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INFLUENCE OF POLYACRYLAMIDE ADDITIONS ON THE HEAD LOSS IN ABRUPT CONTRACTIONS AND EXPANSIONS OF PIPES

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Data of an experimental investigation of the hydraulic resistance of the abrupt contractions and expansions of round pipes to the turbulent flow of polyacrylamide aqueous solutions are presented. An increase and a decrease in the head loss have been revealed. An explanation of the results obtained is given.

The use of hydrodynamically active additions introduced into a liquid flow in pipelines to decrease the head loss in them is a promising trend in the development of energy-conserving technologies [1, 2]. By decreasing the turbulent friction, hydrodynamically active additions influence, in a number of cases, the local pressure loss [3–17] — they decrease or increase it depending on the geometric characteristics of the setting, the local resistance, the Reynolds number, and their concentration in the flow. Additions influence significantly the pressure loss in the local resistances of pipes with diameters smaller than 20–35 mm [13].

We set ourselves the task of investigating the influence of polyacrylamide additions on the resistance coefficients of the abrupt contractions and expansions of pipes at different ratios of their diameters.

Test Bed. The experiments were carried out on a bed of the displacement-circulation type which provides a means for testing liquids moving under gravity or circulating under the action of a pump [10]. The experimental pipeline (Fig. 1) was assembled from removable portions of pipes with diameters D_1, d, and D_2 (see Table 1) and included abrupt contraction and expansion of the pipes, which were investigated at a time. The pipes were flange-joined; the material was stainless steel. We also used the data from [7, 9, 11, 14, 17] (see Table 1).

The inside diameter of pipe connections for tapping pressure was equal to 4 mm. The pipe connections were connected to a piezometric panel with the help of pulse rubber tubes with an inside diameter of 8 mm. The head was measured to an accuracy of 0.5 mm of the water column. The working head in the experimental pipeline was 3.5 mm. The liquid flow rate was controlled by a valve set at the end of the experimental pipeline. The value of the liquid flow rate was determined by the volume method.

Experimental Procedure. The solutions were prepared with the use of an 8% polyacrylamide technical gel (Spec. 6-01-1049-81) with a molecular mass of $3.6 \cdot 10^6$. The latter was calculated from the characteristic viscosity according to the equation $[\eta] = 3.73 \cdot 10^{-4} M^{0.66}$ in a 0.1 N solution of $NaNO_3$ (at 30°C) [18]. The characteristic viscosity of the polyacrylamide solutions ($[\eta] = 0.79\ m^3/kg$) was determined with the help of a Bischof viscosimeter with a capillary diameter of 0.6 mm. By the time of the experiments, the polyacrylamide gel was eight years old since the date of preparation.

The weighed portions of the polyacrylamide gel, necessary for preparation of a series of solutions, were placed in glass cylinders where the gel was kneaded. Into the cylinders we poured tap water (pH 7.25–7.65) heated to 35–40°C and mixed it with the gel. The polyacrylamide, periodically diluted with water and mixed by hand, was kept in the cylinders for at least 1 day. After the complete dissolution of the polyacrylamide, the contents of the cylinders were poured out into solution tanks of capacity 0.4 m^3, where they were mixed thoroughly with tap water heated to ~20°C. The aqueous solutions of polyacrylamide of calculated concentration, prepared in such a way, were kept for 15–24 h. Before the experiments, the solution was mixed once again. We prepared the aqueous solutions of polyacry-

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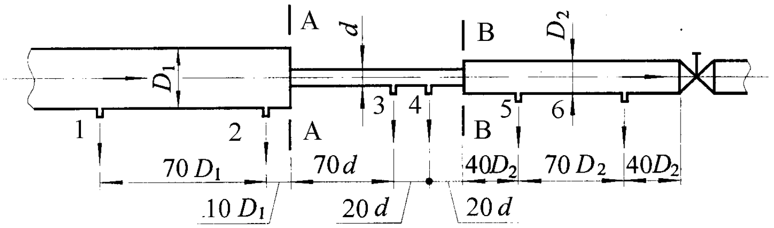

Fig. 1. Scheme of the experimental pipeline: 1, ..., 6) pipe connections for tapping pressure; A–A) plane of joint of the ends of pipes with diameters D_1 and d; B–B) the same, d and D_2.

lamide with mass concentrations of $C = 5{\cdot}10^{-6}$, 10^{-5}, $5{\cdot}10^{-5}$, 10^{-4}, $5{\cdot}10^{-4}$, and 10^{-3} kg/kg. The concentration C was determined from the content of the nonaqueous polyacrylamide in the solution.

The experiments were carried out first for water and then for solutions. To exclude the influence of the mechanical degradation of the polymer on the results of the investigations, we used the solutions only once, and they were flowing under gravity. Recirculation was carried out with the help of a pump only for water. The solutions were investigated in order of increase in their concentration. The Reynolds number $\mathrm{Re} = V_d d/\nu$ was changed from 10^3 to $3{\cdot}10^4$. The temperature of the solutions was within 12–19°C during the experiments. The experimental procedure has been described in detail in [10].

Mathematical Processing of the Investigation Results. The hydrodynamic efficiency of the solutions studied was controlled by their influence on the hydraulic resistance of portion 3–4 of the pipe of diameter d (Fig. 1). In this case, the hydraulic coefficient of friction λ was determined from the Darcy–Weisbach formula: $\Delta h_{3\text{–}4} = \lambda(l_{3\text{–}4}/d) \times (Vd^2/2g)$.

The resistance coefficient ζ referred to the mean velocity of the flow after the local resistance was found from the Weisbach formula:

for the abrupt contraction of the pipe

$$\zeta_{\text{a.c}} = 2gh_{\text{a.c}}/V_d^2 \,;$$

for its abrupt expansion

$$\zeta_{\text{a.e}} = 2gh_{\text{a.e}}/V_{D_2}^2 \,.$$

The local head loss h was calculated by subtraction of the measured friction loss from the total head loss on the measured portion of the pipeline containing the resistance studied (Fig. 1):

for the abrupt contraction of the pipe

$$h_{\text{a.c}} = \Delta h_{2\text{–}3} - (l_{2\text{–A}}/l_{1\text{–}2})\, \Delta h_{1\text{–}2} - (l_{\text{A–}3}/l_{3\text{–}4})\, \Delta h_{3\text{–}4} + \alpha_{D_1} V_{D_1}^2/2g - \alpha_d V_d^2/2g \,;$$

for its abrupt expansion

$$h_{\text{a.e}} = \Delta h_{4\text{–}5} - (l_{4\text{–B}}/l_{3\text{–}4})\, \Delta h_{3\text{–}4} - (l_{\text{B–}5}/l_{5\text{–}6})\, \Delta h_{5\text{–}6} - \alpha_{D_2} V_{D_2}^2/2g + \alpha_d V_d^2/2g \,.$$

In the calculations, we took $\alpha_{D_1} \approx \alpha_d \approx \alpha_{D_2} \approx 1$ for the turbulent regime of flow. For concentrations of the solutions lower than the effective value ($C_{\text{eff}} \approx 10^{-4}$ kg/kg) corresponding to the largest decrease in the resistance of the pipe of diameter d , the kinematic viscosity ν of the polyacrylamide solutions differed insignificantly from the viscosity of water. In the calculations of the Reynolds number, the viscosity of the solutions of all the concentrations was taken to be equal to that of water depending on the temperature. Thus, we determined the real (technical) effect of the influence of polymeric additions, which is an important characteristic for practical calculations [19].

TABLE 1. Abrupt Contractions and Expansions of the Pipes Studied

Diameters of pipes, mm		Contraction ratio, $m = (d/D_1)^2$	Expansion ratio, $n = (D_2/d)^2$	Reference
D_1, D_2	d			
33.42	5.81	0.030	33.09	*
25.01	5.81	0.054	18.53	*
20.95	5.81	0.077	13.00	[7, 9, 11]**
15.72	5.81	0.137	7.32	*
12.82	5.72	0.199	5.02	[14, 17]
10.68	5.81	0.296	3.38	*
8.21	5.81	0.501	2.00	*

*Investigations of the authors

**The polymer is 2 to 3 months old

Investigation Results. *1. Abrupt contraction of a pipe.* The experimental data obtained are presented graphically in Fig. 2 by the dependences $\zeta_{a.c} = f(\mathrm{Re})$ for three different values of the contraction ratio of the flow m and the six studied concentrations C of the polyacrylamide aqueous solutions The results obtained for all the contractions of the pipes studied are presented in the differential coordinates $\Delta\zeta/\zeta = f(m)$ in Fig. 3a and $\Delta\zeta/\zeta = f(C)$ in Fig. 4a. These data are supplemented with the data from [7, 9, 17] for the pipes of diameters given in Table 1. The polymeric additions caused an increase in the resistance coefficient $\zeta_{a.c}$, which increased with increase in C (Fig. 2).

With increase in the value of $m = (d/D_1)^2 = 0.030 \rightarrow 0.054 \rightarrow 0.137$, the jump of the dependence $\zeta_{a.c} = f(\mathrm{Re}, C)$ representing the zone of the unstable regime of flow and separating the laminar and turbulent zones shifts toward larger Reynolds numbers, i.e., $\mathrm{Re} = 2500 \rightarrow 3200 \rightarrow 4200$, respectively (Fig. 2). For water and polyacrylamide solutions with concentrations of $5{\cdot}10^{-6}$ and 10^{-5} kg/kg, the abscissas of the jumps are equal. An increase in m corresponds to a decrease in the degree of deformation of the flow; as a consequence, the laminar regime is realized at higher velocities of the flow. For solutions with a concentration of 10^{-5} kg/kg, the jumps of the turbulent transition shifted to the right along the abscissa axis relative to the curves for water, while for $C \geq 10^{-4}$ kg/kg they are totally absent (Fig. 2). In this case, the curves $\zeta_{a.c} = f(\mathrm{Re}, C)$ gradually pass from the zone of the laminar regime to the region of independence of the coefficient $\zeta_{a.c}$ from the Reynolds number which is in the zone of the turbulent regime. For water and polymeric solutions, $\zeta_{a.c}$ becomes independent of Re at practically identical values of the latter. For comparison, the unstable regime of isothermic flow of water in a straight horizontal pipe with an abrupt contraction of the flow at the inlet begins at Reynolds numbers equal to 2070–2840 [20]. The threshold rate of shear, at which the flow of a polymeric solution becomes unstable in abruptly contracting planar channels, increases with increase in m [21]. When m increases and C decreases, the difference between the values of $\zeta_{a.c}$ (between the largest value and the smallest values) on the ordinate of the jump increases. This resembles the Nikuradze graph $\lambda = f(\Delta, \mathrm{Re})$ for pipes with artificial roughness, on which the difference between the values of the hydraulic coefficient λ increases with decrease in the relative roughness $\Delta = \Delta/d$ in the case of transition from the laminar regime, through the unstable regime, to a turbulent regime where the coefficient λ is independent of the Reynolds number in the region of quadratic resistance [22].

The abrupt contraction of a pipe is the particular case of a convergent channel with a cone angle of $\alpha = 180^{\circ}$. When the aqueous solutions of polyacrylamide with concentrations of $C = 10^{-7}$–$5{\cdot}10^{-5}$ kg/kg flow through conic convergent channels with $\alpha = 10$–140° ($D_1 = 20.95$ mm, $d = 5.81$ mm) [10, 12], their resistance increases with increase in C. When α decreases from 140 to 10°, which corresponds to a decrease in the deformation of the flow, the abscissa of the turbulent-transition jump shifts from $\mathrm{Re} = 3.5{\cdot}10^3$ to $\mathrm{Re} = 5.5{\cdot}10^3$, as is the case for abrupt contractions of pipes with increase in m. In both cases, the friction resistance increases and the form resistance decreases, which finally leads to a decrease in the local energy loss due to the presence of the polyacrylamide additions.

Two factors are mainly responsible for the loss in the flow stability in abrupt contractions of the pipes. They are recirculation formations in the corners before them [23, 24] and the viscoelastic properties of the polymeric solutions [25]. The presence of polyacrylamide additions in water increases the dimensions [23] and the intensity [21] of the vortices upstream, which increase with increase in the flow velocity [21, 25] and the longitudinal viscosity [26]. The latter increases sharply in the case of a polymeric-solution flow with extension [27], which occurs in contractions.

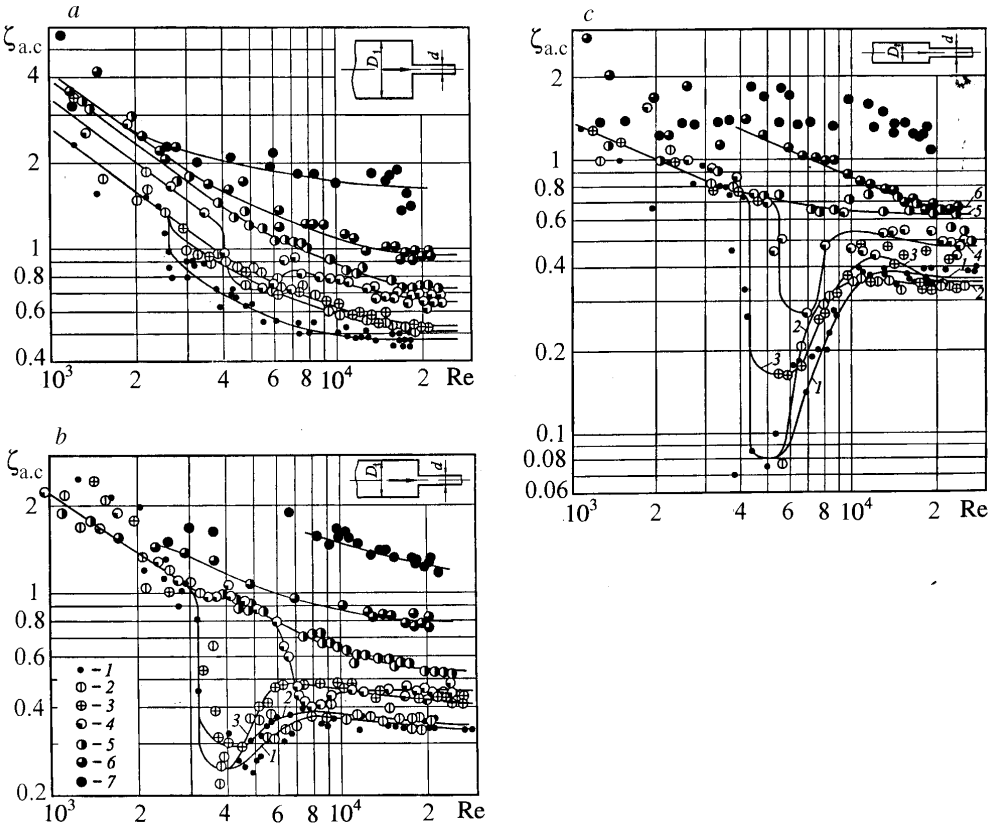

Fig. 2. Dependence of the resistance coefficient of the abrupt expansion of the pipe $\zeta_{a.e}$ on the Reynolds number Re at different values of m: a) 0.030, b) 0.054, and c) 0.137 for a water flow (1) and flows of the aqueous solutions of polyacrylamide with concentrations C, kg/kg: $5 \cdot 10^{-6}$ (2), 10^{-5} (3), $5 \cdot 10^{-5}$ (4), 10^{-4} (5), $5 \cdot 10^{-4}$ (6), and 10^{-3} (7); $D_1 = \text{var}$, $d = 5.81\ \text{mm} = \text{const}$.

Immediately behind the abrupt contraction of the planar-channel cross section, velocity profiles with a maximum on the axis of the pipe are formed in the flow of polyacrylamide solutions in contrast to water, whose velocity diagram on this portion is rectilinear [23].

When the flow reaches a critical velocity, it becomes unstable [25], the vortices before the contraction of the rectangular channel become three-dimensional [24], and the region of recirculation flow becomes nonsymmetric and varying periodically: it increases near one wall and decreases near the other, and then conversely. This results in the fact that the main flow deviates first to one wall and then to the other when it approaches the site of contraction. The rate of shear, at which an instability arises, and the oscillation period are dependent on the viscoelastic properties of the polymeric solutions [25], which agrees with our results. It is precisely the rheological parameters of liquids that may be responsible for different values of the abscissas of the transition jumps (or their absence) at different concentrations C of polyacrylamide solutions. An increase in C is favorable to the laminarization of the flow. At the same time, the local energy loss increases with increase in the viscosity.

For the abrupt contractions of the pipes studied at $m \le 0.3$ and $C \le 10^{-4}$ kg/kg (Fig. 3a) the values of $\Delta\zeta/\zeta$ are independent of the contraction ratio of the flow m. In our opinion, the influence of the polyacrylamide additions on the value of $\zeta_{a.c}$ (for the indicated combinations of m and C) will be analogous to their influence on the value of the resistance coefficient in the case of flow of the solution out of a vessel with a large cross section into the pipe of diameter d. As is seen from Fig. 3a, in the range $0.7 < m < 0.1$ the resistance of the abrupt contraction must decrease due to the polyacrylamide additions for all the investigated concentrations of the solutions. The values of $\Delta\lambda/\lambda$ for the pipe with $d = 5.81$ mm are plotted on the ordinate corresponding to $m = 1$ in Fig. 3a, which reflects the particular case of abrupt contraction with $D_1 \equiv d$.

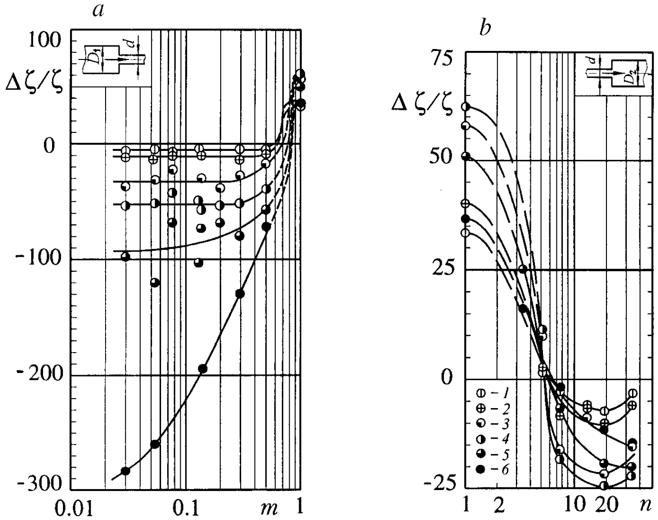

Fig. 3. Dependence of the relative change in the resistance coefficient $\Delta\zeta/\zeta$: a) for the abrupt contraction of the pipe from m; b) for the abrupt expansion of the pipe from n at different concentrations C, kg/kg, of the aqueous solution of polyacrylamide: $5 \cdot 10^{-6}$ (1), 10^{-5} (2), $5 \cdot 10^{-5}$ (3), 10^{-4} (4), $5 \cdot 10^{-4}$ (5), and 10^{-3} (6); $\mathrm{Re} = 2.5 \cdot 10^4$. See Table 1 for the values of D_1, d, and D_2.

If water is flowing through the abrupt contraction of the pipe, the contracted cross section of the flow is formed after the contracted cross section of the channel at a distance of ~0.5d. Then the jet expands, being separated from the walls of the pipe by a swirl zone. The local head loss is concentrated predominantly within the expanding part of the jet [22].

The presence of hydrodynamically active additions in the flow gives rise additionally to the following processes: a) increase and intensification of the vortices before the contracted cross section of the pipe; b) extension of the polymeric molecules at the inlet to the channel with a smaller diameter accompanied by an increase in the longitudinal viscosity, c) a complex of phenomena occurring within the expanding bounded submerged jet (see Sec. 2 below) and weakened by its preliminary of contraction; d) renewal of the orientation effect of the polymeric molecules which has been disturbed on the expansion portion of the jet and its enhancement since it becomes more pronounced with decrease in the pipe diameter at the same flow rate of the liquid.

After the abrupt contraction of the pipe from $D_1 = 20.95$ mm to $d = 5.81$ mm the Thoms effect is restored at a distance of 70–140d or larger from the contracted cross section depending on the Reynolds number, the type of hydrodynamically active additions, and their concentration [28].

If a local head loss is mainly due to the form resistance (at $m < 0.7$ in our experiments), processes a), b), and d) dominate. As a consequence, with hydrodynamically active additions the total expenditure of energy increases. In this case, the values of $\Delta\zeta/\zeta$ increase with increase in the concentration C of the solutions (Fig. 4a). When friction loss dominates (at $m > 0.7$), the forces of groups a), b), and d) become weaker and the additions cause a decrease in the resistance of the abrupt contraction of the pipe [1, 11, 12, and 16].

2. Abrupt expansion of a pipe. For this local resistance, an increase in the expansion ratio of the flow $n = (D_2/d)^2$ corresponds to an increase in the deformation of the flow. However, when n decreases, the dependences $\zeta_{\mathrm{a.e}} = f(\mathrm{Re}, C)$ become more complex. Whereas at $n = 33.09$ and $\mathrm{Re} > 3.5 \cdot 10^3$ (Fig. 5a) the value of the coefficient $\zeta_{\mathrm{a.e}}$ is determined only by the Reynolds number and the concentration of the solution, for $n \le 18.53$ and $\mathrm{Re} < 8 \cdot 10^3$ (Figs. 5b and 5c) the curves $\zeta_{\mathrm{a.e}} = f(\mathrm{Re}, C)$ are separated into two branches at $\mathrm{Re} = 8 \cdot 10^3$. All the dependences $\zeta_{\mathrm{a.e}} = f(\mathrm{Re}, C)$ have turbulent-transition jumps. As the degree of deformation of the flow decreases, their abscissas shift toward smaller Re numbers, as in the case of abrupt contraction. When $\mathrm{Re} \ge (1\text{–}2) \cdot 10^4$ is reached, the coefficient $\zeta_{\mathrm{a.e}}$ becomes independent of the Reynolds number for all the investigated concentrations of the solutions.

At Reynolds numbers larger than 10^4, the polyacrylamide additions increased the hydraulic resistance of the abrupt expansions of the pipes studied at $n > 6$ and decreased it at $n < 6$ (Fig. 3b). This figure shows the values of

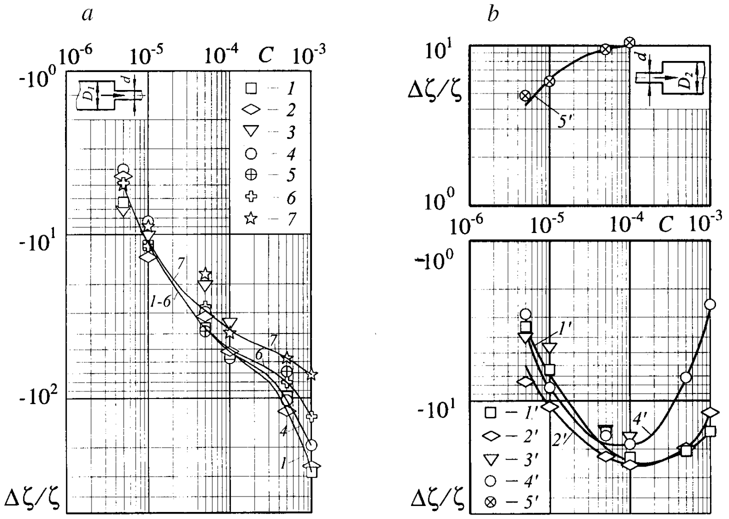

Fig. 4. Dependence of the relative change in the resistance coefficient $\Delta\zeta/\zeta$ on the concentration C of the aqueous solution of polyacrylamide: a) for the abrupt contraction of the pipe at different values of m: 0.030 (1), 0.054 (2), 0.077 (3), 0.137 (4), 0.199 (5), 0.296 (6), and 0.501 (7); b) for the abrupt expansion of the pipe at different n: 33.09 (1′), 18.53 (2′), 13.00 (3′), 7.32 (4′), and 5.02 (5′); $\mathrm{Re} = 2.5\cdot10^4$. See Table 1 for the values of D_1, d, and D_2.

$\Delta\lambda/\lambda$ for $n = 1$ for the pipe with $d = 5.81$ mm since the cylindrical pipe can be considered as a particular case of its abrupt expansion at $D_2 \equiv d$. The concentration of the polyacrylamide solution $C_{\mathrm{eff}} \approx 10^{-4}$ kg/kg is the most effective concentration for decreasing the resistance of abrupt expansions. The excess over C_{eff} led to the weakening of the effect of the additions in both the case of a decrease in the resistance at $n < 6$ and the case of its increase at $n > 6$ (Fig. 3b and Fig. 4b). At $C \approx 10^{-4}$ kg/kg, the curves $\Delta\zeta/\zeta = f(C)$ have extrema which are the absolute maxima for each $n < 6$ and minima at $n > 6$ (Fig. 4b).

The complex of physical phenomena form the hydraulic resistance of the abrupt expansion of a pipe to the flow of a liquid with polyacrylamide additions, which, on a short length of its path, takes the form of a bounded submerged jet propagating with deceleration. A decrease in the velocity of its flow, beginning from the outer layers, gives rise to longitudinal vibrations responsible for the formation of vortex motions and energy loss [29]. These processes develop under the action of hydrodynamically active additions, the basis of which is formed in the case of flow in the pipe of diameter d before the separation cross section. If the length of this channel is sufficient to eliminate the consequences of the inlet effects, at the outlet of it there is a flow with decreased resistance. The transverse velocity pulsations in its near-wall buffer layer are suppressed [30] by polymeric molecules oriented along the wall [31]. The elastic stresses arising as a result of the orientation effect retard the disintegration of the flow on the separation portion [32]. Because of this, free jets flowing out of the pipe are elongated due to the action of the polymeric additions, including hydrodynamically active ones, more markedly (to 270%) than the jets formed in nozzles of the same diameters (to 100%) and at the same heads [33]. The preliminary suppression of turbulence in the feeding pipe of diameter d enhances the influence of additions on the resistance of its abrupt expansion [3, 5].

It has been established that the actions of polyacrylamide on the turbulence are similar in the case where there are solid walls and in the case where they are absent. A triple narrowing of the submerged jet was observed [34]. Hydrodynamically active additions stabilize its surface at the interface with a wake liquid moving more slowly [34, 35], suppress small-scale turbulence, and decrease the transverse velocity oscillations [36].

A Newtonian-fluid flow attaches itself to the wall of a round pipe at a distance of about one gauge from the separation cross section [37] or, more exactly, at a distance of $l_{\mathrm{j}} = (4\text{–}4.5)\,(D - d)$ for $1.3 \le D/d \le 2.5$ [38]. In the presence of hydrodynamically active additions, the length of the separation zone depends on the Reynolds number. At $\mathrm{Re} \le 2000$ it is the same for flows of water and for solutions of a polymer ($C = 5\cdot10^{-5}$ kg/kg) and a surface-active substance ($C = 10^{-3}$ kg/kg) in it. In the presence of additions, it is approximately doubled for $\mathrm{Re} \ge 5000$. In a devel-

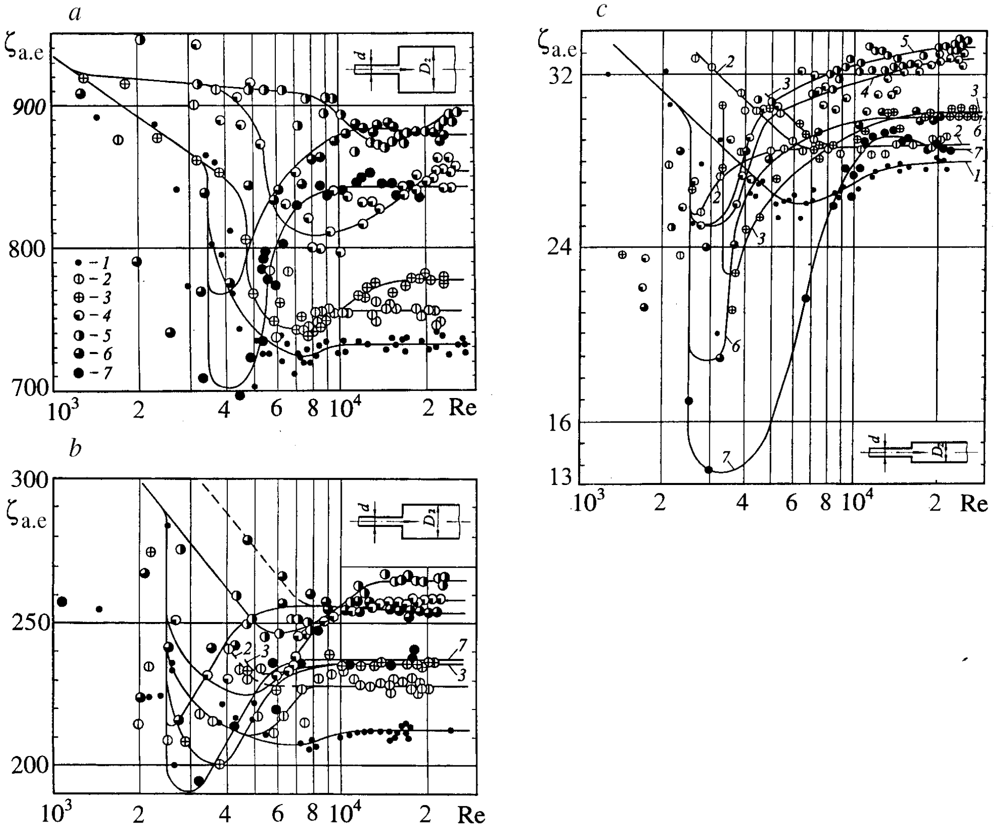

Fig. 5. Dependence of the resistance coefficient of the abrupt expansion of the pipe $\zeta_{a.e}$ on the Reynolds number at different values of n: a) 33.09, b) 18.53, and c) 7.32 for a water flow (1) and flows of the aqueous solutions of polyacrylamide with concentrations C, kg/kg: $5 \cdot 10^{-6}$ (2), 10^{-5} (3), $5 \cdot 10^{-5}$ (4), 10^{-4} (5), $5 \cdot 10^{-4}$ (6), and 10^{-3} (7); $d = 5.81$ mm = const, D_2 = var.

oped turbulent regime, the influence of Re on the length of the separation zone is small for all three liquids [39]. It has been revealed that when the resistance of the abrupt expansion of a round pipe is decreased by polymeric additions, including polyacrylamide, the length of the separation zone coincident with the portion of partial recovery of the pressure increases [5]. The data from [5, 39] agree with the decrease in the coefficient $\zeta_{a.e}$ obtained for the aqueous solutions of polyacrylamide on the portion of the curves $\zeta_{a.e} = f(\mathrm{Re}, C)$ after the jump of the transition (Fig. 5). The region of decrease in $\zeta_{a.e}$ increases along the Re axis with increase in C to $\mathrm{Re} = 8500$ at $C = 10^{-3}$ kg/kg (Fig. 5c). Account should also be taken of the fact that the aqueous solutions of polyacrylamide are viscoelastic liquids with a viscosity decreasing with increase in the rate of deformation [40]. Because of this, for an expansion ratio of the flow of $n = 5.023$, the decrease in the coefficient $\zeta_{a.e}$ was obtained (at $\mathrm{Re} > 10^4$) for all the investigated concentrations of the solutions [14, 17]. As n increased, the range of polyacrylamide concentrations corresponding to a decreased resistance narrowed practically to their maximum value of $C = 10^{-3}$ kg/kg (Fig. 5a).

The influence of hydrodynamically active additions on the flow of submerged jets also manifests itself as an increase in longitudinal velocity pulsations and in large vortex structures [36]. In free axisymmetric shear turbulent flows, including flows of the aqueous solutions of polyacrylamide, there arise large-scale circular vortices that move at an angle to the flow axis with a velocity exceeding significantly the velocity of propagation of the boundary of the turbulent region and leave it rapidly [41]. The introduction of polymeric additions prolongs the time of existence of large vortices [35, 42]. In the presence of walls confining the flow, as a result of the high-speed filming of water flow in the abrupt expansion of a round pipe [43] from $d = 38.4$ mm to $D_2 = 90.0$ mm, we observed a group of toroidal peripheral vortices following one another from the beginning of the pipe of diameter D_2. A transit jet flowing out of the end cross section of the pipe of diameter d with a velocity exceeding significantly the velocity of the vortices moved inside them, damping as on elastic rollers. In the region where the jet was adjacent to the pipe walls, these vortices, having no way of separating from the jet, assimilated in it and were swept away by the flow.

Thus, the disturbances generated by the attachment of the large toroidal vortices to the jet propagate downstream, destabilizing by doing so the process of equalization of the velocity diagram and causing additional expenditure of energy on ejecting [35] these decelerated vortices. The turbulent flow of a Newtonian fluid develops completely in the round pipe at a distance of about 70 gauges after its abrupt expansion [37]. In contrast to water, pressure pulsations in the polyacrylamide solutions do not disappear far behind the zone of reattachment of the jet after the separation. Their frequencies increase [44] and the heat transfer increases by 40–63% depending on the Reynolds number because of the joint action of the abrupt expansion of the round pipe and the polyacrylamide additions [45]. In the presence of hydrodynamically active additions, the portion where the flow develops completely is additionally elongated because its end is determined by the cross section in which the orientation of the polymeric molecules along the wall is restored (see Sec. 1). The resumption of the orientation effect is accompanied by an increase in the energy loss.

The effect of the abrupt expansion of a pipe in the presence of hydrodynamically active additions also propagates upstream to a distance of up to $10d$, but it contributes insignificantly to the total local energy loss.

The processes occurring in the abrupt expansion of a pipe in the presence of hydrodynamically active additions can be subdivided into two groups: a) processes responsible for the decrease in the resistance and manifesting themselves as the elongation and stabilization of the bounded submerged jet; b) processes increasing the head loss and manifesting themselves as the enhancement of longitudinal velocity pulsations and peripheral vortices, which coincides qualitatively with [3]. These processes are also responsible for the expenditure of energy on ejecting these vortices and resuming the orientation effect.

At $n < 6$, the forces involved in the processes of the first group dominate and the coefficient $\zeta_{\text{a.e}}$ decreases (as the polyacrylamide concentration increases to C_{eff}). When $n > 6$, the forces involved in the processes of the second group dominate and the resistance of the abrupt expansion of the pipe increases.

However, at $n \approx 20$ the curves $\Delta\zeta/\zeta = f(n)$ corresponding to $C \le 10^{-4}$ kg/kg have minima, and for $n > 20$ the effect of the influence of hydrodynamically active additions becomes weaker. The values of $\Delta\zeta/\zeta$ tend to zero. The action of the additions will apparently be such as in the case where a polymeric solution flows out of the pipe of diameter d to a vessel with a large cross section, when $D_2 >> d$. According to [46], at $n = 125$ and $\text{Re}_d = 22{,}000$ the flow in the abrupt expansion of the pipe is similar to the efflux of a submerged turbulent jet into an undisturbed flow.

In our opinion, realization of the flow of a polyacrylamide solution along the lower (main) branch of the curves $\zeta_{\text{a.e}} = f(\text{Re}, C)$ in Fig. 5 corresponds to a deviation of the flow to the wall. In this case, in the region of their contact the turbulent friction decreases due to the additions and, what is more important, the area of contact of the jet surface with the vortex zone decreases. The upper branch characteristic of solutions with higher concentrations corresponds to the central position of the jet. For divergent channels with $\alpha = 10\text{–}140^{\circ}$, $d = 5.81$ mm, and $D_2 = 20.95$ mm, the curves $\zeta = f(\text{Re}, C)$ were not subdivided into branches for the flow of polyacrylamide solutions with $C = 10^{-7}$–$5 \cdot 10^{-4}$ kg/kg [10, 11].

The investigation results obtained for solutions which have been prepared from the polyacrylamide gel within 2 to 3 months after its manufacture [7, 9–12] and the results obtained for the gel kept for 8 years are practically identical.

The problem can be investigated in more detail with the use of the methods of visualization of the structure of flows in the local resistances of round pipelines, including high-speed photographing and filming [43] and laser Doppler velocimeters [47].

CONCLUSIONS

1. The influence of polyacrylamide additions on the hydraulic resistance of contractions and expansions of pipes depends on the degree of deformation of the flow in them, the concentration of the additions, and the Reynolds number. If the loss influencing the form dominates in the local head loss, which occurs at $m < 0.7$ for the abrupt contraction of a pipe and at $n > 6$ for the abrupt expansion, for $\text{Re} > 10^4$ polyacrylamide additions increase the resistance. When the friction loss dominates (respectively, at $m > 0.7$ and $n < 6$) the total energy loss decreases.

2. The resistance of the abrupt expansion of a pipe decreases due to additions in the region next in the Reynolds number to the jump of the turbulent transition and extending with decrease in the deformation of the flow toward larger Re numbers.

3. For $n > 20$ at $\mathrm{Re} = 8000$, the curves $\zeta_{\mathrm{a.e}} = f(\mathrm{Re}, C)$ are subdivided into two branches diverging with decrease in Re and the range of concentrations at which the curves bifurcate is extended. The main lower position of the curves corresponds, apparently, to a deviation of the bounded submerged jet to the wall of a pipe of diameter D_2 in its abrupt expansion, while the upper position corresponds to the axial flow.

4. At a contraction ratio of the flow of $m \leq 0.3$ and $C \leq C_{\mathrm{eff}}$ the influence of the polyacrylamide additions on the resistance of the abrupt contraction of a pipe remains constant with decrease in m. When the expansion ratio of the flow n exceeds 20, the effect of influence of the polyacrylamide additions on the hydraulic resistance of the abrupt expansion of a pipe becomes weaker (to the point of total disappearance).

NOTATION

C, mass concentration of the solution; D_1, d, and D_2, diameters of the pipes of the experimental pipeline (Fig. 1); g, free-fall acceleration; $h_{\mathrm{a.c}}$ and $h_{\mathrm{a.e}}$, head losses in the abrupt contraction and expansion of the pipes, respectively; Δh_{1-2}, ..., Δh_{5-6}, head losses, respectively, on portions 1–2, ..., 5–6 of the experimental pipeline; l_{1-2}, ..., l_{5-6}, lengths of the measured portions 1–2, ..., 5–6; M, molecular mass; $m = (d/D_1)^2$, contraction ratio of the flow in the abrupt contraction of the pipe; $n = (D_2/d)^2$, expansion ratio of the flow in the abrupt expansion of the pipe; V_{D_1}, V_d, V_{D_2}, and α_{D_1}, α_d, α_{D_2}, mean velocities of the flow in the cross sections of the pipes of diameter D_1, d, and D_2 and corrections of the kinetic energy for them, respectively; α, cone angle of the convergent channel or divergent channel; Δ, height of the asperities on the pipe wall; Δ, relative roughness; $\zeta_{\mathrm{a.c}}$ and $\zeta_{\mathrm{a.e}}$, coefficients of the local resistance of the abrupt contraction and expansion of the pipes, respectively; ζ_{w} and ζ_{s}, resistance coefficients for a water flow and for a flow of the aqueous solution of polyacrylamide, respectively; $[\eta]$, characteristic viscosity; λ, hydraulic coefficient of friction for a pipe; λ_{w} and λ_{s}, the same for a water flow and a flow of the aqueous solution of polyacrylamide, respectively; $\Delta\zeta/\zeta = (\zeta_{\mathrm{w}} - \zeta_{\mathrm{s}})/\zeta_{\mathrm{w}}$ and $\Delta\lambda/\lambda = (\lambda_{\mathrm{w}} - \lambda_{\mathrm{s}})/\lambda_{\mathrm{w}}$, relative change in the coefficients ζ and λ due to the presence of polyacrylamide additions in the flow at equal Reynolds numbers; l_{j}, length of the bounded submerged jet after the abrupt expansion of the pipe. Subscripts: a.c, abrupt contraction; a.e, abrupt expansion; eff, effective; w, water; s, solution; j, jet.

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