8. P. Ya. Cherepanov, in; Processes of Turbulent Transfer [in Russian], Minsk (1985), pp. 56-74.
9. Yu. M. Dmitrenko, in: Structure of Turbulent Flows [in Russian], Minsk (1982), pp. 82-90.

CALCULATION OF GAS MOTION AND HEAT TRANSFER AT THE PERIPHERY OF A CYCLONE STREAM

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UDC 533.6.011:536.244.45

Methods of generalizing test data and calculating friction and convective heat exchange at the lateral surface of a cyclone chamber are discussed on the basis of an analysis of flow at the boundary of the wall region.

The investigation of convective heat exchange in the wall region of a cyclone stream is very timely at present. It has been established that the action of inertial mass forces on the hydrodynamics leads to considerable intensification of heat transfer to the lateral surface of a chamber in comparison with straight flows under similar conditions [1, 2]. In this connection, there is a considerable interest in generalizing the available test data on heat transfer from unified standpoints, allowing for the peculiarities of the hydrodynamics of a swirled stream.

We will take the swirled stream in the core of the flow out to the end surfaces as axisymmetric, incompressible, quasiisothermal, and with constant physical properties. The highest velocity w_φ in the core of cyclone flow varies along the radius r in a complicated way. We assign the characteristic form of the distribution $w_\varphi = w_\varphi(r)$ in the peripheral region, just as in the axial region [3], using a generalized approximating function,

$$\bar{w} = \left(\frac{2\eta}{1+\eta^{\varkappa}}\right)^{n}, \tag{1}$$

where n is a coefficient determined by the conditions of generation of the swirling and κ is a constant.

The distribution of the tangential velocity component at $1 \le \eta \le \eta_c$ can be calculated from Eq. (1), in which n is found from the condition of a maximum of $\bar{\Gamma} = \bar{w}\eta$ [4] at the outer boundary r_c of the "quasipotential" zone (Fig. 1a),

$$\left(\frac{\partial \bar{\Gamma}}{\partial \eta}\right)\Big|_{\eta=\eta_c} = \frac{\partial}{\partial \eta}\left[\left(\frac{2\eta}{1+\eta^{\varkappa}}\right)^{n}\eta\right]\Big|_{\eta=\eta_c} = 0, \tag{2}$$

$$n = n_c = \frac{1+\eta_c^{\varkappa}}{(\varkappa-1)\eta_c^{\varkappa}-1}. \tag{3}$$

The value of the coefficient κ has been chosen from the best agreement of calculated and test data on the coefficient of twist in the stream core:

$$\varepsilon_c = w_{\varphi m}/w_{\varphi c} = \left(\frac{1+\eta_c^{\varkappa}}{2\eta_c}\right)^{\frac{\eta_c^{\varkappa}+1}{(\varkappa-1)\eta_c^{\varkappa}-1}}. \tag{4}$$

As can be seen from Fig. 1b, the test data are described quite satisfactorily by the equation for a straight line [5]

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$$\varepsilon_c = 0{,}5(1+\eta_c), \tag{5}$$

which actually is an approximation of the function (4) for $\kappa \approx 2.055$.

The gas motion at the boundary of the wall region (at $\eta = \eta_c$) can be treated approximately as spiral motion.

In the general case with localized stream entry, the value of r_c varies along the length of the chamber (Fig. 1). The radial extent of the wall zone is greatest in the entrance cross section ($r_{c,x} = r_{c,o}$), while at a certain distance $x_{b.l}$ from the entry point the width of the peripheral region is limited to the thickness of the wall boundary layer ($r_{c,x} = r_{b.l}$).

The law of variation of the dimensionless velocity at the boundary of the core of the flow along the length of a cyclone chamber is nearly linear, as an analysis of test data shows. Using the relation (5), we obtain

$$\bar{w}_{c\,x} = \frac{2}{1+\eta_{c\,x}} = \frac{2}{1+\eta_{c\,0}}\left(1-\frac{\eta_{b.l}-\eta_{c,0}}{1+\eta_{b.l}}X\right). \tag{6}$$

From Eq. (6) we find the connection between the dimensionless boundary of the stream core and the longitudinal coordinate,

$$\eta_{c,x} = \frac{(1+\eta_{c,0})(1+\eta_{b.l})}{1+\eta_{b.l}(1-X)+\eta_{c,0}X} - 1. \tag{7}$$

The values of $\eta_{c,o}$, $\eta_{b.l}$, and $x_{b,l}$ must be assigned from test data or an analysis of the corresponding dynamic problem for the wall region of flow [9-11]. It has been established that broadening or narrowing of the jet can occur, depending on the ratio of the velocities of the peripheral and comoving streams. Up to the main radial cross section, characterized by the coordinate angle $\varphi = 0$ (Fig. 1a), the thickness of the wall boundary layer is $\delta = 0.5h_{en}$. As the jet propagates in the initial section, the wall maximum of tangential velocity shifts toward the lateral surface [9, 10],

$$\bar{\delta} = \delta/h_{en} = \exp(-1{,}145\varphi), \tag{8}$$

where φ is in radians.

In the main section $(\varphi > \varphi_i)$ the flow has features characteristic for semiconfined wall jets in a comoving stream. Here the differences in the distrubutions of w_φ for jets formed by entrance channels of rectangular and round cross sections [10] disappear. In the wall boundary layer the radial velocity profile is well described by a "1/14" power law. The thickness of the wall boundary layer varies (grows) by a practically linear law,

$$\bar{\delta} = 5{,}725\cdot 10^{-3}\varphi/\bar{h}_{en}. \tag{9}$$

Below the entrance cross section the individual features of the jet degenerate rapidly and the stream flow becomes practically axisymmetric. Under these conditions the variation of δ along the length of the chamber, especially for distributed entry of gases into the working volume of the cyclone, is not very pronounced [12] and can be ignored in a first approximation when solving the thermal problem. As the characteristic value of δ we take the thickness in the cross section $\varphi = \varphi_{b.l}$.

$$\delta_{b.l} = B[2\pi - \arccos(1-2\bar{h}_{en})]D, \tag{10}$$

where $B = 2.8625\cdot 10^{-3}$. The calculated values of $\delta_{b.l}$ are in satisfactory agreement with the average δ along the length of a cyclone chamber with peripheral gas entry [13]. Hence,

$$\eta_{b.l} = (R-\delta_{b.l})/r_{\varphi m} = \eta_{ch} - 2B[2\pi - \arccos(1-2\bar{h}_{en})]/\bar{r}_{\varphi m}. \tag{11}$$

Reduction of the equation of averaged motion in the form of the transfer of vorticity to dimensionless form (through the choice of the normalizing quantities $\omega_{c,o}$ and D) enables us to distinguish the determining Reynolds number in the thermal problem:

$$\mathrm{Re}_{\omega_{c,0}} = \omega_{c,0}D^2/\nu = 2\mathrm{Re}_{\varphi c,0}/\bar{r}_{c,0}. \tag{12}$$

In the calculations $\mathrm{Re}_{\varphi c,0}\, w_{\varphi c,0}$ was determined from the recommendations of [9, 14]. In accordance with (12), the complex $K_c = 1/\bar{r}_{c,0}$ was taken as the dimensionless similarity number allowing for the influence of the chamber geometry on the properties of the stream flow in

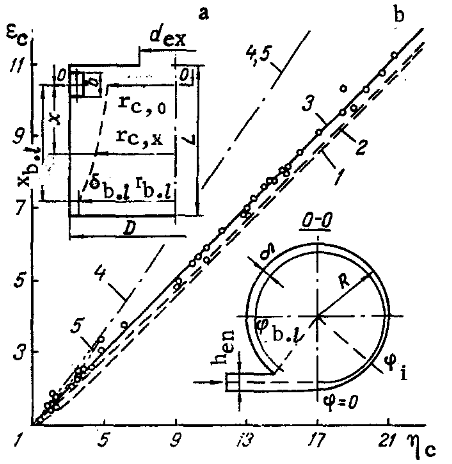

Fig. 1

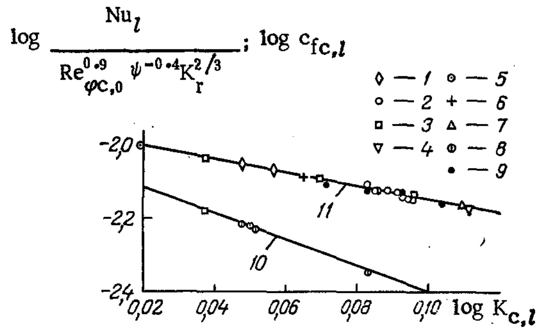

Fig. 2

Fig. 1. Determination of the radial boundary of the core of a cyclone stream (a) and generalization of test data on the coefficient of twist ε_C (b): test points are the authors' data; 1) calculation from Eq. (1) with $n = 1$ and $\kappa = 2$ [6]; 2) (4) with $\kappa = 2$ [4]; 3) (5); 4) by the method of [7]: $\varepsilon_C = \eta_C/1.4\cdot[1 - \exp(-1.251\eta_C^2)]^{-1}$; 5) by the method of [8]: $\varepsilon_C = [(1 + \eta_C^2)/2]^{1/2}$.

Fig. 2. Generalization of experimental data on friction and heat transfer at the lateral surface of a cyclone chamber: 1) [16]; 2) [17]; 3) [18]; 4) [19]; 5) [20]; 6) [21]; 7) [22]; 8) [23]; 9) [24]; 10) calculation from Eq. (16); 11) (17).

the wall region. (We note that the complex $(1 - \bar{r}_{C,0})^3/\bar{r}_{C,0}$, similar in form, was obtained earlier in [15]).

In the generalization of test data on heat transfer in cyclone chambers with localized entry, when r_C varies along the length of the chamber, instead of $\mathrm{Re}_{\omega C,0}$ we must use the local Reynolds number,

$$\mathrm{Re}_{\omega_C,x} = 2K_{C,x}\mathrm{Re}_{\varphi C,0}, \tag{13}$$

in which $K_{C,x} = 1/\bar{r}_{C,x} = \eta_{ch}/\eta_{C,x}$.

Thus, experimental data on local heat transfer can be represented in the form of the functional dependence

$$\mathrm{Nu}_x = A_1 K_{C,x}^{m_1}\mathrm{Re}_{\varphi C,0}^{n_1}, \tag{14}$$

where A_1, m_1, and n_1 are constants found from experiment.

The average values of α along the length of the chamber are calculated from (14) with $K_{C,x}$ replaced by $K_{C,l} = \eta_{ch}/\eta_{C,l}$, where

$$\eta_{Cl} = \int_0^1 \eta_{C,x}\,dX = \frac{(1+\eta_{C,0})(1+\eta_{b.l})}{1+0{,}5(\eta_{C,0}+\eta_{b.l})} - 1. \tag{15}$$

An approach similar to that discussed above is also possible in the analysis of experimental data on frictional shear stress at the lateral surface of a cyclone chamber.

In Fig. 2 we show a generalization of the results of investigations of friction and heat transfer with allowance for the influence of the temperature factor and wall roughness [16, 17]. The test points correspond sufficiently well (with a root-mean-square deviation not exceeding ±7%) to the similarity equations

$$c_{fC,l} = 0{,}009K_{C,l}^{-3,6}; \tag{16}$$

$$\mathrm{Nu}_l = 0{,}0109K_{C,l}^{-1,8}\mathrm{Re}_{\varphi C,0}^{0,9}\psi^{-0,4}K_r^{2/3}. \tag{17}$$

Equation (16) is valid for $K_{c,l}$ = 1.045–1.3 and $Re_{\varphi c,0} = 3.2\cdot 10^5 - 10^6$ and Eq. (17) is valid for ψ = 0.5–1.25, $K_r = F_r/F_{sm}$ = 1–2, and $Re_{\varphi c,0} = 6.3\cdot 10^4 - 10^6$.

At the bottom of the analysis of heat transfer by the internal method we place a relation of the type

$$\frac{d}{dr_{c,0}}\int_0^{\delta_{t.l}} w_\varphi \vartheta dy = \frac{q_w}{\rho c_p}. \tag{18}$$

Earlier [9, 10] it was shown that the formation of the wall boundary layer in the main section and along the length of a cyclone chamber is determined primarily by the geometrical characteristics of the entrance channel: $\bar{h}_{en}$ and $\bar{f}_{en}$. The influence of these parameters on $\delta_{b.l}$ can be taken into account in generalized form by the radius $r_{c,0}$ of the stream core. Calculations from Eq. (10) show that the thickness of the boundary layer is small compared with the characteristic linear size, the chamber diameter, so that the influence of the curvature of the layer on the heat transfer can be neglected and the latter can be taken as plane. Assigning the distributions of tangential velocity and excess temperature in the wall layer by the power-law functions $w_\varphi/w_{\varphi b.l} = (y/\delta)^m$ and $\vartheta/\vartheta_{t.l} = (y/\delta)^m$ and defining $\tau_{\varphi w}$ and q_w as

$$\tau_{\varphi w} = \rho(\nu + \varepsilon_\sigma) dw_\varphi/dy,$$

$$q_w = \rho c_p (a + \varepsilon_q) d\vartheta/dy$$

with allowance for $\nu \ll \varepsilon_\sigma$ and $a \ll \varepsilon_q$ we obtain the expression

$$\frac{q_w}{\tau_{\varphi w} c_p} = \frac{1}{Pr_t}(\delta_{t.l}/\delta_{b.l})^{-m}\vartheta_{t.l}/w_{\varphi b.l} \tag{19}$$

We express the velocity $w_{\varphi b.l}$ at the boundary of the boundary layer through the characteristic velocity $w_{\varphi c,0}$ from Eq. (6) at X = 1:

$$w_{\varphi b.l} = \frac{1+\eta_{c0}}{1+\eta_{b.l}} w_{\varphi c 0}. \tag{20}$$

Using (20), we represent Eq. (19) in dimensionless form, isolating the Nusselt number of the left side,

$$Nu = \frac{c_{fc}}{2}\frac{Pr}{Pr_t}\frac{1+\eta_{b.l}}{1+\eta_{c0}}(\delta_{t.l}/\delta_{b.l})^{-m} Re_{\varphi c 0}, \tag{21}$$

where the friction law in the general case (in a broad range of $Re_{\varphi c,0}$) is

$$c_{fc} = A\, Re_{\varphi c 0}^{-z}. \tag{22}$$

Let us calculate the integral on the left side of Eq. (18):

$$\int_0^{\delta_{t.l}} w_\varphi \vartheta dy = \frac{1}{2m+1} w_{\varphi b.l}\vartheta_{t.l}(\delta_{t.l}/\delta_{b.l})^{m+1}\delta_{b.l}. \tag{23}$$

Substituting (23) into (18) using the heat-transfer Eq. (21), after transformations, leads to a differential equation of the Bernoulli type,

$$\frac{d}{d\eta_{c,0}}(\delta_{t.l}/\delta_{b.l})^{2m+1} + \frac{1}{1+\eta_{c0}}(\delta_{t.l}/\delta_{b.l})^{2m+1} = \frac{E}{(1+\eta_{c,0}^2)} Re_{\varphi c 0}^{-z}, \tag{24}$$

which has the solution

$$\delta_{t.l}/\delta_{b.l} = \left\{\frac{E}{\eta_{c0}+1}\ln[(\eta_{c0}+1)(\eta_{ch}+1)]\right\}^{\frac{1}{2m+1}} Re_{\varphi c,0}^{-\frac{z}{2m+1}}, \tag{25}$$

where

$$E = \frac{A}{B}\frac{2m+1}{4}\frac{\bar{r}_{\varphi m}(1+\eta_{ch})^2}{2\pi - \arccos(1-2\bar{h}_{en})}.$$

Substituting Eqs. (22) and (25) into (21) and allowing for ψ, we obtain the equation for calculating the local heat transfer or that averaged over the inner surface of a cyclone chamber,

$$Nu = \frac{A}{2}\frac{Pr}{Pr_t}\frac{1+\eta_{b.l}}{1+\eta_{c0}}\left\{\frac{E}{\eta_{c0}+1}\ln[(\eta_{c,0}+1)(\eta_{ch}+1)]\right\}^{-\frac{m}{2m+1}} Re_{\varphi c,0}^{n}\psi^{-0,4} = \frac{1}{2}\frac{Pr}{Pr_t} Ko\, Re_{\varphi c,0}^{n}\psi^{-0,4}, \tag{26}$$

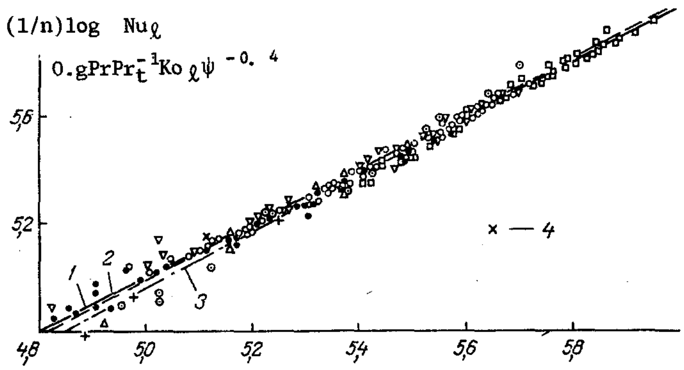

Fig. 3. Comparison of calculated functions with test data on average heat transfer: 1) calculation from Eq. (17); 2) (26); 3) (28); test points: 4) [26]; remaining notation same as in Fig. 2.

where $n=1-\frac{m+1}{2m+1}z$; Ko is a dimensionless complex allowing for the geometry of the cyclone chamber and reflecting the influence of the longitudinal coordinate on surface friction and heat exchange.

Equation (26) with m = 1/14, Pr = 0.7, $Pr_t \simeq 0.95$ [25], $A_l = 0.0486K_{c,l}^{-3.6}$ and z = −2/15 can be written in a form more convenient for use, similar to (17), replacing the cofactor Ko_l/A_l by $0.84K_{c,l}^{1.8}$ to within ±5%:

$$Nu_l=0{,}015\ K_{c,l}^{-1,8}\ Re_{\varphi c,0}^{0.875}\psi^{-0,4}. \tag{27}$$

A graphic interpretation of the test data and Eqs. (26) and (17) describing them is shown in Fig. 3. Also in good agreement with the calculated recommendations, as can be seen from Fig. 3, is the equation obtained in [27] when the friction law (22) is substituted into it:

$$Nu_l=0{,}044\ Re_*=0{,}00686\ K_{c,l}^{-1,8}\ Re_{\varphi c,0}^{0,933}\psi^{-0,4}. \tag{28}$$

NOTATION

R, D, L, radius, diameter, and length of the working volume of the cyclone chamber; F, lateral surface; h, height; r, x, current radius and longitudinal coordinate; y = R − r; δ, thickness of the boundary layer; $\bar{r} = r/R$; $\eta = r/r_{\varphi m}$, $X = x/x_{b.l}$, dimensionless current radius and longitudinal coordinate; φ, coordinate angle; $\bar{d} = d/D$, dimensionless diameter; $\bar{f} = 4f/\pi D^2$, dimensionless area; w_φ, ω, tangential and angular velocities of rotational motion; $\bar{w}$, $\bar{\omega}$, dimensionless (normalized to $w_{\varphi m}$ and $\omega_{\eta=1}$) tangential and angular velocitites; Γ, circulation of velocity; T, temperature; $\vartheta = (\mp T_w \pm T)$, excess temperature; $\psi = T_w/T_g$, temperature factor; q, heat-flux density; ρ, c_p, ν, a, density, isobaric specific heat, and coefficients of kinematic viscosity and thermal diffusivity, respectively; ε_σ, ε_q, turbulent analogs of ν and a; Pr, Pr_t, molecular and turbulent Prandtl numbers; τ_φ, tangential component of frictional stress; $c_f = 2\tau_\varphi/\rho w_{\varphi c,0}^2$, coefficient of frictional drag; V*, dynamic velocity; $Re_{\varphi c} = w_{\varphi c}D/\nu$, $Re_* = V_*D/\nu$, $Nu = \alpha D/\lambda$, Reynolds numbers and Nusselt number. Indices: w, quantity at the wall of the working volume; en, ex, entrance and exit quantities; m, quantity pertaining to the maximum value of a component of the linear velocity; c, quantity at the boundary of the stream core; sm, smooth; r, rough; x, local; l, averaged over length; b.l, t.l, quantities at the boundaries of the hydrodynamic and thermal boundary layers; dimensionless quantities are denoted by a bar above.

LITERATURE CITED

1. A. B. Reznyakov, B. P. Ustimenko, V. V. Vyshenskii, and M. R. Kurmangaliev, Principles of Heat Engineering of Cyclone Furnaces and Technological Processes [in Russian], Alma-Ata (1974).
2. V. K. Shchukin, Heat Exchange and Hydrodynamics of Internal Streams in Mass Force Fields [in Russian], Moscow (1980).
3. S. V. Karpov, Inzh.-Fiz. Zh., 47, No. 6, 892-903 (1984).
4. A. N. Shtym and P. M. Mikhailov, Izv. Vyssh. Uchebn. Zaved., Energ., No. 11, 50-53 (1965).
5. S. V. Karpov and É. N. Saburov, Topical Trends in the Development of Wood Drying [in Russian], Arkhangel'sk (1980), pp. 273-279.
6. L. A. Vulis and B. P. Ustimenko, Teploenergetika, No. 9, 3-10 (1954).
7. J. M. Burgers, Proc. Acad. Sci. Amsterdam, 43, No. 1, 2-12 (1940).
8. M. I. Deveterikova and P. M. Mikhailov, Informational Warrant, Adaptation, Dynamics, and Strength of Systems-74 [in Russian], Kuibyshev (1976), pp. 395-399.
9. É. N. Saburov, Aerodynamics and Convective Heat Exchange in Cyclone Heaters [in Russian], Leningrad (1982).

10. S. V. Karpov and É. N. Saburov, in: Scientific-Engineering Conference of Graduate Students and Young Scientists on the Comprehensive Utilization of Wood; Abstracts of Papers [in Russian], Arkhangel'sk (1977), pp. 52-54.
11. T. K. Luk'yanovich, "Aerodynamics of the peripheral zone of a cyclone chamber," Candidate's Dissertation, Engineering Sciences, Leningrad (1975).
12. A. Ogawa and Y. Fujita, J. Coll. Eng. Nihon Univ., A25, No. 3, 31-42 (1984).
13. É. N. Saburov and Yu. L. Leukhin, Inzh.-Fiz. Zh., 48, No. 3, 369-375 (1985).
14. S. V. Karpov and É. N. Saburov, Khim. Neft. Mashionstr., No. 7, 20-22 (1977).
15. É. N. Saburov and T. G. Zagoskina, Izv. Vyssh. Uchebn. Zaved., Lesn. Zh., No. 2, 131-137 (1978).
16. B. D. Katsnel'son and A. A. Shatil', Energomashinostroenie, No. 11, 8-13 (1959).
17. A. V. Tonkonogii and V. V. Vyshenskii, Probl. Teploenerg. Prikl. Teplofiz., No. 1, 183-205 (1964).
18. M. A. Bukhman, V. V. Vyshenskii, and B. P. Ustimenko, Probl. Teploenerg. Prikl. Teplofiz., No. 6, 184-194 (1970).
19. G. M. Druzhinin and A. V. Arseev, Gorenie, Teploobmen Nagrev Metalla, No. 24, 191-198 (1973).
20. V. V. Sterligov, V. F. Evtushenko, and V. P. Zaitsev, Izv. Vyssh. Uchebn. Zaved., Chern. Metall, No. 2, 165-169 (1974).
21. V. P. Voichak, V. E. Messerle, T. S. Tulegenov, and Kh. K. Shalina, Probl. Teploenerg. Prikl. Teplofiz., No. 11, 153-159 (1976).
22. V. N. Dolgov, A. P. Baskakov, and Yu. M. Goldobin, Inzh.-Fiz. Zh., 41, No. 4, 690-694 (1981).
23. G. N. Abramovich, M. A. Bukhman, and B. P. Ustimenko, Kompleskn. Ispol'z. Mineral. Syr'ya, No. 10, 10-15 (1980).
24. T. G. Zagoskina and É. N. Saburov, Rational Exploitation and Recovery of Natural Resources in the European North [in Russian], Arkhangel'sk (1980), p. 89.
25. A. Malhortra and S. S. Kang, Int. J. Heat Mass Transfer, 27, No. 11, 2158-2161 (1984).
26. J. Tomeczek and W. Komornicki, Int. J. Heat Mass Transfer, 27, No. 8, 1149-1155 (1984).
27. M. A. Bukhman and B. P. Ustimenko, Probl. Teploenerg. Prikl. Teplofiz., No. 7, 213-219 (1971).

COLLISION OF POLYMER PARTICLE WITH RIGID BARRIER

B. M. Khusid

UDC 536.25:532.135

The article establishes a correlation of the relaxation spectrum with the dissipation of kinetic energy of a polymer particle upon impact.

Impact of polymer particles against a rigid barrier is encountered in many technological processes: in the application of polymer coatings by spraying, in the production of composite materials, in dispersion, etc. For comparatively low velocities, when the dynamic head is smaller than the modulus of elasticity: $\rho U_0^2 \leqslant G(t_i)$, the principal influence on the characteristics of the impact is exerted by the rheological properties of the polymer. For small bodies: $l \ll ct_i$, $c = \sqrt{G/\rho}$ is the velocity scale of the shear wave, the problem of impact may be dealt with in quasistatic approximation, which is widely used in the theory of elastic bodies [1]. For calculating the deformation of a particle upon impact the results of the solution of contact problems are used. In view of the comparatively small deformations, the rheological properties of the polymer are described by the linear theory of viscoelasticity. The solution of the contact problem for viscoelastic material is constructed with the aid of the principle of correspondence proceeding from the relations for elastic material with analogous geometry [2, 3]. In [4] the impact of a polymer particle was examined for the case of forces of adhesion originating on the contact spot. This made it possible to estimate the force of adhesion required for maintaining the particle on the barrier. The present article examines impact without adhesion. In that case the particle rebounds from the barrier. The decrease of its kinetic energy is determined solely by viscous losses in the polymer. To evaluate the

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