RESISTANCE OF CONVERGING SECTIONS DURING THE TURBULENT FLOW OF WATER WITH POLYACRYLAMIDE ADDITIVES

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UDC 532.517.4:532.135:532.555

Results are presented from an experimental investigation of the effect of the addition of polyacrylamide additives on the hydraulic resistances of conical converging sections.

The use of additives for reducing energy losses during the transport of liquids in pipelines [1, 2] requires the study of and the accounting for their effects on local hydraulic resistances. The simplest of these, such as gradual and sudden constrictions, expansions, pipe bends, etc., are of particular interest. Some information is known on the effects of additives in converging sections and diffusers [3, 4]. In investigating turbulent flows of aqueous solutions of polymers (polyethylene oxide (PEO) WSR-301 of mass concentrations 3×10^{-5}, 10^{-4}, and 3×10^{-4} and also guar gum J2-FP of concentration 3×10^{-4}) through a converging section with a cone angle of $\alpha = 8°$, length 250 mm, and diameters D and d of 41 and 6 mm at the inlet and outlet, respectively, B. V. Lipatov [3] did not observe any effect of the additives on the flow resistance. V. B. Amfilokhiev [4] found reductions (of up to 20%) in the flow resistance of a converging section with $\alpha = 40°20'$, D = 20 mm, d = 8 mm, for the turbulent flow through it of aqueous solutions of the same PEO of concentrations 2×10^{-6} to 5×10^{-5}.

The present work is a continuation of investigations carried out by the authors on diffusers [5], and has as its objective the study of the effects of polyacrylamide (PAA) additives on the flow resistances in converging sections.

Converging sections were investigated with cone angles α equal to 10, 15, 30, 40, 50, 60, 80, and 140° which were installed between flanges in pipes of diameters D = 20.95 mm and d = 5.81 mm, and had the same values of the diameters of the inlet and outlet cross sections respectively (Fig. 1). Sudden constrictions were formed by coaxially connecting a section of pipe of D = 20.95 mm with tubes of d = 5.81, 10.68, and 15.64 mm, which were investigated as special cases of converging sections with cone angles of $\alpha = 180°$. The degree of constriction of the stream $m = (d/D)^2$ therefore assumed values of 0.077, 0.260, and 0.557. The material of construction of the pipes was stainless steel. The sections of the pipelines were connected by flanged and threaded fittings. The test loop and the procedure for carrying out the experiments have been described in detail in [6].

The PAA (TU 6-011049-81*), supplied industrially in the form of a technical grade gel, was dissolved in tap water (pH = 7.65) over a period of two days with periodic agitation and the concentration of the solution was then diluted to the calculated value. The mass concentrations C of the solutions which were prepared varied from 10^{-7} to 5×10^{-4}, calculated on the basis of the anhydrous PAA material. In order to eliminate the effects of the mechanical destruction of the polymer on the results of the investigation, the solutions were used once only and their motion was accomplished under the influence of the force of gravity. During the time of the experiments the temperature of the solution was maintained in the range 18-23°C, which was measured to an accuracy of 0.1°C. The Reynolds number varied from 2×10^3 to 4×10^4.

The effectiveness of the solution being investigated was checked by its effect on the hydraulic resistance of the section 3-4 of the pipe of diameter d (see Fig. 1). The hydraulic friction coefficient λ was determined in this case from the Darcy–Weisbach formula: $\Delta h_{3-4} = \lambda(\ell_{3-4}/d)(v_d^2/2g)$.

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*TU = Technical Regulation.

L'vov Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No 5, pp. 709-712, November, 1989. Original article submitted April 26, 1988.

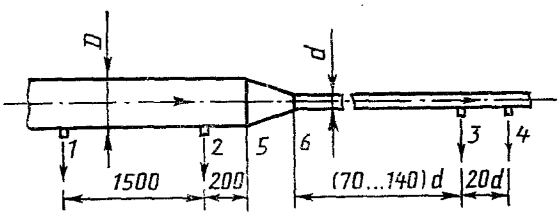

Fig. 1. Sketch of the experimental pipeline: 1)-4): connections for pressure tappings; 5) and 6): inlet and outlet cross sections of converging section; dimensions are given in mm.

The resistance coefficient of the converging section ζ referred to the mean velocity of the flow after the local resistance was found from the Weisbach formula: $h = \zeta v_d^2/2g$. The local head loss h was calculated by the method of subtracting the measured friction loss from the overall head loss over the measurement section 2-3 of the pipeline which contains the converging section (see Fig. 1):

$$h = \Delta h_{2-3} - (l_{2-5}/l_{1-2})\,\Delta h_{1-2} - (l_{6-3}/l_{3-4})\,\Delta h_{3-4} + \alpha_D v_D^2/2g - \alpha_d v_d^2/2g.$$

In the calculation it was assumed that $\alpha_D \approx \alpha_d \approx 1$. Since the kinematic viscosity of the solutions being investigated differed very little in practice from the viscosity of the solvent, the value was taken as a function of the solution temperature as for water.

The additives led to an increase in the resistance for all the converging sections and sudden contractions of the pipes which were investigated. The largest values of the coefficient of local resistance corresponded to the highest concentrations of the solution (Fig. 2). As in the case of diffusers [5, 6], the presence of the PAA additive in the water stream led to an earlier onset of the self-similarity of the coefficient ζ with respect to the Reynolds number. In this zone, which falls within the range of Reynolds numbers investigated and commenced at $Re > (15\text{-}20) \times 10^3$, the resistance coefficient of the converging section depended only on the solution concentration for each value of α. The additives showed practically no effect on the resistance of the converging section when $C \leq 10^{-4}$ in the zone $2 \times 10^3 < Re < (3.5\text{-}5.5) \times 10^3$. In the interval between these zones, i.e., for $(3.5\text{-}5.5) \times 10^3 < Re < (15\text{-}20) \times 10^3$, the value of the coefficient ζ depends on the solution concentration and the Reynolds number. In this case for solution concentrations exceeding 10^{-4} the curves of the relationship $\zeta = f(Re)$ show a hysteresis pattern. As the cone angle of the converging section increases, the boundaries of this zone shift towards lower Reynolds numbers.

The largest values of the resistance of the converging sections with PAA additives were obtained at $\alpha = 10\text{-}30°$. At cone angles exceeding 60° the relative change in the coefficient ζ, defined as the ratio $\Delta\zeta/\zeta$, varied little in practice as the value of α increased. Reductions in the resistance by the PAA additives were not observed for the converging sections which were tested, but for cone angles close to zero these could occur, since this always occurred for all the solution concentrations investigated for the cylindrical tubes, for which $\alpha = 0$ [5, 6].

The reductions in the resistance of the converging section in the experiments of V. B. Amfilokhiev [4] at $\alpha = 40°20'$ and values of D and d close to ours can be explained by the greater hydrodynamic activity of PEO compared to PAA. Backing up this statement are the results which we obtained during investigations of the turbulent flows of polymer solutions through orifices of opening $d_0 = 16.95$ mm placed in a pipe of D = 20.95 mm [7]. Aqueous solutions of PAA of mass concentration 5×10^{-4} showed no effect on the resistance of the orifice, while solutions of PEO (Polyox Coagulant (Union Carbide Corp.) of molecular weight 6.5×10^6) of concentrations 3×10^{-5} and 10^{-4} caused reductions in the resistance of 9.7 and 18.9%, respectively.

On the basis of the data obtained here and already existing in the literature the following conclusions were reached. The PAA additives increase the resistances of converging sections. The relative change in the resistance coefficient ζ caused by the effects of the additive depends on the solution concentration, the cone angle of the converging section, and the Reynolds number. A reduction in the resistances of converging sections by polymer

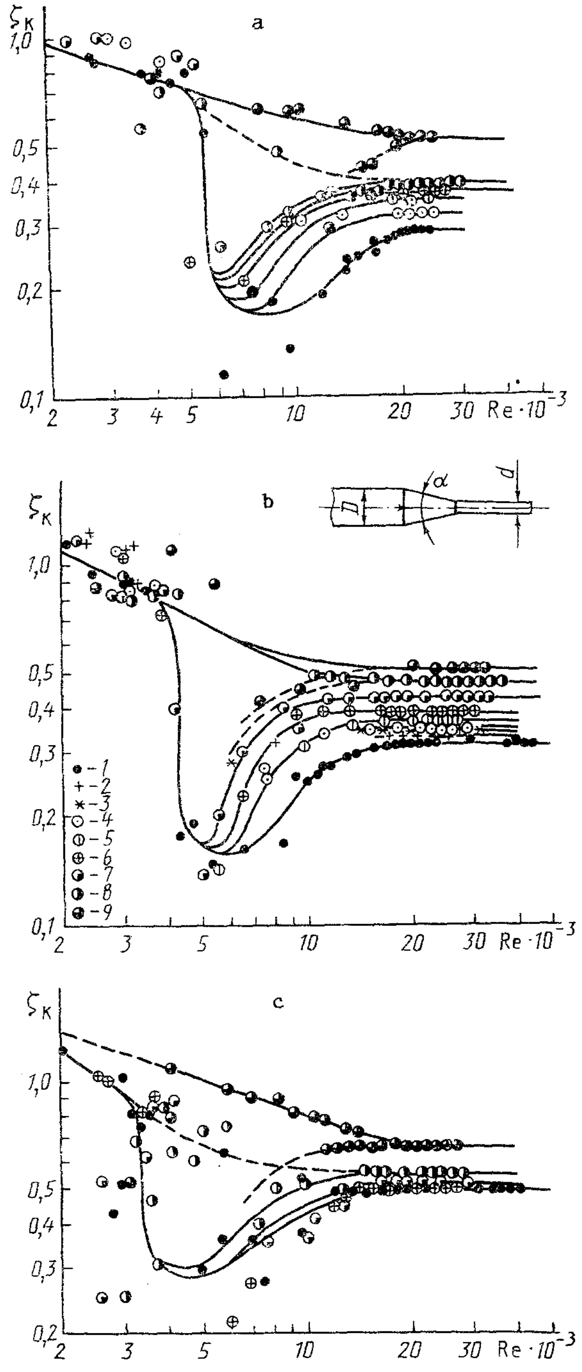

Fig. 2. Dependence of the resistance coefficient of a converging section on the Reynolds number for various cone angles (a): α = 10°; b): α = 30°; c) α = 140°) for flows of water (1) and aqueous PAA solutions with the following concentrations: 2): 10^{-7}; 3): 5×10^{-7}; 4): 10^{-6}; 5): 5×10^{-6}; 6): 10^{-5}; 7): 5×10^{-5}; 8): 10^{-4}; 9): 5×10^{-4}; D = 20.95 mm, d = 5.81 mm.

additives can be expected when their cone angles are close to zero and also when polymers, such as PEO, with higher molecular weights are used.

NOTATION

D, d, diameters of the inlet and outlet cross-sections of the converging section and the pipe sections adjacent to them; $m = (d/D)^2$, degree of contraction of the stream in the converging section; α, cone angle of the converging section; $\ell_{1-2}, \ldots, \ell_{3-4}$, lengths of the sections 1-2 and 3-4 of the pipeline (see Fig. 1); c, mass concentration of solution; h, head loss in converging section, mm H_2O gage; Δh_{1-2} and Δh_{3-4}, head losses in sections 1-2 and 3-4, respectively; α_D, α_d and v_D, v_d, corrections for the kinetic energy and mean velocity of the flow in the pipe sections of diameters D and d; g, acceleration of free fall; $Re = v_d d/\nu$, Reynolds number; ν, kinematic viscosity; λ, hydraulic friction coefficient for pipe; ζ, resistance coefficient of converging section; ζ_B, ζ_π, resistance coefficients during the flow of water and of aqueous PAA solution; $\Delta\zeta/\zeta = 100\%$, $(\zeta_B - \zeta_\pi)/\zeta_B$ relative change in the coefficient ζ caused by the introduction of the PAA additive to the stream under otherwise equal flow conditions.

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CONJUGATE HEAT TRANSFER IN THE LAMINAR FLOW OF A SWIRLED INCOMPRESSIBLE FLUID IN A HORIZONTAL ANNULAR DUCT

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UDC 536.242:532.542.2

The heat transfer associated with swirled flow of a heat-transfer medium in a semi-infinite annular duct is analyzed numerically. The walls of the duct have a finite thickness and exert a significant influence on the formation of the temperature fields in the fluid.

The swirling of flow in ducts, annular ducts in particular, is widely employed in engineering as an effective means of intensifying heat- and mass-transfer processes, stabilizing plasmas and flames, and protecting the walls of equipment against high-temperature and chemically aggressive flows. The types of swirled flow are extremely diverse: completely and partially swirled flows, flows with local and constant swirling along the length (ducts fitted with augers, helical liners and windings, etc.), flows in septate and conical ducts, etc. A detailed classification of the types of swirled flows is given in two recently published books [1, 2].

The influence of flow rotation on the velocity distribution in an annular duct and the onset of zones of flow separation from the inner wall have been investigated [3-5] over a wide range of swirling factors, Reynolds numbers, and thicknesses of the annular space. The specific characteristics of the intensification of convective heat transfer by swirled flow of a heat-transfer medium in an annular duct are discussed in [6, 7]. The main experimental and theoretical results on the hydrodynamics and heat transfer of swirled flows in axisymmetrical ducts are generalized in [2].

Lately a growing importance has been placed on the solution of both the inner and outer problems of convective heat transfer in the conjugate setting: in general, the temperature fields in the duct walls and in the fluid flow are highly interdependent, and appreciable errors can arise in thermal calculations if this coupling is ignored. Data from investiga-

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A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 5, pp. 713-720, November, 1989. Original article submitted May 7, 1988.

0022-0841/89/5705-1270$12.50