Table 2 Average molecular weights reported[1] for each sample and its *Gex* model given by parameters *m*, *k*, and *y*[a]

Sample	Molecular weights X 10^3			
	M_n	M_w	M_z	M_{z+1}
1-Polyisobutylene (M_0 = 56.1):				
Reported[1] from g.p.c.	171	597	1730	5012
Model, y = 19.4499	176.1	620.8	1854	4873
. . Polyisobutylene:				
Reported[1] from g.p.c.	565	3382	10930	24372
Model, y = 0.2987	565	3381	10695	25083
2-Polystyrene (M_0 = 104.1):				
Reported[1] from g.p.c.	74	165	304	479
Model, y = 0.26733	74	165.1	296.9	461.9
3-Poly(vinylidene fluoride) (M_0 = 64):				
Reported[1] from g.p.c.	75	191	409	689
Model, y = 0.32406	74.6	192.1	380.5	653.4
4-Poly(vinyl alcohol) (M_0 = 44):				
Reported[1] from g.p.c.	66	294	941	1846
Model, y = 3.3216	65.7	295.1	933.3	2376
5-Poly(vinyl acetate):				
Reported[1] from g.p.c.	217	611	1821	5287
Not *Gex*; (if *LN*, H = 2.8)	(217)	(611)	(1715)	(4800)
6-Poly(vinyl pyrrolidone) (M_0 = 111):				
Reported[1] from g.p.c.	10	24	54	100
Model, y = 66.7324	9.86	24.5	56.6	122.5
7-Poly(methyl methacrylate) (M_0 = 100):				
Reported[1] from g.p.c.	252	481	766	1196
Model, y = 0.05676	250.8	483.3	780.9	1141
8-Polyacrylonitrile (M_0 = 53):				
Reported[1] by g.p.c.	38	116	249	405
Model, y = 0.17914	38	116	239.6	417.4
9-Polybutadiene (M_0 = 54):				
Reported[1] by g.p.c.	142	443	1076	1745
Model, y = 1.71021	142.3	442.2	1067	2195
10-Poly(2,6-dimethyl-1,4-phenylene oxide) (M_0 122):				
Reported[1] by g.p.c.	26	56	88	117
Model, y = 0.01969	25.7	56.7	97	130.5
11-Poly(2,6-diphenyl-1,4-phenylene oxide) (M_0 = 246):				
Reported[1] by g.p.c.	297	550	875	1319
Model, y = 0.051843	295.1	553.6	872.7	1247
12-Poly(ethylene terephthalate) (M_0 192):				
Reported[1] by g.p.c.	27	62	116	198
Model, y = 2.1549	26.8	62.3	119.6	202.3
13-Poly(6-aminohexanoic acid) (M_0 = 113):				
Reported[1] by g.p.c.	50	118	233	371
Model, y = 1.2649	49.5	118.6	231.7	399.8

[a] For each sample, the parameters *m* and *k* given in *Table 1* were used with the value of *y* estimated for its model.

of sample 12, a poly(ethylene terephthalate), are close in value to those of several samples of this polymer reported by Browning and Overton[7]. These authors gave g.p.c. data on 30 samples of this polyester; of these 27 could be assigned *Gex* parameters.

It is suggested that since the *Gex* distributions offer adequate descriptions of many of the polymers of ref 1, they may provide the new theoretical approach sought by its authors.

From *Tables 1* and *2*, one notes that the quotients and models of average molecular weights provided by the *Gex* distribution agree quite well with the g.p.c. data of ref 1 for these economically important polymers: polyisobutylene, polystyrene, poly(methyl methacrylate), polyacrylonitrile, and poly(ethylene terephthalate). The greatest deviations were found for poly(vinyl acetate) and its chemical derivative, poly(vinyl alcohol). It has already been shown[2,3] that the *Gex* distribution describes many polyolefins.

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Turbulent flow characteristics of solutions of hydroxylpropylmethyl cellulose

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INTRODUCTION

The phenomenon of turbulent drag reduction by means of polymer additives has recently been reviewed by Hoyt[1,2], Virk[3], and Little *et al.*[4]. A disadvantage associated with effective drag-reducing polymers, such as poly(ethylene oxide), is the occurrence of rapid diminuation of the drag-reducing efficiency of the polymer as a result of shear degradation. Recently, considerable effort has been put in by researchers to search for shear-resistant polymers which can be used in recirculatory pipe flows. In the present Note, results from a study of the friction-reducing properties of a new polymer belonging to the cellulose family are reported.

The polymer used in the present investigation is hydroxylpropylmethyl cellulose – a commercial product of the Imperial Chemical Industries, UK. This polymer is marketed as Methofas. Methofas is a non-ionic methyl cellulose derivative modified by the inclusion of a small percentage of the hydroxylpropyl

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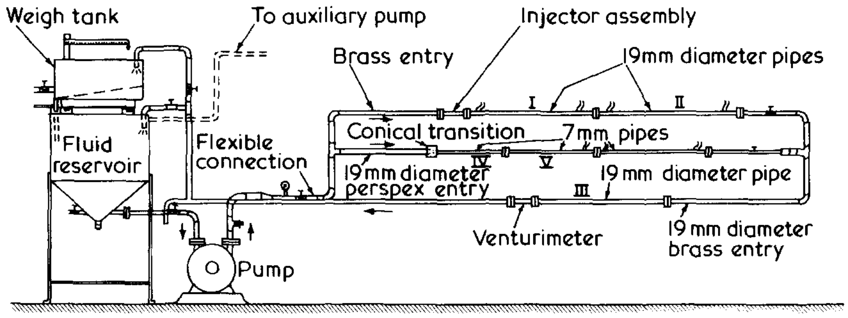

Figure 1 Schematic sketch of closed loop system

group. The structural details of this polymer have been published by ICI[5]. In the present study, Methofas P designated as PM–10 000 has been used. The numeral which follows the grade designation indicates the viscosity limit in centipoise of a 2% aqueous solution of the polymer at 20°C.

EXPERIMENTAL

The rheological properties of various concentrations of the Methofas solution were investigated with the help of a capillary viscometer. Three sizes of glass capillary tubes with diameters of 0.403, 0.604 and 1.00 mm were used. The sizes of the capillary tubes were chosen to cover the entire range of the stress expected to occur in turbulent pipe flows. In order to minimize entrance effects, tubes with length to diameter ratios larger than 200 were used.

A closed loop flow system (*Figure 1*) consisting of acrylic test pipes of 7 and 19 mm diameter was used to study the friction-reducing properties of the Methofas. Each test section was 2 m long and arranged in parallel in a vertical plane. Each test pipe was provided with two 2 mm diameter static pressure taps spaced 1.53 m apart. Pressure drop was measured manometrically. The flow rate through the test loop was measured gravimetrically. Complete details of the instrumentation used in the study are described by Sharma[6].

Experiments were conducted on Methofas solutions with average concentrations in the range of 100–2500 ppm (by wt). Possible effects of shear degradation on the rheological properties of the Methofas solutions were eliminated by using fresh samples for carrying out the capillary viscometer tests. The homogeneous solutions of Methofas used in the pipe flow experiments were prepared by gradually sprinkling fine Methofas powder over a stream of water entering the weighing tank. A homogeneous solution of Methofas was ensured by continuously recirculating it through the system for approximately 0.5 h prior to taking the measurements. According to the results of the degradation studies presented in the last section of the paper, it will be seen that this recirculation would not cause any degradation of the polymer.

RESULTS AND DISCUSSION

The variation of the wall shearing stress with average strain rate for solutions of various concentrations tested is shown in *Figure 2*. Best fit lines have been drawn through the data points by the method of least squares. The tap water line can be seen to be in good agreement with the correlation $\mathrm{dln}(D\Delta P/4L)/\mathrm{dln}(8\bar{U}/D) = 1$, where ΔP is the pressure drop in a capillary tube of diameter D and length L at an average flow velocity of $\bar{U}$. Since the slope of each line is constant, Methofas solutions essentially behave as power law fluids. The slope of the lines corresponding to solutions up to an average concentration of 2000 ppm is nearly unity. For a solution of 2500 ppm, the slope has been found to be approximately 0.93 thereby indicating a slight non-Newtonian behaviour. A carboxymethyl cellulose (CMC) solution having a concentration of 500 ppm has the same value of the flow behaviour index[7]. This comparison indicates that the shear thinning tendency of Methofas solution is low compared with that of a carboxymethyl cellulose solution. The variation of the apparent wall viscosity with wall velocity gradient is shown in *Figure 3*. Apparent wall viscosity is defined as the ratio of wall shear stress to the wall velocity gradient. It may be observed from *Figure 3* that, except at the highest concentration used in the investigation, the apparent wall viscosity is constant throughout the shear rates investigated and it increases as the concentration increases.

The friction factor – Reynolds number curves for tap water for both sizes of test pipes were found to be in good agreement with the Blasius correlation. *Figures 4* and *5* represent composite plots of the f–$Re)_w$ variation for solutions of different concentrations in the 7 and 19 mm test pipes, respectively. In these plots f is the Fanning friction factor defined as:

$$f = \frac{1}{2} \cdot \frac{\Delta P}{\rho \bar{U}^2} \cdot \frac{D}{L}$$

where ΔP is the pressure drop, L is the

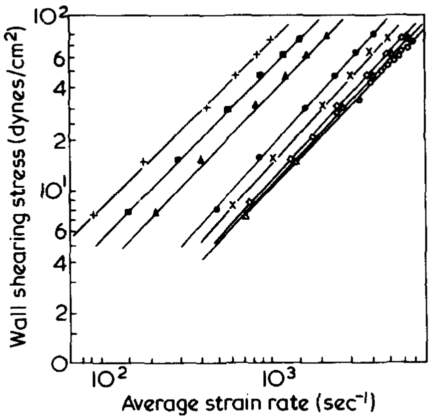

Figure 2 Wall shear stress as a function of average strain rate for Methofas solutions of different concentrations: ○, tap water; △, 100 wppm; □, 250 wppm; ×, 500 wppm; ●, 1000 wppm; ▲, 1500 wppm; ■, 2000 wppm; +, 2500 sppm. A, dln $(D\Delta P/4L)/\mathrm{dln}(8\bar{U}/D) = 1.0$

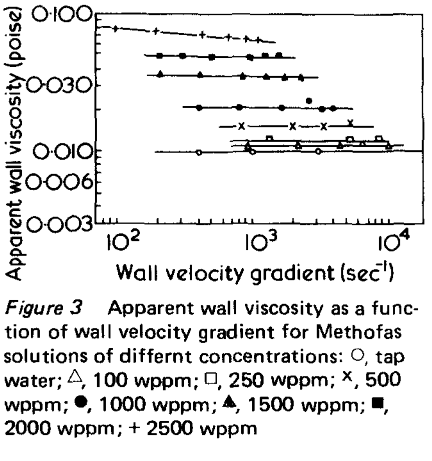

Figure 3 Apparent wall viscosity as a function of wall velocity gradient for Methofas solutions of differnt concentrations: ○, tap water; △, 100 wppm; □, 250 wppm; ×, 500 wppm; ●, 1000 wppm; ▲, 1500 wppm; ■, 2000 wppm; + 2500 wppm

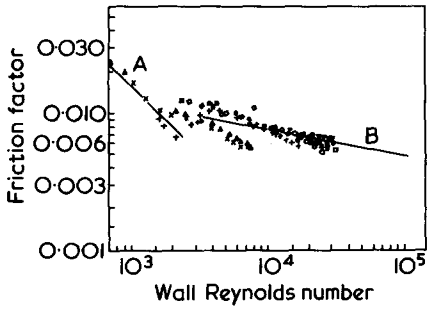

Figure 4 Friction factor as a function of wall Reynolds number for Methofas solutions of different concentrations in 7 mm i.d. pipe: ▽, tap water; ◇, 100 wppm; □, 250 wppm; ○, 500 wppm; +, 1000 wppm; △, 2000 wppm; ×, 2500 wppm. A, $f = 16/R_e$; B, tap water line

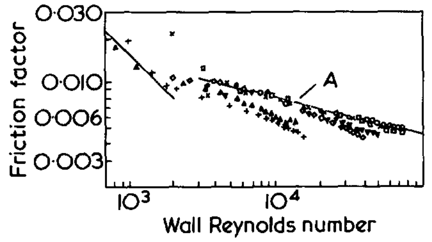

Figure 5 Friction factor as a function of wall Reynolds number for Methofas solutions of different concentrations in 19 mm i.d. pipe: ○, tap water; ×, 100 wppm; □, 250 wppm; ▽, 500 wppm; ◇, 1000 wppm; +, 2000 wppm; △, 2500 wppm

length of the pipe, D is the pipe diameter, $\bar{U}$ is the mean flow velocity and ρ is the density of the flowing fluid. The wall Reynolds number is defined by:

$$Re)_w = \frac{\rho \bar{U} D}{\mu_w^{app}}$$

where μ_w^{app} is the apparent wall viscosity at vanishing shear rate. *Figures 4* and *5* indicate that the Reynolds number corresponding to the onset of friction reduction decreases as the concentration of the Methofas solution increases. Also the friction reduction was found to be a function of the tube diameter, the concentration and the Reynolds number. A comparison of *Figures 4* and *5* shows a discernible diameter effect on friction reduction as has been observed in the case of other polymers[1].

For solutions having concentrations up to 1000 ppm the f–$Re)_w$ data lie above the tap water line for values of $Re)_w$ below the critical Reynolds number. A similar behaviour has been observed by Brandtl *et al.*[8] for the flow of an aqueous solution of CMC in both smooth and rough pipes. However, a comparison of the present results with those of Brandtl *et al.*[8] indicates that the polymer hydroxylpropylmethyl cellulose is superior to CMC as a friction reducer.

The results plotted in *Figure 4* show that the pipe flow of a solution of concentration 1000 ppm exhibits a continuous and smooth transition from the laminar to the turbulent region. For concentrations beyond 1000 ppm the transition appears to have disappeared completely with all the data points lying on a single smooth curve which is an extension of the laminar line up to a maximum achievable Reynolds number of approximately 7000. Such a vastly altered transition process has also been observed by Wells[9] for flows of guar gum solutions, and by Pirih and Swanson[10] for flows of crystal suspensions of milling yellow dye. These authors have interpreted these results to imply that flow instabilities appear in the flow of viscometric solutions at a retarded rate compared with that of water during the transition process. As a result, stabilized viscometric flows of the polymer solution occur which are insensitive to local disturbances.

Degradation studies were conducted with Methofas solutions of concentrations 500 and 1000 ppm by keeping the solution under constant recirculation through the test loop for extended periods of time. The friction factor was measured at various time intervals and the results are shown in *Figure 6*. It is observed from this Figure that the friction factor remains approximately constant for both solutions. Thus, it can be concluded that Methofas offers resistance to the shearing forces produced in the pump. Such a conclusion is in agreement with degradation results obtained with other polymers belonging to the cellulose family.

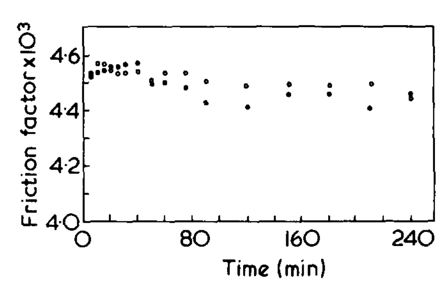

Figure 6 Variation of friction factor with time for Methofas solutions of 500 and 1000 wppm:

Symbol	Concentration (wppm)	$R_e)_w$
○	500	4.7 × 10⁴
●	1000	3.5 × 10⁴

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