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FLOW OF VISCOELASTIC LIQUIDS THROUGH METAL FILTER SCREENS

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This article reports on the results of the pressure drop measurements in dependence on the liquid volume flow rate in the creeping flow of viscoelastic aqueous polymer solutions through woven metal screens. The respective experiments were performed in a plastic cell of 50 mm inner diameter in which the tested screen had been placed. In such measurements, the six types of screens of different weaving were examined in the flow of nine various polymer solutions. In the flow, a strong elastic pressure drop excess manifests itself. By analysing the experimental data, it has been verified that the pressure drop excess can be evaluated using the corrective Deborah number function.

Introduction

The flow of fluids through the woven metal screens takes place in numerous areas of technology and engineering processes. For example, the metal filter screens are

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used in the polymer processing as a filter medium owing to their good resistance towards chemical and mechanical attacks and a relatively narrow distribution of the pore size.

While a large number of theoretical and experimental works have been devoted to the investigation of the flow of Newtonian fluids (e.g., Fischer and Gerstmann [1]) there are only a few studies on the flow of non-Newtonian liquids through the screens. Among them, Chhabra and Richardson [2] studied experimentally the flow of shear thinning carboxymethyl cellulose solutions through a screen, proposing a relationship between the drag coefficient and the power law Reynolds number. Kiljanski and Dziubinski [3] extended this study by using shear thinning molten polyethylene and obtained a correlation of the drag coefficient with the Reynolds number also for multiple screens. Prasad and Chhabra [4], based on the analogy between the flow through arrays of cylinders and a bed of screens, proposed yet another relationship between the drag coefficient and modified power law Reynolds number. This relationship correlates their pressure drop measurements in the flow of inelastic aqueous solutions carboxymethyl- cellulose and sodium alginate for both above-mentioned flow configurations.

Ting *et al.* [5,6] investigated the effect of weave pattern, aperture/diameter ratio, and non-Newtonian fluid behaviour on the pressure drop by means of mathematical modelling. Observations of these authors were found to be in good agreement with the existing experimental data. Finally, the results of the pressure drop measurements in the flow of purely viscous aqueous polymer solutions through six different types of metal filter screens were presented by Surý and Machač [7]. Analogously to the porous media flow, the resulting elastic effects, in a form of a pressure drop excessive to that accountable for a liquid shear viscosity, manifest themselves in the flow of viscoelastic liquids through the screens [8].

In this contribution, we report on the results of our experimental investigation of the pressure drop excess in the flow of viscoelastic polymer solutions through six mesh metal screens previously used in the work [8].

Fundamentals

A pressure drop in the flow of a liquid through a filter screen depends on the liquid rheological behaviour, its velocity, and the screen geometry. For solution of an inner non-Newtonian flow problem, one can use the power law model

$$\tau = K\dot{\gamma}^{n} \qquad (1)$$

with parameters K and n, to approximate the flow curve of a non-Newtonian liquid. It is generally accepted that the flow of a purely viscous fluid through a screen can be described; namely, in the form of a dependence of the drag coefficient *f* on the Reynolds number *Re*. The drag coefficient was defined by Weighart [9] as

$$f = \frac{2\Delta p_{\mathrm{pv}}}{\rho(u/\varepsilon)^2}\frac{1}{1-\varepsilon} \tag{2}$$

where Δp_{pv} is the pressure drop, ρ the fluid density, *u* the fluid superficial velocity, and ε is the fraction of total screen area available for the flow.

By evaluating experimental data, Chhabra and Richardson [2], as well as, Kiljanski and Dziubinski [3] found that, for the power law liquids in the creeping flow region

$$f = \frac{C}{Re_{\mathrm{n}}} \tag{3}$$

The Reynolds number is defined, similarly to a relation for a pipe flow,

$$Re_{\mathrm{n}} = \frac{\rho(u/\varepsilon)^{2-\mathrm{n}}d^{\mathrm{n}}}{K} \tag{4}$$

where *d* is the wire diameter.

Ting *et al*. [5] argued that a more appropriate expression for Re_{n} is a formula that includes the screen hydraulic diameter d_{h} instead of wire diameter *d*, i.e.

$$Re_{\mathrm{n}} = \frac{\rho(u/\varepsilon)^{2-\mathrm{n}}d_{\mathrm{h}}^{\mathrm{n}}}{K} \tag{5}$$

Considering that a fluid element experiences the consecutive contraction and expansion as it traverses the screen pore, the elastic pressure drop excess can manifest itself during the flow of a viscoelastic fluid running through the screens analogously to the flow in porous media.

The results of numerous works dealing with modelling the flow of viscoelastic polymer solutions through porous media (e.g., Bendová *et al*. [10] or Sobti and Wanchoo [11]) show that the viscoelastic pressure drop excess $\Delta p_{\mathrm{ve}}/\Delta p_{\mathrm{pv}}$ can be expressed by means of the Deborah number correction function,

$$\frac{\Delta p_{\mathrm{ve}}}{\Delta p_{\mathrm{pv}}} = f(De) \tag{6}$$

where Deborah number *De* is defined as a ratio of the fluid characteristic time λ_{f} and the process characteristic time t_{p}

$$De = \frac{\lambda_{\mathrm{f}}}{t_{\mathrm{p}}} \tag{7}$$

The resulting form of the Deborah number depends on the expression of both characteristic process time t_p and the characteristic liquid time λ_f.

Characteristic time of process t_p is directly proportional to the liquid path in the flow direction and indirectly proportional to the liquid velocity. Therefore, for the flow through a wire screen, it can e.g. be determined as

$$t_p = \frac{d}{u/\varepsilon} \tag{8}$$

The determination of a suitable representative liquid characteristic time λ_f from rheological models is not an unambiguous task if one considers that the liquid elastic response depends on the flow history. It has been found [12] that from the tested relaxation times determined from molecular theories, linear elasticity, normal stress, and capillary thinning measurements, the use of the characteristic time , λ_E, evaluated from the capillary thinning measurements, is the most acceptable for Deborah number calculation when estimating the pressure drop excess in the creeping flow of viscoelastic polymer solutions through fixed beds of particles. By expecting the analogy between the flows through porous beds and wire screens, the Deborah number

$$De_E = \frac{\lambda_E u}{d\varepsilon} \tag{9}$$

was used for testing of the applicability of the Deborah number corrective function in the following form (defined in Ref. [10])

$$f(De_E) = 1 + C_1 \frac{(C_2 De_E)^{C_3}}{1 + (C_2 De_E)^{C_3}} \tag{10}$$

Experimental

The dependence of the pressure drop on the volume flow rate was measured in the flow of aqueous solutions of polymers, exhibiting various measures of shear thinning and elasticity, through six different mesh woven metal screens. The polymeric liquids were solutions of polyacryl amides Praestol 2935/74, Kerafloc KX4026, and Hercofloc 818. Their characteristics are given in Table I. Rheological properties (flow curves, normal stresses, oscillatory, creep, and recovery tests) of liquids were measured on the rotational rheometer MARS. Additional measurements of capillary thinning and break-up process of liquids were performed using rheometer CABER 1 [13].

Basic characteristics of the filter screens used, differing in the wire diameter, aperture dimension, and the type of weaving, are summarized in Table

II. The screens dimensions were determined using a micrometre together with analysis of the corresponding microscopic images. The scheme of knitting of screens is shown in Fig. 1. The hydraulic diameters d_h of the screens II and III were evaluated from the pressure drop measurements in the flow of Newtonian solution of polyalkylene glycol Emkarox.

Table I Characteristics of test liquids

Liquid symbol	Concentration	Density	Shear rate range	Power law parameters		Relaxation times
	w, wt. %	ρ, kg m^{-3}	$\dot{\gamma}$, s^{-1}	K, Pa s^n	n	λ_E, s
Pr08	0.8	1001	20-2 000	1.01	0.44	0.44
Pr10	1	1002	10-2 000	1.464	0.4	0.56
Pr12	1.2	1004	10-2 000	1.75	0.38	0.71
Ke04	0.4	1001	30-2 000	0.771	0.43	0.42
Ke05	0.5	1001	10-2 000	0.958	0.4	0.39
Ke06	0.6	1002	10-2 000	1.513	0.38	0.47
He04	0.4	1001	10-2 000	1.169	0.41	0.4
He05	0.5	1001	10-2 000	1.785	0.38	0.42
He06	0.6	1001	10-2 000	2.695	0.36	0.46

Table II Characteristics of filter screens

Screen symbol	Type of weaving	Shute wire diameter	Warp wire diameter	Porosity	Screen height	Hydraulic diameter
		d_s, mm	d_w, mm	ε	H, mm	d_h, mm
I	plain twilled	0.037	0.037	0.796	0.091	0.051
II	Dutch	0.036	0.053	0.418	0.136	0.016
III	twilled Dutch	0.150	0.215	0.543	0.650	0.055
IV	plain square	0.025	0.025	0.758	0.062	0.040
V	plain square	0.045	0.045	0.809	0.109	0.080
VI	plain square	0.095	0.095	0.859	0.228	0.160

The pressure drop measurements were performed in a laboratory device consisting of a plastic pressure drop measuring cell of 50 mm in inner diameter with a calming tube of 40 mm in length. The liquid volume flow rate was determined by weighing on a digital balance. The pressure drop was measured with the aid of a differential pressure transducer, and the flow rate data were recorded by a personal computer. The respective experiments are described in detail in a PhD thesis by Surý [13].

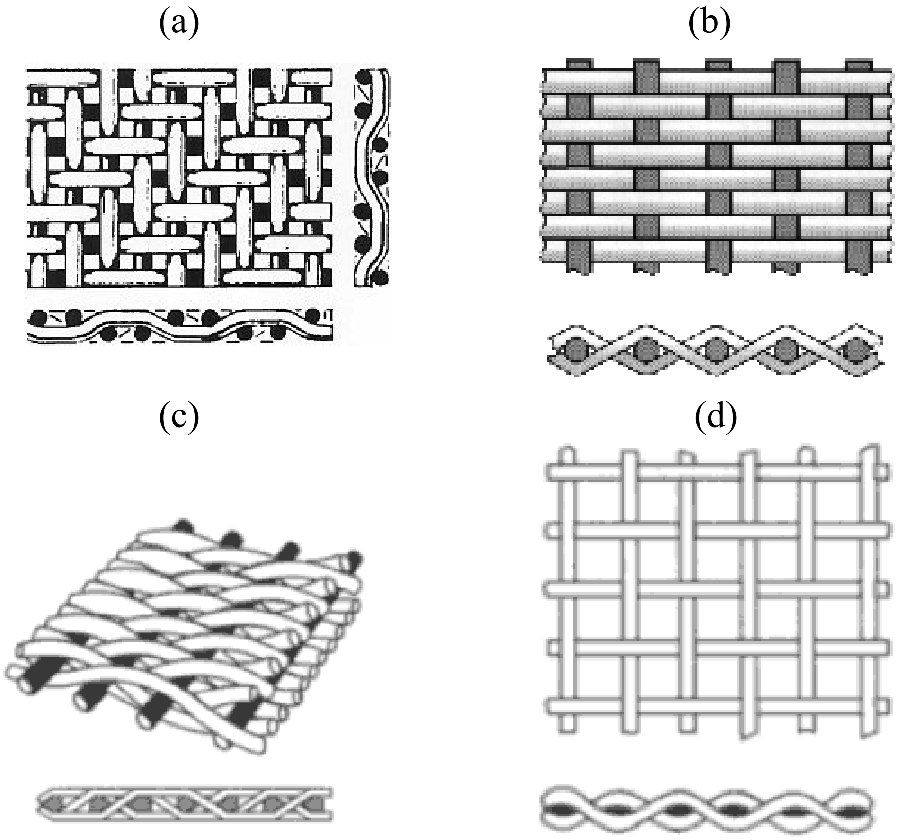

Fig. 1 Weave of filter screens; (a) – screen I, plain twilled weave; (b) – screen II, Betamesh Dutch weave; (c) – screen III, twilled Dutch weave; (d) – screens IV-VI, plain square weave

Results and Discussion

Rheological Characteristic of Liquids

From the shear rate-shear stress rheometric data, the parameters n and K of the power law model (1) were determined. Their values, evaluated in the shear rate interval $\Delta\dot{\gamma}$, are summarized in Table I. Examples of viscosity function for 0.8% Praestol, 0.4% Kerafloc, and 0.6% Hercofloc are shown in Fig. 2, where one can see that all the polymer solutions are shear thinning. The values of the times λ_E show that these liquids are evidently viscoelastic.

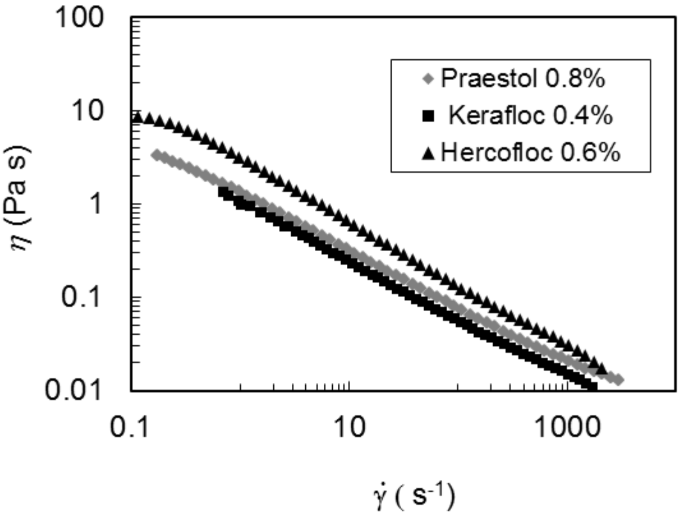

Fig. 2 Viscosity functions of 0.8% Praestol, 0.4% Kerafloc, and 0.6% Hercofloc

Pressure Drop

It was found in the work [7] that pressure drop data for the flow of purely viscous non-Newtonian liquids through filter screen tested can be predicted according to the relationship

$$f = \frac{1\,021}{Re_n} \tag{11}$$

The pressure drop data Δp_{ve} measured in the flow of viscoelastic liquids were compared with the corresponding pressure drop data Δp_{pv} calculated for the flow of purely viscous liquids according to Eq. (11). It was found that these liquids had exhibited a strong elastic pressure drop excess. In our experiments, the ratio $\Delta p_{ve}/\Delta p_{pv}$ increased surprisingly, unlike the flow through fixed beds of particles, as much as sixty times.

The possibility to use the Eq. (10) to estimate the elastic pressure drop excess was further verified. At the same time, the diameter d in the Deborah number (9) was substituted by quantity $d = (d_s + d_w)/2$. The examples of the dependences obtained, i.e. $\Delta p_{ve}/\Delta p_{pv}$ on De_E , are plotted in Figs 3 and 4. For determining the form of the Deborah corrective function dependence (10), the values of parameters C_1-C_3 were evaluated by optimizing the experimental data. It has been found that the value of parameter C_1 = 120 can be taken for all the liquids and screens.

The best values of parameters C_2 and C_3 for the individual screens depended on the type and concentration of polymer solution. Examples of these parameters for the three screens I, III, and V are shown in Table III. The accuracy of approximation of the pressure drop excess experimental data for the individual

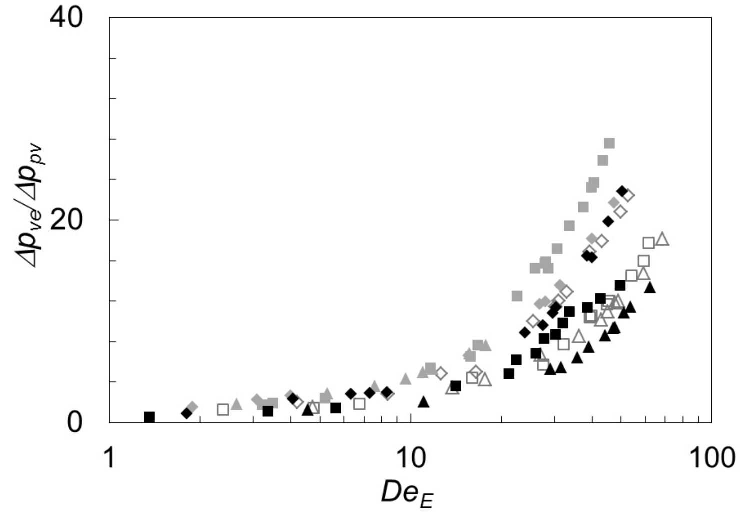

Fig. 3 Dependences of the ratio $\Delta p_{ve}/\Delta p_{pv}$ on Deborah number De_E for filter screen II: ◇ – 0.8% Praestol; □ – 1.0% Praestol; △ – 1.2% Praestol; ◆ – 0.4% Kerafloc; ■ – 0.5% Kerafloc; ▲ – 0.6% Kerafloc; ◆ – 0.4% Hercofloc; ■ – 0.5% Hercofloc ; ▲ – 0.6% Hercofloc

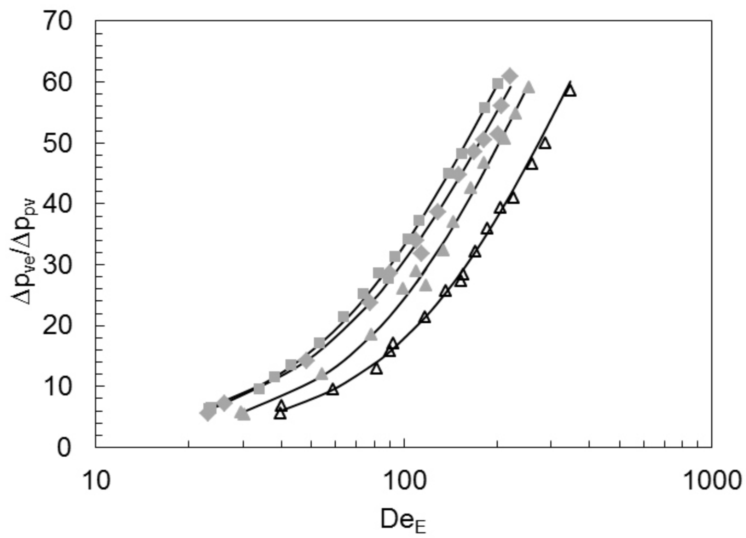

Fig. 4 Dependences of the ratio $\Delta p_{ve}/\Delta p_{pv}$ on Deborah number De_E for filter screen IV: △ – 1.2% Praestol; ◆ – 0.4% Kerafloc; ■ – 0.5% Kerafloc; ▲ – 0.6% Kerafloc; —— – Eq. (11))

systems was evaluated according to mean relative deviations δ_m between experimental data and those calculated from Eq. (10); the respective values of δ_m ranging from 2.1 % to 9.1 %. The example of the dependence expressed by Eq. (10) is illustrated in Fig. 4, seen as the full lines for the flow through the screen IV.

However, the predictability of the Deborah number function (10) is limited due to the dependence of the characteristic time λ_E and parameters C_2 and C_3 on the polymer solution concentration. Nevertheless, a rough estimate of the elastic pressure drop excess can be obtained for each filter screen and polymer solution independently on their concentration by substituting the average values of the relaxation times λ_E and parameters C_2 and C_3 into the Eq. (10). In this case, the mean relative deviation calculated for all the measurements, δ_m = 11 %, with the maximum relative deviation δ_m = 32 %, was reached for the solution He06 in the flow through the screen II, and with the individual maximum relative deviation δ = 42 %.

Table III Values of parameters C_2 and C_3 for screens I, III, V, C_1 = 120

Liquid	Screen I			Screen III			Screen V		
	C_2	C_3	δ_m, %	C_2	C_3	δ_m, %	C_2	C_3	δ_m, %
Pr08	90.0	1.18	5.3	-	-	-	-	-	-
Pr10	87.8	1.41	3.5	-	-	-	-	-	-
Pr12	100.0	1.40	9.1	50.0	1.30	5.3	59.3	1.43	2.4
Ke04	96.4	1.26	6.0	28.3	1.00	4.0	60.3	1.43	8.5
Ke05	115.0	1.46	4.1	32.2	1.21	4.0	58.7	1.23	2.2
Ke06	96.4	1.33	4.1	24.0	1.08	5.8	54.0	1.38	3.5
He04	57.6	1.43	5.0	-	-	-	-	-	-
He05	59.9	1.33	4.1	-	-	-	-	-	-
He06	44.2	1.37	4.4	-	-	-	-	-	-

Conclusion

The pressure drop measurements in the flow of viscoelastic polymer solutions through woven metal filter screens have been performed in consequence of which a substantial elastic pressure drop excess has been observed.

It has been verified that the pressure drop excess observed can be predicted with a satisfactory accuracy by using the Deborah number corrective functions defined in Eq. (10). The parameters C_1-C_3 needed to determine this function must be evaluated from the pressure drop measurements.

Symbols

C parameter in Eq. (3)
C_1-C_3 parameters in in Eq. (10)
De Deborah number, Eq. (7)
De_E Deborah number, Eq. (9)
d wire diameter, m

d_{ap} aperture diameter, m
d_h screen hydraulic diameter, m
d_s shute wire diameter, m
d_w warp wire diameter, m
f drag coefficient, Eq. (2)
K power law parameter (consistency), Pa s^n
n power law parameter (flow index)
Δp pressure drop, Pa
Δp_{pv} pressure drop of purely viscous fluid, Pa
Δp_{ve} pressure drop of viscoelastic fluid, Pa
Re_n Reynolds number, Eqs (4) and (5)
t_p process characteristic time, Eq. (8), s
u superficial velocity of liquid, m s^{-1}
w weight concentration, %
$\dot{\gamma}$ shear rate, s^{-1}
δ_m mean relative deviation, %
ε fraction of total screen area available for flow
ρ density of liquid, kg m^{-3}
λ_E characteristic time for viscoelastic stress growth, s
λ_f liquid characteristic (relaxation) time, s
τ shear stress, Pa

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