vortex generators were mounted in a row perpendicular to the flow at a distance λ_z whose magnitude was determined from the condition for the existence of a natural transition form the laminar to the turbulent flow in the section for a system of longitudinal vortices separated by a definite spacing.

The problem of boundary layer susceptibility to perturbations of a given kind is separated into three parts. The first was solved within the framework of linear stability theory: the introduced plane perturbations wre small and their parameters were chosen from the condition of their downstream amplification [3, 9]. While keeping the wave nature of the perturbations inserted in the second part of the problem, their amplitude was chosen finite and the frequency corresponded, according to the stability diagram, to damped vibrations, where the possibility of vortex street generation was realized. The third part of the problem was investigation of the boundary layer reaction to the introduced longitudinal vortex perturbations.

Experiments were performed on the flat bottom of a hydrodynamic test stand [9] with working section dimensions 0.25 × 0.1 × 3 m and a regulatable turbulence level $\varepsilon = 0.05$-10% in the $U_\infty = 0.03$-0.6 m/sec velocity range. The velocity field was recorded by using photography of the visualized flow (dye streaks [7] or an electrochemical tellurium method [9]) and measurements by a laser anemometer [3, 4].

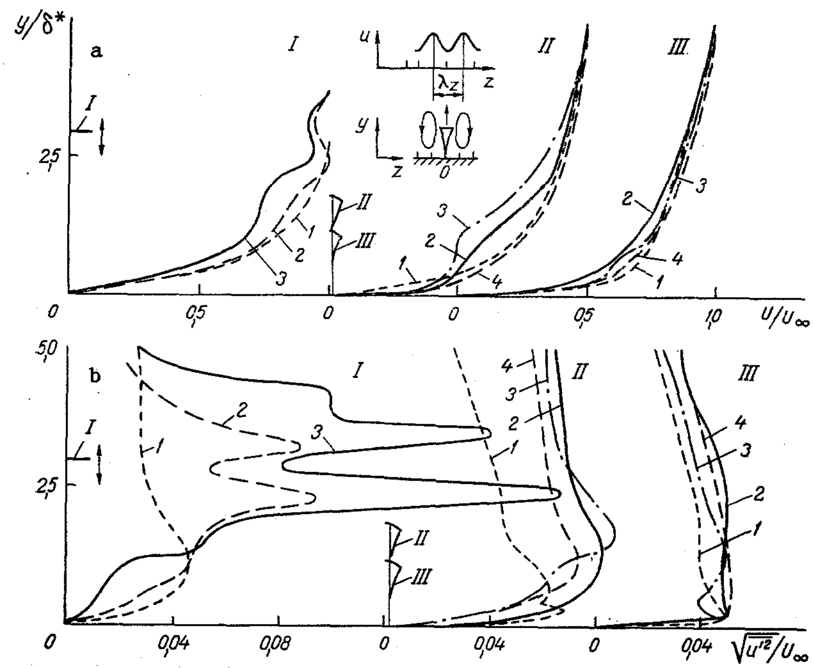

Fig. 3. Profiles of the mean (a) and fluctuation (b) longitudinal velocity components: I) upon boundary layer excitation on a vibrating plate: $Re^* = 200$, $H = 15$ mm, $A = 1$ mm, $f = 2$ sec^{-1}; the curve 1 is measurements without the plate; curves 2 and 3 are measurement with the plate whose width equals 2 and 15 mm, respectively; II, III) upon introduction of perturbations by using a cascade of vortex generators in the transitional and turbulent boundary layers: $Re = 4 \cdot 10^5$ and $1.3 \cdot 10^6$, respectively; $\lambda_z = 12$ mm, curve 1 is for the unperturbed boundary layer, curves 2-4 are measurements at a distance $x/H \approx 10$ downstream of the vortex generator cascade; 2 for $z = 0$; 3) $z = \lambda_z/4$; 4) $z = \lambda_z/2$.

It was established in the first part of the problem that the excitation of a laminar boundary layer results in acceleration of the transition. The natural vibrations occurring in the boundary layer rapidly become three-dimensional, as is expressed by the appearance of inflection points on the profiles U(y) and two maximums, twice as great as the maximum for the turbulent boundary layer in magnitude, on the u'(y) profiles. Susceptibility of the pre-turbulent and turbulent boundary layers to plane perturbations (even somewhat increases in amplitude) appears less substantially and is characterized by a certain diminution in the fluctuation level. Therefore, despite the stimulation of the accelerated development of vortex perturbations, such actions influence the boundary layer insufficiently effectively.

When formulating the second part of the problem, the dimensionless plate vibration frequency, selected by starting from their stability at the site of generation $Re^* = 200$, was $\beta_r \nu/U_\infty^2 = 4 \cdot 10^{-3}$, which corresponded to the dimensional frequency 1 sec^{-1} [7]. The vibration amplitude was increased to 1 mm, the plate width was 2 mm (as in the first case) and 15 mm, while the plate height above the surface was $H = \delta_0 = 15$ mm. Visualization of the perturbed flow field showed that the nonsymmetric vortex sheet that forms depends on the plate width and the amplitude and frequency of its vibrations. Laser anemometer measurements of the velocity profiles U(y) and u'(y) are represented in Fig. 3 (I) and the position of the vibration plate in y/δ_0^* is shown in the ordinate axis. It is seen from the figures that even for a finite vibrations amplitude a two-millimeter plate produces perturbations that damp out rapidly along the normal to the surface. Although the velocity profiles become close in form to the profiles typical for a boundary layer with longitudinal vortex perturbations propagating therein, this similarity remains purely formal. The boundary layer does not sustain, "does not perceive" the perturbations introduced. An increase in the vibrating plate width results in a boundary layer perturbation over its whole thickness. However, the quantity u' drops near the streamlines surface and the maximum fluctuation velocity is concentrated, as before, in the wake behind the plate. This means that, as in the case of an obstacle

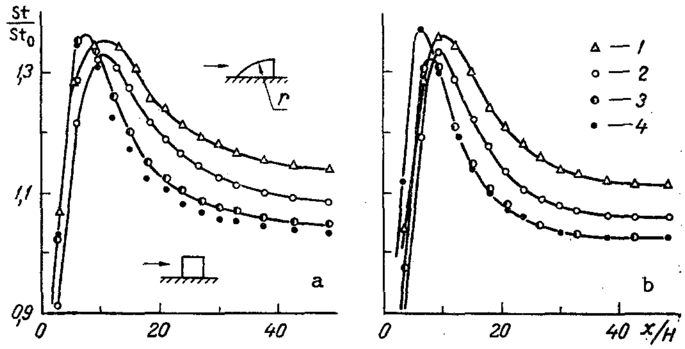

Fig. 4. Influence of rounding off of the leading edge on the heat elimination increment behind an obstacle in an air flow: 1) r = 0; 2) r = H; 3) 4H; 6) 8H; a) Re = $8.5 \cdot 10^5$; $H/\delta_0 = 0.37$; b) Re = $1.7 \cdot 10^6$; $H/\delta_0 = 0.35$.

mounted on a surface, the greatest influence of the perturbing factor is observed in the external domain of the boundary layer.

Therefore, kinematic boundary layer singularities corresponding to different kinds of perturbing motion permit making the deduction that longitudinal vortex structures contribute to the best mixing of the medium (large velocity gradients $\partial u/\partial y$, magnitudes u', the presence of two maximums in the u'(y) profiles). This is confirmed by results of an experimental investigation of the natural and forced convection. It is known that the main kind of flow instability above concave and heated surfaces is associated with perturbations in the form of longitudinal vortices. Conditions for the appearance of large-scale secondary flows of this kind [10, 11] can be produced in a turbulent boundary layer also. It is established that the origination of longitudinal vortices in a boundary layer is accompanied by an abrupt increase in the heat elimination [11, 12]. But the intensity of the perturbations themselves depends on the degree of velocity field inhomogeneity in the transverse direction.

Heat and mass transfer processes occurring in a stream with longitudinal vortex structure are chracterized by still another important feature. The friction coefficient takes on a minimal value in the formation of longitudinal vortices in a boundary layer (preturbulent transition domain) despite the high level of velocity fluctuations exceeding the level of the developed turbulent boundary layer [13]. This fact was also remarked by Klebanoff and was explained by the slight correlations between the fluctuation velocities u' and v'. Moreover, the minimal hydraulic losses because of the formation of longitudinal vortices in the flow around smoothly outlined obstacles wre mentioned in [14, 15]. Results of measuring the heat elimination in the attachment zone behind poorly and well streamlined obstacles [15] are presented as an illustration of the last assertion in Fig. 4. It turns out that the heat elimination intensity is not only not diminished as the streamlining of the obstacle increases, as should follow by analogy with the regularity of the change in friction drag, but even increases somewhat. The fact itself of the diminution of the recirculation zone length indirectly reflects the growing ordering of the separation flow structure.

It should be noted that the longitudinal vortices occurring in a natural manner are characterized by irregulatiry, nonstationarity, and consequently, rapid destruction. Hence, artificial formation and maintenance of the mentioned flow configurations near the surface is expedient for the solution of heat and mass transfer problems. Both the kinematic flow characteristics and the results of direct measurement of the heat paameters might be a criterion of the efficiency of the longitudinal vortices being generated. The methods for exciting a system of ordered longitudinal vortices in a boundary layer are based on producing inhomogeneities, periodic in z, in the flow around the surface. This is achieved by using arrangement of the vortex generator cascade along z [4, 8] or organizing the influence of the surface itself on the flow field because of the regular change of the properties of this surface, temperature or other characteristics, say, [4], along z.

Laser anemometer measurements of the mean and fluctuation longitudinal velocity components in the boundary layer are represented in Fig. 3 (II, III) during excitation of a system of longitudinal vortices therein by using vortex generators. The spacing between adjacent vortex generators governs the scale λ_z of the three-dimensional perturbations introduced. Displayed schematically in the upper part of Fig. 3a (II) are a longitudinal vortex section in the yz plane, and a wavelike profile of the velocity U(z) corresponding to such a profile, and the measurement sections are shown: displayed on the left in dimensionaless form are vortex generator profiles for the given II and III. The measurements were performed in three z sections: z = 0 (i.e., downstream of the vortex generator, the streamlines are directed upward), $z = \lambda_z/4$ (in the neighborhood of a longitudinal vortex axis) and $z = \lambda_z/2$ (in the gap between adjacent vortices, the streamlines are directed downward). It is seen that the average profiles acquire inflection points (except the profile 4 which becomes more filled than unperturbed), and the maximums of the fluctuation profiles shift from the wall as the general level of the fluctuations increases. Comparison of the series of curves II for the transition and III for the turbulent boundary layer shows that the latter is an inertial system from the viewpoint of transformation of its structure. However, even therein it turns out to be possible to have a flow type modification by using excitation of vortices of a given scale and intensity.

A certain analogy between the flow behind an obstacle and a cascade of vortex generators is manifest even upon comparing the spectrum characteristics. The troughs in the inertial subdomain of the turbulent boundary layer spectrum perturbed by a vortex generator cascade (Fig. 1c) agree with changes in the spectrum curves (Fig. 1a and b) obtained in measurements behind a two-dimensional obstacle. However, because of the direction action of the vortex generators on the scale of turbulence, the changes are expressed more substantially in this case.

It can therefore be concluded that methods of studying the susceptibility are a useful instrument for extending the results of different actions on a boundary layer in the interests of heat transfer intensification. It follow from these investigations that purposeful generation of vortex configurations results in growth of the role of the low-frequency part of the turbulence energy spectrum and diminution of the dissipative losses. The criteria for such ordering start to appear when utilizing two-dimensional obstacles of conveniently streamlined shape and can be strengthened substantially by using discrete vortex generators. The most favorable conditions for longitudinal vortex generation hold in the Reynolds transition number domain.

Generation of an ordered vortex configuration in the developed turbulent flow domain is a more complex problem and requires substantial energy expenditures. However, it should be kept in mind that different flow modes hold in a turbulent boundary layer. During the flow over a rough surface the roughness elements excite a transient in the near-wall viscous layer that is similar in its physical substance to the direct transition from laminar into turbulent flow. If a definite kind of roughness, in the form of three-dimensional uniformly distributed projections of small height, say [15], is used, then a stable configuration of artificial fine-scaled vortices is formed near the wall. This results in attenuation of the turbulence generation intensity and a drop in the heat elimination at Prandtl numbers close to 1. However, for Pr >> 1 the heat elimination in the mode of partial appearance of roughness is just always elevated because of the concentration of the resistance to heat transfer in the near-wall layer. Consequently, there is the possibility of an additional elevation of the heat elimination efficiency for Pr >> 1 by generation of an optimal vortex configuration at the wall, that would significantly raise the efficiency of a smooth surface even without it. Raising the heat elimination efficiency in a gas flow should be realized by a combination of the actions on diminishing turbulence generation in the shortwave range and on increasing the large-scale mixing in the whole flow section.

NOTATION

x, y, z, longitudinal, normal, and transverse coordinate axes; U_∞, free stream velocity; U, u', longitudinal components of the mean and fluctuation velocities in the boundary layer; v', normal component of the fluctuation velocity; Re, Re*, Reynolds numbers along the displacement length and thickness; St, Stanton number; A, f, amplitude and frequency of the vibrating plate; b, H, width and height of the obstacle; r, radius of curvature of an obstacle with a rounded off leading edge; E, power spectral density of the longitudinal velocity fluctuations; k, wave number; δ_0, unperturbed boundary layer thickness; δ^*, displacement thickness; δ^{**}, loss of momentum thickness; β_r, circular frequency of the plane perturbations; λ_z, wavelength of the longitudinal vortex perturbations along z; ν, kinetic viscosity coefficient.

LITERATURE CITED

1. E. Reshotko, Ann. Rev. Fluid Mech., 8, 311 (1976).
2. Yu. S. Kachanov, V. V. Kozlov and V. Ya. Levchenko, Origin of Turbulence in the Boundary Layer [in Russian], Novosibirsk (1982).
3. V. V. Babenko, V. P. Ivanov, and N. F. Yurchenko, Avtometriya, No. 3, 91-96 (1982).
4. V. V. Babenko and N. F. Yurchenko, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 6, 68-74 (1985).
5. A. A. Shlanchyauskas, A. A. Pyadishyus, and G. P. Zigmantas, Heat and Mass Transfer-VI [in Russian], 1, Pt. 2, 185-199, Minsk (1980).
6. A. A. Pyadishyus and G. P. Zigmantas, Turbulent Transfer Problems [in Russian], Minsk (1979), pp. 113-122.
7. V. V. Babenko, L. F. Kozlov, S. A. Dovgiy, et al., Proc. IUTAM Symp., 509-513, Novosibirsk (1984).
8. N. F. Yurchenko, Inzh.-Fiz. Zh., 41, No. 6, 996-1002 (1981).
9. L. F. Kozlov and V. V. Babenko, Experimental Boundary Layer Investigations [in Russian], Kiev (1978).
10. R. N. Meroni and P. Bradshaw, AIAA J., 13, No. 11, 43-50 (1975).
11. V. K. Shchukin, Heat Transer and Hydrodynamics of Internal Flows in Mass Flow Fields [in Russian], Moscow (1970).
12. R. R. Gilpin, H. Imura, and K. Ts. Chen, Heat Transfer [Russian translation], No. 1, 74-82 (1978).
13. V. V. Babenko and N. F. Turchenko, Hydromechanics [in Russian], No. 53, 41-47 (1986).
14. É. K. Kalinin, G. A. Dreitser, and S. A. Yarkho, Intensification of Heat Transfer in Channels [in Russian], Moscow (1981).
15. A. A. Pyadishyus and A. A. Shlanchyauskas, Turbulent Heat Transfer in Near-Wall Layers [in Russian], Vilnius (1987).

ASYMPTOTIC THEORY OF THE SPREADING OF PARTIALLY WETTING LIQUID

K. B. Pavlov, A. S. Romanov, and A. P. Shakhorin

UDC 541.24

A mathematical model of the spreading of liquid along a plane solid surface is constituted for a finite equilibrium angle of wetting.

There is presently no closed consistent method of describing the spreading of a partially wetting liquid along a dry surface by methods of continuum mechanics. The basic reason for this is the incompatibility of the equations of motion of the viscous liquid and the adhesion conditions at a solid surface close to the line of three-phase contact [1, 2].

In [3, 5], it was proposed to resolve this contradiction by specifying the slip of the spreading liquid relative to the solid surface. However, the reason for the appearance of the contact angle θ and its dependence on the velocity of motion of the line of three-phase contact remains unclear here.

In [6, 7], it was proposed to reject any consideration of the liquid-film motion at small thicknesses $h < h_m$, $h_m \sim 10^{-10}$ m close to the film boundary, because of the inapplicability of the hypotheses of continuum mechanics there. In this case, the corresponding boundary problem is unclosed, since the angle of slope of the free surface $\theta(h_m)$ and the velocity of motion of the film boundary are specified quantities.

It was noted in [8, 9] that the reason for the formation of a contact angle is the additional "splitting" pressure arising in thin liquid layers on account of the action of Van der Waals forces. Van der Waals forces are diffuse in character, and appear at distances of the order of $\ell \sim 10^{-6}$-10^{-7} m, $\ell >> h_m$. Therefore, the action of the splitting pressure may be included in the hydrodynamic description of the spreading of liquid films. Analysis of the correspondingly modified equations of liquid-film motion may be formally extended into the region $h < h_m$ up to the film boundary $h \to +0$ [6, 10].

N. É. Baumann Moscow Higher Technical School. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 6, pp. 924-930, June, 1989. Original article submitted December 8, 1987.