the results merely relate to the mode of flow in the particular instrument (with localized velocity distribution). It is clear that in the latter case any calculation should be based on the limiting stresses for a specimen of undisrupted structure, since the localization of the deformation in weakened areas, which is responsible for the fall in resistance, should be specific to this form of strain, particularly when the sense of strain is reversed.

The structural state of each of these specimens is thus dependent on many external factors, particularly the temperature, storage conditions, and previous state of strain, and therefore the rheology is substantially affected. The only way of incorporating the rheological behavior into production practice is to compare results from tests performed under identical conditions.

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ENTRANCE EFFECTS IN VISCOELASTIC FLUID FLOW IN CYLINDRICAL NOZZLES

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The pressure losses prior to entry into a nozzle are determined in the flow of a viscoelastic medium in broad ranges of the viscosity and the discharge. A generalized dependence of the entrance pressure losses on the rate of shear is obtained in dimensionless form. An empirical equation is proposed for the computation of entrance pressure losses.

It is known that an "entry effect" [1], the crux of which is additional pressure losses in the plastic and elastic deformation of the medium during influx into the channel and in the shaping of the stream at the initial section of the channel, occurs in the flow of polymer solutions and melts in nozzles of finite length. The standard method of estimating the magnitude of the entrance effect at his time is the determination of the "entrance correction" according to Bagley [2], which is expressed as an additional fictitious nozzle length (in radii). However, in a number of papers [3], the correctness of the Bagley method is open to doubt. At the same time, an objective quantitative determination of the entry effect during the flow of polymer systems through a molding instrument is an actual scientific-technical problem whose solution is needed for the production of highly productive processes of polymer reworking.

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TABLE 1. Characteristics of the Viscoelastic Fluids (25°C)

Fluid No.	Polymer	$\bar{M}_v$	Solvent	c, %	ρ, kg/m³	η_0, N·sec/m²	ξ_0, N·sec²/m²	$\theta_0 = \xi_0/\eta_0$, sec
I	Vinylchloride (60%) copolymer with acrylonitrile (40%) SKhN = 60/40	6,0·10⁴	Dimethyl formamide DMFA	18,0	1000,0	4,217	0,152	3,60·10⁻²
II	"	"	"	20,0	998,8	8,913	0,641	7,19·10⁻²
III	"	"	"	24,0	1009,7	31,62	7,18	2,27·10⁻¹
IV	Acrylonitrile (92.5%) copolymer with vinyl acetate (6.75%) and metalylsulfonate (0.75%)	7,0·10⁴	"	19,1	989,5	23,28	1,83	7,87·10⁻²
V	Acrylonitrile (94.5%) copolymer with methylacrylate (5.5%)	6,0·10⁴	"	14,2	976,1	44,16	20,0	4,53·10⁻¹
VI	Polymetaphenylene isophthalamide PmPhIPhA	2,5·10⁵	Dimethyl acetamide DMAA	19,4	1016,0	34,28	2,89	8,44·10⁻²
VII		3,2·10⁵	"	19,4	1010,0	87,10	19,8	2,27·10⁻¹

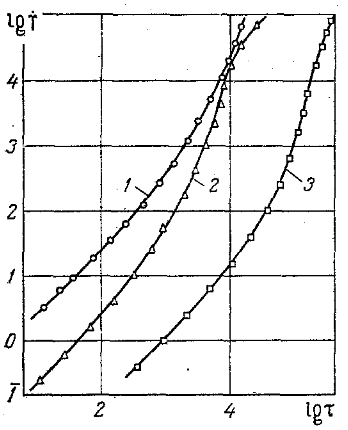


Fig. 1

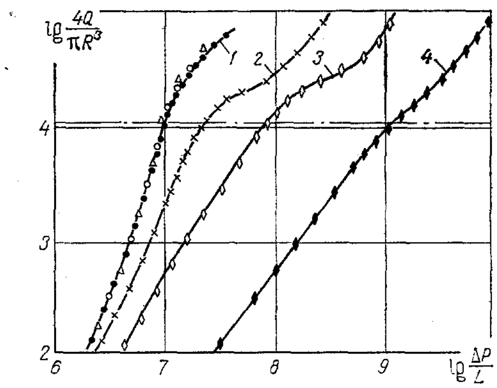


Fig. 2

Fig. 1. Flow curves of the fluids I (curve 1), V (2), and VII (3). $\dot{\gamma}$, sec^{-1}; τ, N/m^2.

Fig. 2. Pressure-flow characteristics of fluid V flow in nozzles of different length. Nozzle L/R: 1) 320, 242, 128; 2) 11, 1; 3) 2, 17; 4) 0, 214. ΔP/L, (N/m^2)/m; 4Q/πR^3, sec^{-1}.

It was noted in our first report [4] that the total value of the entrance effect is due to the contribution of three components: the viscous, the elastic, and the structural. According to the results of an experimental investigation of a flow of viscous inelastic fluids, a deduction was made about the dependence of the entrance pressure losses on the viscosity of the medium and the discharge, generalized as the empirical formula

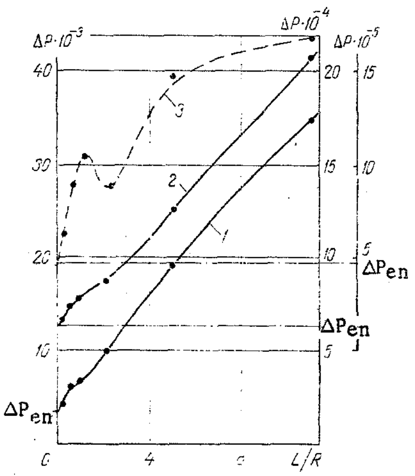
$$\Delta P^{\mathrm{V}}_{\mathrm{en}} = 6.03\, q^{0.84}\, \eta^{0.24+0.20 \lg q}. \qquad (1)$$

Results of measuring the entrance pressure losses in the flow of viscoelastic fluids are discussed in this report. Polymer solutions in organic solvents typical to synthetic fiber production (Table 1) were the objects of the investigation. A description of the experimental apparatus and the characteristics of the nozzle has already been presented [4]. It is just necessary to indicate here that the highly elastic and relaxational properties of the solutions were estimated by means of the flow curves by the method proposed in [5], which permits determination of the initial normal stress coefficient ξ_0 from the results of capillary viscometry to an accuracy no worse than that of direct measurement on rotational elastoviscometers (relative error ±20%).

Flow curves of polymer solutions of a different nature are shown in Fig. 1. It should be noted that the curves were not corrected for the thermal effect of the flow in the high discharge region, although the temperature rise of the escaping jet was indeed recorded (for example, by 1.7°C for the fluid VII with log $\dot{\gamma}$ = 3.5 sec^{-1}).

TABLE 2. Comparison of the Entrance Pressure Losses ΔP_{en} and Entrance Corrections l_{en}

Reduced discharge q, sec⁻¹	Fluid II		Fluid V		Fluid VII	
	ΔP_{en}, N/m²	l_{en}= nR	ΔP_{en}	l_{en}	ΔP_{en}	l_{en}
$1\cdot10^2$	$1,73\cdot10^3$	1,19	$3,70\cdot10^3$	1,29	$9,55\cdot10^3$	1,26
$3,16\cdot10^2$	$4,50\cdot10^3$	1,34	$9,50\cdot10^3$	1,84	$2,19\cdot10^4$	1,69
$1\cdot10^3$	$1,15\cdot10^4$	1,67	$2,43\cdot10^4$	2,89	$4,90\cdot10^4$	2,46
$3,16\cdot10^3$	$2,88\cdot10^4$	2,22	$6,18\cdot10^4$	4,89	$1,10\cdot10^5$	3,94
$1\cdot10^4$	$7,20\cdot10^4$	3,37	$1,72\cdot10^5$	10,0	$2,51\cdot10^5$	6,85



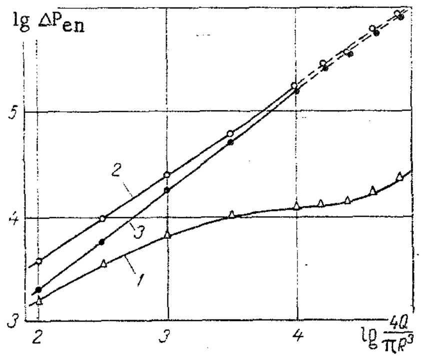


Fig. 3 Fig. 4

Fig. 3. Dependence of the pressure drop on the relative nozzle length for fluid V flow in the initial section of the channel. Reduced discharge q: 1) $1\cdot10^2$; 2) $3.16\cdot10^3$; 3) $3.16\cdot10^4$ sec^{-1}. ΔP, N/m²; L/R, units.

Fig. 4. Dependence of the entrance pressure losses in fluid V flow on the reduced discharge: 1) ΔP^V_{en}; 2) ΔP_{en}; 3) $(\Delta P_{en}-\Delta P^V_{en})$. ΔP_{en}, N/m²; $4Q/\pi R^3$, sec^{-1}.

The pressure-flow characteristics of fluid V flow in nozzles of different extent are shown in Fig. 2. The reduced flow—reduced pressure coordinates are selected because of the lack of computational formulas to determine the velocity and shear stress gradients during the flow of viscoelastic media in the transition mode, when the velocity profile is still not fully developed. Curve 1 is obtained by using three capillaries: L/R = 320, 242, and 128. Good agreement between the measurement results on long capillaries indicates the presence of a flow with a developing velocity profile in a sufficiently long section of the channel. The dependences for short nozzles (curves 2-4) are shifted toward higher pressure drops, i.e., the relative channel length L/R = 11.1 is already insufficient for stream formation. The characteristic break in these curves is associated with the onset of an irregular flow ("elastic turbulence"). The magnitude of the reduced discharge, above which such an irregularity was observed visually in the majority of cases, is denoted by the dashed-dot lines in the figure.

Dependences of the pressure drop on the nozzle length for a constant discharge ("Bagley diagram" [2]) were constructed by means of the pressure-flow characteristics for the ranges L/R = 320-11.1 and 11.1-0.214. It appeared that the dependences ΔP—L/R in the L/R = 320-11.1 range were extrapolated to the origin for all the fluids investigated, i.e., determination of the entrance correction for long nozzles is impossible. Other investigators [3] obtained an analogous result earlier.

The "Bagley diagrams" for the initial section of the channel (Fig. 3) turn out to be nonlinear, which, in principle, excludes their extrapolation to a zero pressure drop in order to determine the traditional correction l_{en} = nR. A similar character of the ΔP—LR graphs for short nozzles has already been noted repeatedly [6]. The essential difference between our results and known data is that nozzles with L/R equal to 0.214 were used in the present investigation (the actual length is $L \approx 1\cdot10^{-4}$ m), i.e., practically membranes with holes; this circumstance permits reliable extrapolation of the curves 1-2 (Fig. 3) to zero channel length and, therefore, determination of the pressure loss prior to entrance into the nozzle ΔP_{en}.

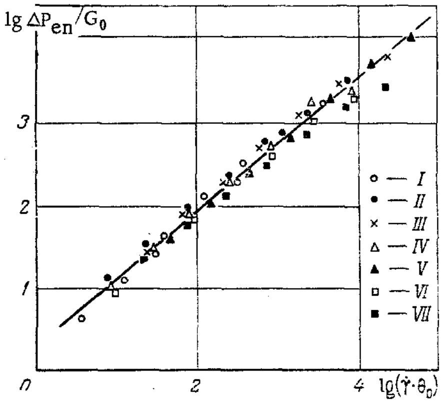


Fig. 5. Generalized dependence of the reduced entrance pressure losses on the reduced shear velocity. Points are the fluid indicator.

An analysis of the experimental results we obtained in the flow of viscoelastic fluids with a broad set of values η_0 (4.217-87.10 N·sec/m²) and ξ_0 (0.152-20.0 N·sec²/m²) verifies the deduction of Kuvshinskii et al. [6] that the terminal effect dissociated into two components characterizing the additional pressure drops before entry into the channel and on its initial section. Convincing proofs of this situation are also presented by Han et al. [7], who performed direct measurements of the pressure distribution along the channel length.

Comparative results on the magnitudes of the entrance pressure losses and entrance corrections are presented in Table 2. The values of l_{en} = nR were obtained by conversion of ΔP_{en} under the assumption of a linear pressure drop. Let us note that l_{en} = (3-15)R in [8] for polymer solutions.

The empirical relationship (1), which established a dependence between the entrance pressure losses during the flow of inelastic fluids, and the discharge and the viscosity, was used to evaluate the "viscous" component (ΔP^V_{en}) of the total pressure losses prior to entry into the nozzle (ΔP_{en}). Hence, the value of the viscosity was taken equal to its effective magnitude determined from the flow curve for a given discharge. The results being referred to here are presented in Fig. 4, from which it is seen that the relative fraction of the viscous component will be less, the greater the discharge; at the same time, the contribution of ΔP^V_{en} becomes inessential only for very significant q($1\cdot10^4$-$1\cdot10^5$ sec^{-1}).

It follows from the above on the three components of the entrance effect that the difference $\Delta P_{en}-\Delta P^V_{en}$ determines the total magnitude of the elastic and structural parts of the complete entrance pressure losses. The distribution of this latter is impossible as yet because of the lack of rotational devices permitting the realization of high shear velocities ($1\cdot10^3$-$1\cdot10^5$ sec^{-1}). In this respect the Han [9] proposal on the estimation of the highly elastic properties of running systems by means of the "terminal pressure" is interesting.

We performed two special series of tests on fluid VII during the experiment in order to determine the influence of the hole diameter on the quantity ΔP_{en}. Nozzles with R = $4.70\cdot10^{-4}$ m and R = $2.20\cdot10^{-4}$ m were used; the ratio between the reservoir radius and the hole radius R_r/R was 10.6 and 22.7, respectively. Practically identical values of ΔP_{en} were obtained in both series in the whole range of discharges investigated (q = $1\cdot10^2$-$1\cdot10^5$ sec^{-1}).

The relaxational nature of the effects accompanying the flow of the viscoelastic medium, the viscosity anomaly, high elasticity, and thixotropy affords a foundation for generalizing the data obtained on the entrance pressure losses. Let ΔP_{en} be determined in the general case by the following function of many variables:

$$\Delta P_{en} = f\,[V,\ R,\ \eta(\dot\gamma),\ \theta(\dot\gamma)]. \tag{2}$$

Then on the basis of dimensional analysis the power-law equation

$$\Delta P_{en} = a\left[\frac{V}{R}\right]^{\alpha}[\theta(\dot\gamma)]^{\alpha-1}\,\eta(\dot\gamma) \tag{3}$$

can be obtained. Regrouping the factors in (3) and combining quantities with identical exponents, we obtain a formula for the pressure loss at the entrance in the form of the dimensionless equation

$$\frac{\Delta P_{en}\theta(\dot\gamma)}{\eta(\dot\gamma)} = a\,[\dot\gamma_{av}\theta(\dot\gamma)]^{\alpha}. \tag{4}$$

It is known that for a broad circle of polymer systems there exist a generalized relaxational characteristic [10] and a temperature-invariant viscosity characteristic [11], which in the general case are

$$\frac{\theta}{\theta_0} = f_1(\dot{\gamma}\theta_0) \text{ and } \frac{\eta}{\eta_0} = f_2(\dot{\gamma}\theta_0). \quad (5)$$

Substituting the values of θ and η from (5) into (4) and replacing $\dot{\gamma}_{av}$ by $\dot{\gamma}$, we obtain

$$\frac{\Delta P_{en}\theta_0}{\eta_0} = \frac{\Delta P}{G_0} = f(\dot{\gamma}\theta_0). \quad (6)$$

Hence, it follows that a single dependence should exist between the reduced value of the entrance pressure losses and the reduced strain rate for polymers. Processing the results of experiment showed that such a dependence actually exists (Fig. 5). In constructing the generalized dependence, the values of $q = 4Q/\pi R^3$ were converted into the corresponding quantities $\dot{\gamma}$ by using flow curves. The arrangement of the points on the graph affords a possibility for a quantitative description of the dependence mentioned in the form of a power-law equation

$$\Delta P_{en} = 2.4\frac{\eta_0}{\theta_0}(\dot{\gamma}\theta_0)^{0.78}, \quad (7)$$

which reproduces the results of experiment with a relative error not exceeding 30%.

NOTATION

L, nozzle length; R, hole radius; Q, volume fluid discharge; $q = 4Q/\pi R^3$, reduced fluid discharge; V, mean linear stream velocity in the nozzle; $\dot{\gamma}_{av} = V/R$, average shear velocity; $\dot{\gamma}$, shear velocity on the capillary wall; τ, shear stress on the capillary wall; ΔP, pressure drop in fluid flow through nozzles; ΔP_{en}, pressure losses prior to fluid entry into the nozzle; ΔP_{en}^V, "viscous" component of the entrance pressure losses; $l_{en} = nR$, entrance correction; R_r, reservoir radius in front of the nozzle; $\overline{M}_V$, mean viscous molecular weight of the polymer; C, polymer concentration in the solution; ρ, solution density; η_0, initial viscosity; ξ_0, initial normal stress coefficient; $\theta_0 = \xi_r/\eta_0$, characteristic relaxation time; $G_0 = \eta_0/\theta_0$, initial modulus of high elasticity; $\eta(\gamma)$, $\theta(\gamma)$, dependences of the effective viscosity and relaxation time on the shear velocity; a, α, constants.

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