Drag Reduction by Polymer–Polymer Mixtures

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Synopsis

An extensive study on the turbulent drag reduction caused by the various mixtures of polyacrylamide, purified guargum, xanthangum, and their graft copolymers has been conducted at low concentrations and Re = 14,000 using a turbulent flow rheometer. It has been found in most of the cases that the drag reduction caused by mixtures shows a positive deviation from the linearly additive straight line. This effect is more prominent when the drag reduction caused by both the constituents differ appreciably. In most of the cases, the drag reduction caused by the mixtures is higher than the DR caused by either of the constituent polymers; however, the drag reduction caused by the mixture is less than the sum of the drag reduction caused by both the constituents at their respective concentration in the mixture. It has also been noticed that there is no evidence of synergism in these mixtures at low concentrations.

INTRODUCTION

Polymer drag reduction, the phenomenon whereby a few parts per million of dissolved macromolecules reduce fluid friction to one-half or less than that of the pure solvent, is currently a very active research area. Generally, high polymers, polymer–fibers, and some soap systems are used as drag reducing agents. These materials reduce the turbulent intensity in the flow, consequently decreasing the flow resistance and input energy. The percentage drag reduction (DR) for conduit flow of an incompressible fluid–additive system is defined as

$$DR = 100 \times (1 - \Delta P_t / \Delta P_s) \qquad (1)$$

where ΔP_t is the pressure drop with test fluid–additive system and ΔP_s is the pressure measured under the same conditions with the fluid. The fluid–additive system is said to be drag reducing if the percentage drag reduction is positive.

The phenomenon of drag reduction is observed in turbulent flow or in laminar–turbulent transition regions. The reduced drag in turbulent flow past solid boundaries, e.g., aerofoils, streamline bodies, and flat plates has also been observed. The practical applications of this phenomenon are in the reduced pumping requirements in oil well fracturing operations, in firefighting and irrigation systems, and in external flows encountered in naval and other nautical systems. The drag reducing polymers may be used in blood stream to aid cases of heart disease by reducing the pumping power required.

The drag reduction has become an important research topic at present due to energy crisis and investigations are in progress in so many different directions regarding the drag reduction problem. The various aspects in which research is going on are loosely defined in the following categories[1]:

(a) Drag reduction in various experimental geometries, new experimental techniques.
(b) Structure and conformation of polymers in solution.
(c) Theories and experiments to study turbulence structure and the mechanism of drag reduction by additives.
(d) Drag reducing suspensions.
(e) Drag reduction of polymer–polymer mixtures in solution.
(f) Drag reduction of polymer–fibers suspensions.
(g) Synthesis of new drag reducing materials.
(h) Heat transfer in drag reducing fluids.

Biodegradability of some polymer materials and shear degradability of polymer and fibers systems are other problems about the applications of drag reducing polymers. According to some studies,[2] the combined exploitation of both the mechanisms, i.e., of polymer and of fiber suspensions, the drag reducting effect can be considerably enhanced. However, this area of drag reduction appears still to be in the exploratory stage.

So far only a limited study has been carried out on the drag reduction caused by polymer–polymer mixtures. Dschagarowa and Bochossian[3] studied the drag reduction in the solutions of polymer–polymer mixtures. The mixtures of polyisobutylene and isoprene rubber dissolved in toluene were used. Polyisobutylene is a better drag reducing agent than the latter polymer. The total concentration of polymer–polymer mixture solution was taken in the range of 200 to 600 ppm. The polymer mixture showed a positive deviation in drag reduction from additive straight line at all compositions, depending upon the ratio of the components in the mixture. The deviation was stronger when the proportion of less effective drag reducing agent (isoprene rubber) in the mixture was higher. Also the deviation increased with flow rate at a given concentration. This deviation is due to the change of polymer coil dimensions and due to the copresence of the molecules of both the polymers in the solution.

Dschagarowa and Menning[4] studied drag reduction in the mixtures of polyisobutylene and polystyrene and a mixture of two polyisobutylenes differing in molecular weights. Positive deviation from the additive straight line was shown by the former mixture, but no deviation was shown by the latter. Dingilian and Ruckenstein[5] reported drag reduction in dilute polymer solutions of polymer–polymer mixtures. The following mixtures were studied: poly(methylene oxide)–carboxymethyl cellulose, polyacrylamide–carboxymethylcellulose and poly(ethyleneoxide)–polyacrylamide. In the solutions of first two mixtures, synergism was observed whereas, in the case of third one, a negative deviation is observed. They suggested that the synergism in drag reduction results when either both of the components or at least one of the

components in the mixture has rigid structure. The drag reduction in the solutions of mixtures of polyethylenimine with poly(ethylene oxide), polyacrylamide, and poly(acrylic acid) was studied by Parker and Joyce.[6] The loss of drag reduction effectiveness of polyacrylamide and poly(acrylic acid) mixture solutions may be due to interaction between anionic polymers. The interaction with nonionic polymers is found to be negligible.

Reddy[7] and Reddy and Singh[8] have extensively studied the aqueous solutions of the mixtures of relatively shear stable polymers such as polyacrylamide, guargum, xanthangum, and carboxymethyl cellulose. They have also studied the drag reduction caused by the mixtures of asbestos fibers with guargum and xanthangum. Both positive and negative deviations from linearly additive straight line have been observed in drag reduction caused by the polymer–polymer mixtures, depending upon their compositions, flow rate, and the polymer species in the mixtures. The drag reduction in the mixtures has been predicted by using simple mixture rule equation, having interaction parameter, i.e.,

$$DR_M = DR_1 W_1 + DR_2 W_2 + I W_1 W_2 \qquad (2)$$

where DR_M is the drag reduction percentage by the mixture and DR_1, DR_2 and W_1, W_2 are the drag reduction percentages and weight fractions of components 1 and 2, respectively, in the mixtures. It is to be noted that

$$W_1 + W_2 = 1 \qquad (3)$$

I is the interaction parameter believed to depend upon the interaction in the polymer mixture. The random coil size, solvation and rigidity of the polymer molecules appear to be responsible for synergism observed in the drag reduction caused by the mixtures. A qualitative relationship has been established between the synergism in drag reduction and solvation number of the polymer. In general, mixture having larger solvation number seems to give positive synergism.

Reddy[7] and Reddy and Singh[8] have studied the drag reduction caused by mixtures using recirculatory system employing centrifugal pump at Reynolds numbers 20,000–60,000, in the concentration range of 200–1000 ppm. Recently Deshmukh et al.[9,10] have developed graft copolymers of guargum and xanthangum which show higher drag reduction effectiveness and biodegradation resistance. Singh et al.[9,12] have also measured the drag reduction percentage vs. composition profiles for commercial, purified, and grafted guargums. They have observed that the purified guargum causes higher percentage drag reduction than the commercial one.

In order that the drag reducing polymers may be used in technical and industrial applications, they should cause considerable drag reduction at lower concentrations and should be shear stable. Keeping these aspects in view, an extensive study has been carried out on homopolymer–homopolymer, graft copolymer–homopolymer, and graft copolymer–graft copolymer mixtures as drag reducing materials by turbulent flow rheometer supplied by Hoyt.[13] By this system, the possibility of polymers being degraded by pump is eliminated.

EXPERIMENTAL

Materials

The following materials were used in the present study.

(1) Guargum (GG) (Hindustan Gums and Chemicals, Bhiwani, India).
(2) Purified guargum (PGG). The commercial guargum was purified by using a method given by Whitecomb.[14]
(3) Xanthangum (XG) (Kelco, U.S.A.).
(4) Purified xanthangum (PXG). The commercial xanthangum was also purified by the method of Whitecomb.[14]
(5) Polyacrylamide (PAM) (Hoechst, France, trade name Bozofloc N-46 BT. Average molecular weight 6×10^6).
(6) Grafted guargum (Gm$_3$) was synthesized by Deshmukh et al.[9] Intrinsic viscosity of Gm$_3$ is 408.7 mL/g in $1M$ NaNO$_3$ solution at 30°C.
(7) Grafted xanthangum (XGm$_3$) was synthesized by Deshmukh and Singh.[10]
(8) Grafted xanthangum (XGm$_4$) was synthesized by Deshmukh and Singh.[10]

Experimental Apparatus and Procedure

Turbulent flow rheometer designed by Hoyt[13] was used for the measurements of initial drag reduction and drag reduction at various pass numbers. It has the following special features. It requires only 150 cc of the solvent and consequently few milligrams of polymers for the measurement of the percentage drag reduction. The percentage drag reduction can be evaluated
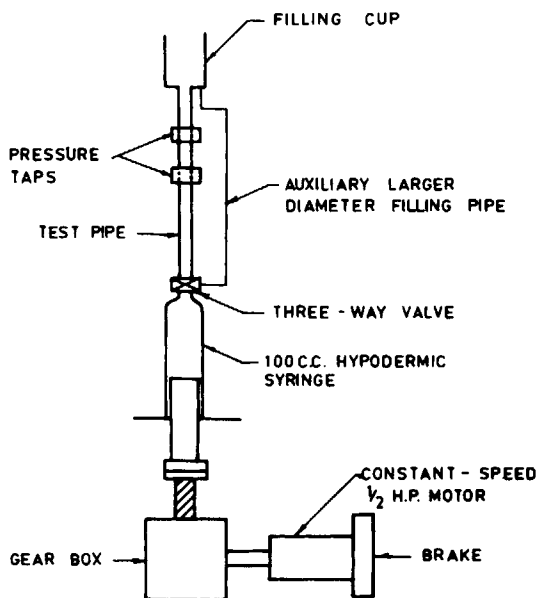

Fig. 1. Turbulent flow rheometer.

within few minutes. Due to incorporation of pressure transducers for pressure drop measurements, the accuracy of measurements has improved appreciably.

Figure 1 depicts the schematic diagram of turbulent flow rheometer due to Hoyt.[13] Essentially the device is a motor-driven glass syringe, the delivery rate of which is determined by a motor speed controller. Flow pipe is stainless steel capillary tube with a diameter of 0.1575 cm. The first tap is placed 200 diameters from the entrance and the second tap is placed 100 diameters from the first. The Statham universal transducers with 10 psi pressure diaphram were used to determine the pressure drop between taps. The pressures are recorded on a dual channel recorder. The linear actuator which directly drives the syringe plunger is coupled to the 1/4 hp electric motor. The travel limits of the actuator were set by two microswitches. The apparatus operates at the Reynolds number of 14,000. The percentage drag reduction (DR) is calculated using eq. (1).

RESULTS AND DISCUSSION

The following mixtures have been studied for their drag reducing effectiveness at the Reynolds number of 14,000 and the concentrations of 20 and 100 ppm.

 (1) Purified guargum–polyacrylamide.
 (2) Purified guargum–purified xanthangum.
 (3) Purified guargum–grafted guargum.
 (4) Purified guargum–grafted xanthangum.
 (5) Grafted guargum–polyacrylamide.
 (6) Grafted guargum–grafted xanthangum.
 (7) Purified xanthangum–grafted xanthangum.
 (8) Purified xanthangum–grafted guargum.
 (9) Polyacrylamide–purified xanthangum.
(10) Polyacrylamide–grafted xanthangum.

Purified Guargum–Polyacrylamide Mixtures

The commercial guargum–polyacrylamide mixtures were studied at total concentration of 200 ppm at Reynolds numbers 20,000–56,000 over the entire composition range by Reddy and Singh.[8] In this particular case, both positive and negative deviations from linear additive straight line have been observed. At higher Reynolds numbers, the theoretical values obtained by mixture law equation are in good agreement with experimental values. In the present case, the mixtures of purified guargum with polyacrylamide have been studied at lower concentrations and at a lower Reynolds number at 14,000. Figure 2 depicts the drag reduction percentage vs. composition for PGG–PAM at 20 ppm concentration, and Figure 3 depicts the drag reduction percentage vs. composition at 100 ppm. In both the cases, there is positive deviation from the additive straight line. The theoretical values of drag reduction calculated on the basis of eq. (2) according to the method of Reddy and Singh[8] are close to experimental values of drag reduction as shown in Tables IA and IB. It is also obvious from these tables that the drag reduction by the mixtures is less than
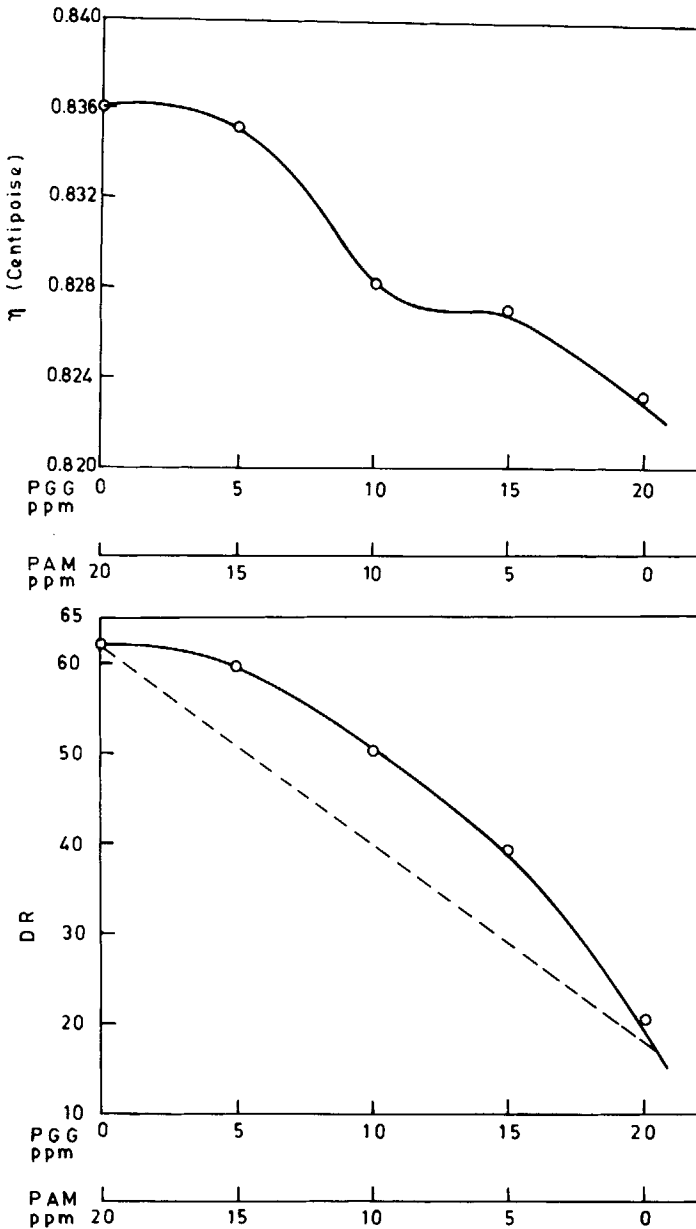
Fig. 2. Absolute viscosity and DR vs. composition of mixtures of purified guargum and polyacrylamide at total concentration of 20 ppm and Reynolds number 14,000.

the sum of the drag reduction caused by the constituent polymers at their respective concentrations, indicating the negative value of the interaction parameter (I), if the mixture law equation is applied. The concentration of polyacrylamide could not be increased further beyond 20 ppm as, in these cases, the drag reduction attains maximum at this concentration for the present equipment.
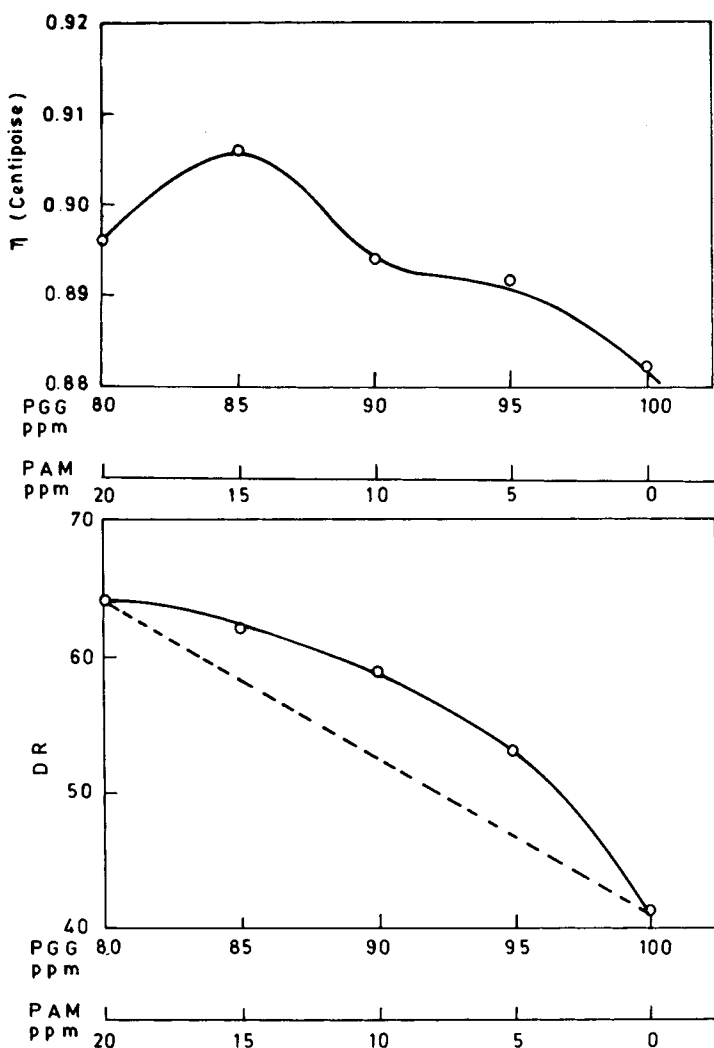
Fig. 3. Absolute viscosity and DR vs. composition of mixtures of purified guargum and polyacrylamide at total concentration of 100 ppm and Reynolds number 14,000.

TABLE IA

Drag Reduction Effectiveness in PAM + PGG Mixtures at Total Concentration of 20 ppm

Concn of PAM (ppm)	Concn of PGG (ppm)	DR % by PAM	DR % by PGG	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
0	20	0.0	20.0	20.00	20.0	
5	15	34.0	17.1	51.10	39.0	36.32
10	10	51.0	12.3	63.33	51.0	51.82
15	5	59.5	6.7	66.20	59.5	61.43
20	0	63.5	0.0	63.50	63.5	

TABLE IB
Drag Reduction Effectiveness in PAM + PGG Mixtures at Total Concentration of 100 ppm

Concn of PGG (ppm)	Concn of PAM (ppm)	DR % by PGG	DR % by PAM	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
100	0	41.0	0.0	41.00	41.0	
95	5	39.33	34.0	73.33	53.2	48.57
90	10	39.00	51.0	90.00	59.0	58.21
85	15	38.50	59.5	98.00	62.3	67.16
80	20	38.00	62.5	100.50	64.0	74.91

Purified Guargum (PGG)–Purified Xanthangum (PXG) Mixtures

The commercial guargum–commercial xanthangum mixtures have been studied at various compositions and flow rates (Re = 20,000–56,000) by Reddy and Singh.[8] The total concentration of the mixture was kept at 200 ppm. Under the present study, the concentration has been kept at 100 ppm at Reynolds number of 14,000. This has been done mainly because the purified guargum and xanthangum cause higher drag reduction, and, for industrial and technical applications, lower concentrations are preferred.

From Table II, it is obvious that the drag reduction caused by the mixtures is less than the simple additive value obtainable by the addition of the drag reductions, caused by the constituent polymers individually at their respective concentrations. However, the drag reduction calculated by eq. (2) in terms of drag reductions of pure polymers is close to the experimental values of drag reduction. The absolute viscosity of the solution varies almost linearly with the composition (Fig. 4).

Purified Guargum (PGG)–Grafted Guargum (Gm_3) Mixtures

These mixtures have been studied for the first time, and the results are depicted in Figure 5. The concentration has been chosen at 100 ppm. It has been observed by Deshmukh et al.[9] that the grafted guargum is more effective as drag reducing agent. It has been also found less susceptible to biological degradation; hence its mixtures with purified guargum are chosen for the present study. In this case as well, the drag reduction caused by the mixtures

TABLE II
Drag Reduction Effectiveness in PGG + PXG Mixtures

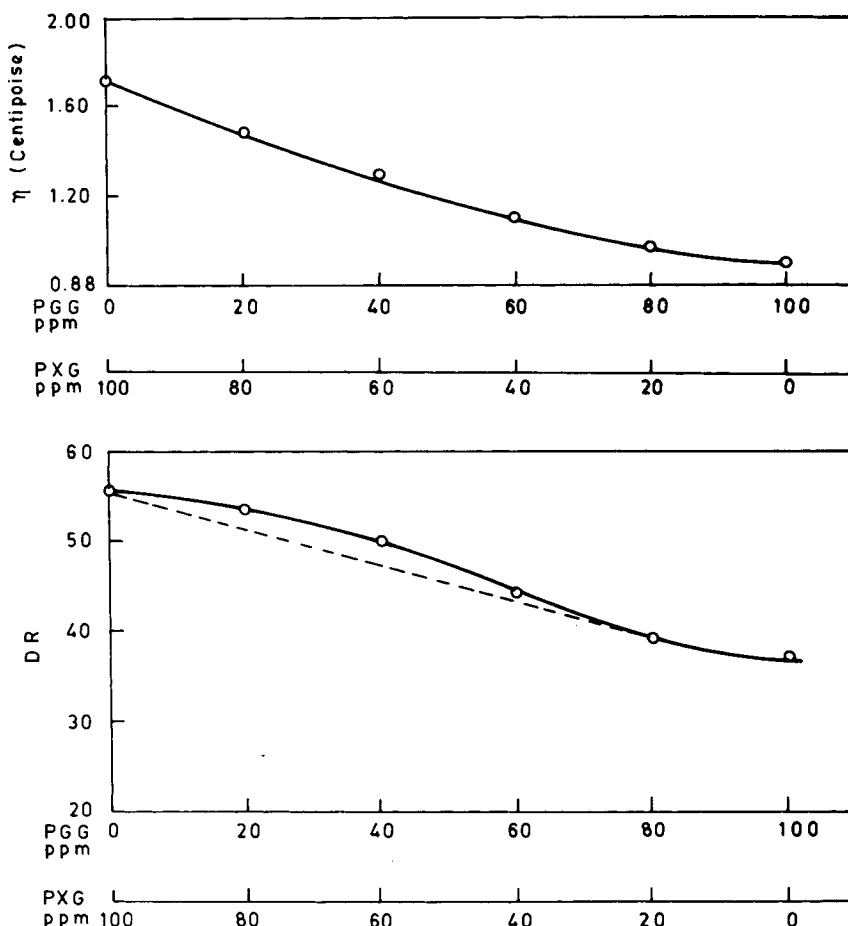| Concn of PGG (ppm)	Concn of PXG (ppm)	DR % by PGG	DR % by PXG	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
100	0	36.50	0.0	36.50	36.50	
80	20	34.00	20.33	54.33	39.20	40.13
60	40	29.33	34.00	63.33	42.66	44.49
40	60	24.33	43.66	68.00	50.00	49.22
20	80	16.00	49.75	65.75	53.50	51.86
0	100	0.0	55.00	55.00	55.00	

Fig. 4. Absolute viscosity and DR vs. composition of mixtures of purified guargum and purified xanthangum at total concentration of 100 ppm and Reynolds number 14,000.

is less than the drag reduction obtained by addition of drag reductions caused by the constituent polymers at all compositions (Table III).

Purified Guargum (PGG)—Grafted Xanthangum (XGm$_4$) Mixtures

These mixtures have also been studied at the total concentration of 100 ppm. The results are depicted in Figure 6. The drag reduction caused by the purified guargum is less than XGm$_4$; however, here again (Table IV) the drag reduction caused by the mixture is lower than the simple addition of the drag reductions caused by the constituent polymers individually at their respective concentrations in the mixture.

Grafted Guargum (Gm$_3$)–Polyacrylamide (PAM) Mixtures

The drag reduction caused by grafted guargum is higher than the purified guargum at the same concentration. Hence, the possibility exists of using this
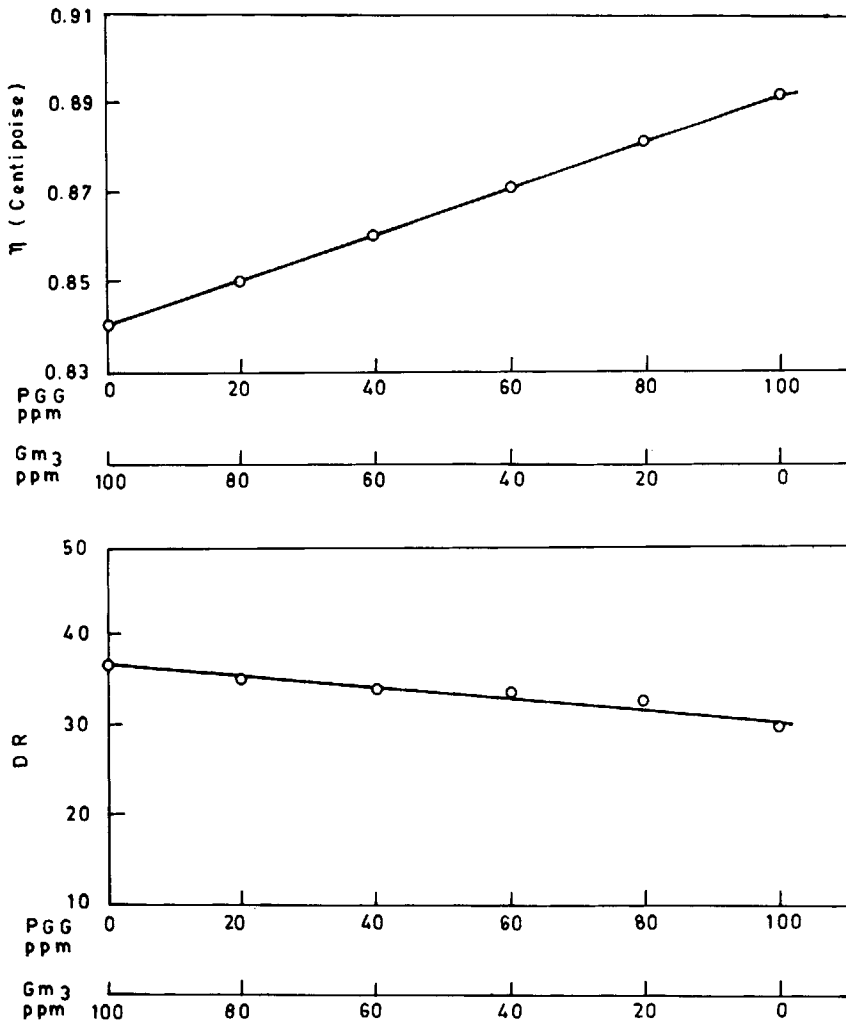
Fig. 5.   Absolute viscosity and DR vs. composition of mixtures of purified guargum and grafted guargum (Gm_3) at total concentration of 100 ppm and Reynolds number 14,000.

TABLE III
Drag Reduction Effectiveness in PGG + Gm_3 Mixtures

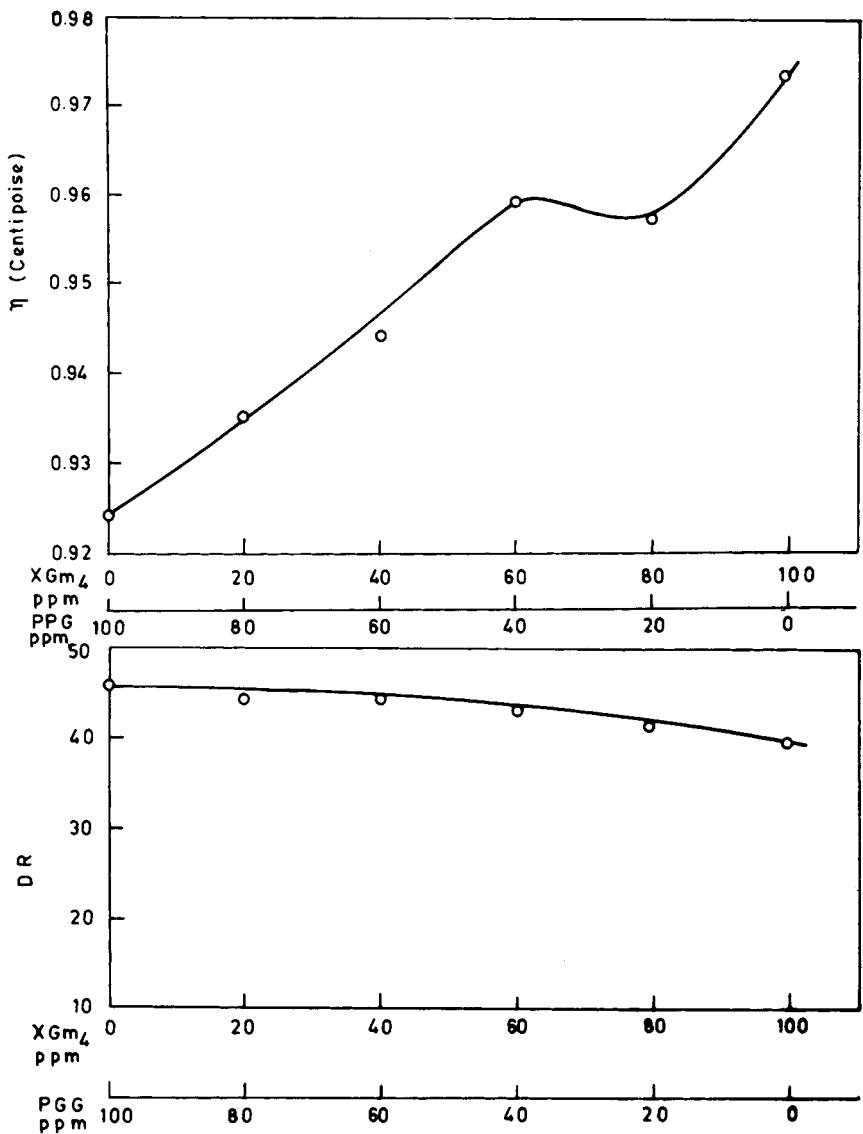| Concn of PGG (ppm)	Concn of GM_3	DR % by PGG	DR % by Gm_3	Additive DR %	Expt. DR (mol %)	Calcd DR (mol %)
100	00	40.7	0.00	40.70	40.7	
80	20	37.8	21.33	59.13	41.5	40.89
60	40	33.8	31.50	65.30	42.5	42.46
40	60	28.0	38.33	66.33	44.0	43.78
20	80	21.0	44.00	65.00	45.0	45.78
0	100	0.0	47.00	47.00	47.0	

Fig. 6. Absolute viscosity and DR vs. composition of mixtures of purified xanthangum and graft copolymer of xanthangum at total concentration of 100 ppm and Reynolds number 14,000.

sample at very low concentrations to have considerable drag reduction. Hence the mixtures, of grafted guargum with polyacrylamide were studied at the total concentrations of 20 and 100 ppm; the results are shown in Figures 7 and 8. In this case, drag reduction by PAM is less because of the hygroscopic nature of the PAM sample. It is evident from Tables VA and VB that the drag reduction caused by the mixture is less than the additive value of the drag reductions caused by the constituent polymers at their respective concentrations.

TABLE IV
Drag Reduction Effectiveness in PGG + XGm_4 Mixtures

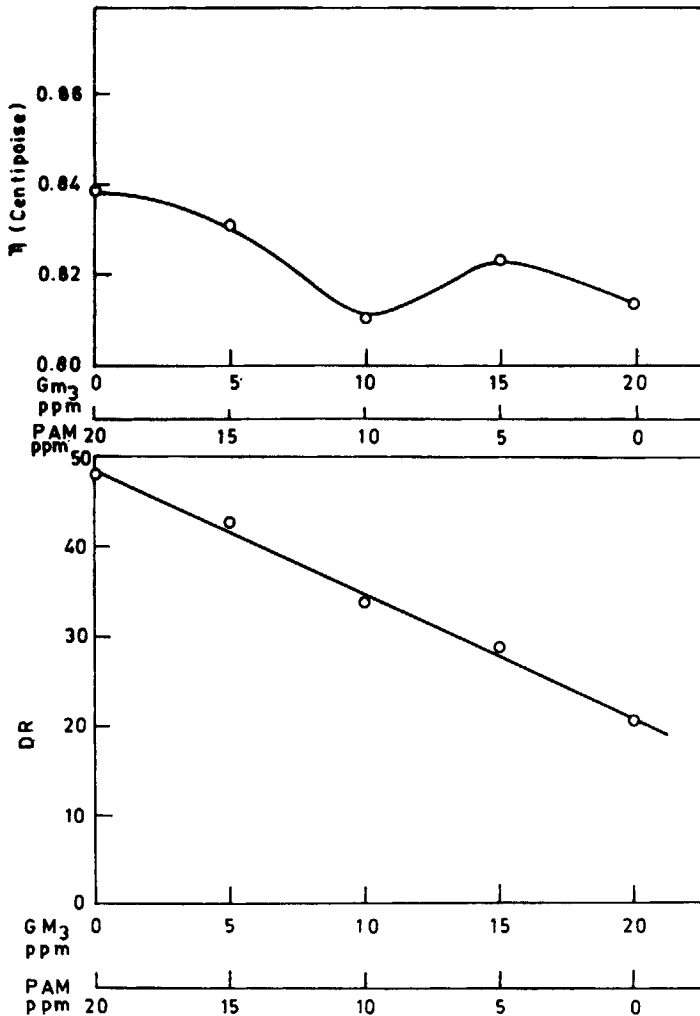| Concn of PGG (ppm)	Concn of XGm_3 (ppm)	DR % by PGG	DR % by XGm_3	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
100	0	40.7	0.00	40.70	40.7	
80	20	37.8	21.00	58.80	41.5	41.80
60	40	33.8	31.50	65.30	43.5	43.92
40	60	28.0	37.33	65.33	45.0	44.64
20	80	21.0	42.00	63.00	45.5	45.16
0	100	0.0	46.00	46.00	46.0	

Fig. 7. Absolute viscosity and DR vs. composition of mixtures of polyacrylamide and graft copolymer of guargum at total concentration of 20 ppm and Reynolds number 14,000.
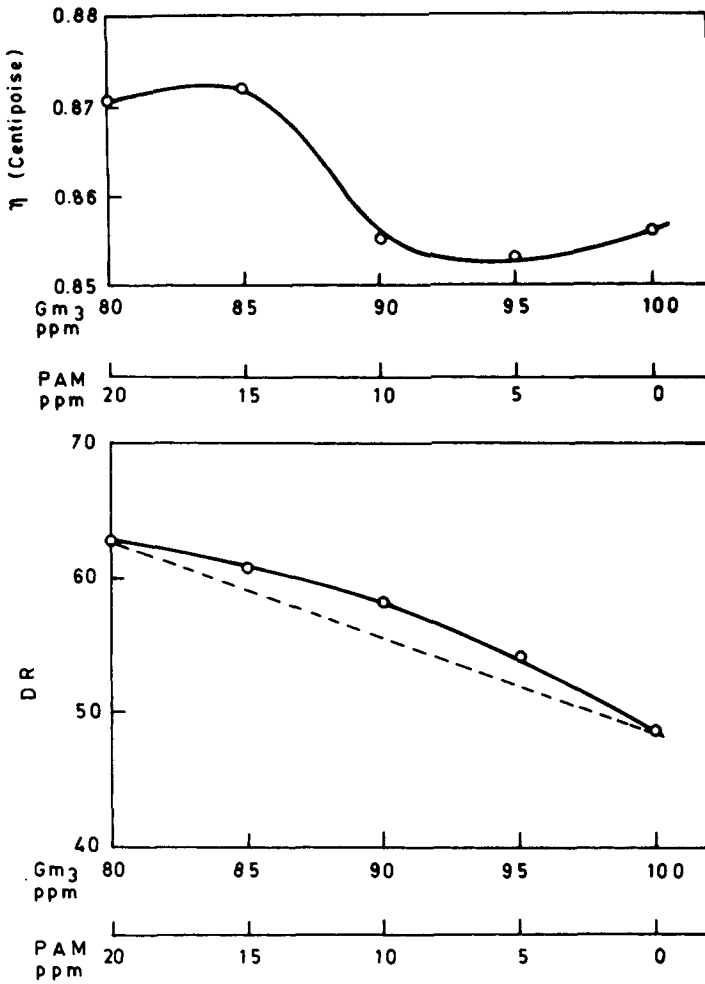
Fig. 8.   Absolute viscosity and DR vs. composition of mixtures of polyacrylamide and graft copolymer of guargum at total concentration of 100 ppm and Reynolds number 14,000.

TABLE VA

Drag Reduction Effectiveness in PAM + Gm_3 Mixtures at Total Concentration of 20 ppm

Concn of PAM (ppm)	Concn of Gm_3 (ppm)	DR % by PAM	DR % by Gm_3	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
0	20	0.0	21.33	21.33	21.33	
5	15	18.5	18.00	65.50	27.50	28.06
10	10	30.5	13.50	44.00	34.50	35.24
15	5	39.0	6.80	45.80	42.00	40.88
20	0	48.0	0.00	48.00	48.00	

TABLE VB
Drag Reduction Effectiveness in PAM + Gm_3 Mixtures at Total Concentration of 100 ppm

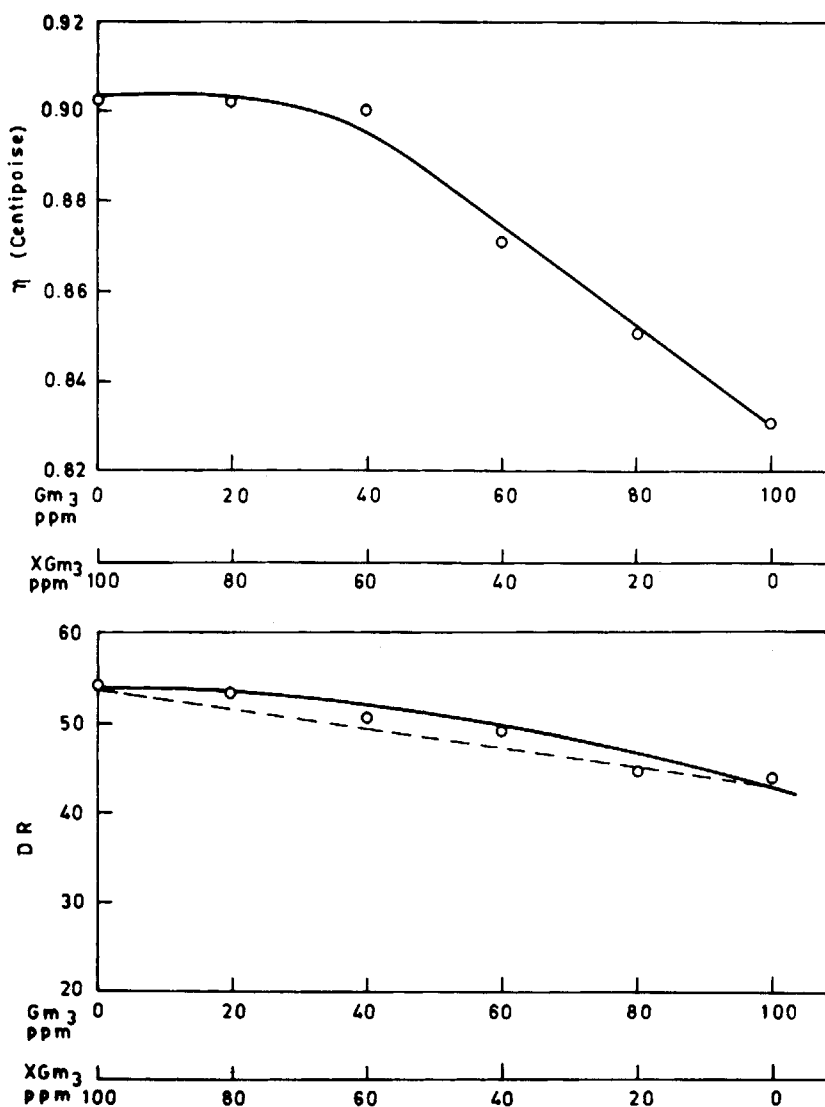| Concn of PAM (ppm)	Concn of Gm_3 (ppm)	DR % by PAM	DR % by Gm_3	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
0	100	0.0	48.00	48.00	48.00	
5	95	32.5	47.00	79.50	54.00	52.06
10	90	51.0	46.20	47.20	58.00	57.64
15	85	59.5	45.33	104.83	60.66	62.98
20	80	63.0	44.00	107.00	63.00	67.28

Fig. 9.   Absolute viscosity and DR vs. composition of mixture of graft copolymer of guargum and graft copolymer of xanthangum at total concentration of 100 ppm and Reynolds number 14,000.

TABLE VI
Drag Reduction Effectiveness in XGm_3 + Gm_3 Mixtures

Concn of XGm_3 (ppm)	Concn of GM_3 (ppm)	DR % by XGm_3	DR % by Gm_3	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
100	0	54.0	0.00	54.00	54.0	
80	20	50.5	21.33	71.83	53.5	51.26
60	40	47.0	31.50	78.50	51.5	50.69
40	60	39.5	38.33	77.83	49.0	48.69
20	80	36.0	44.0	80.00	46.0	48.99
0	100	0.0	47.0	47.00	47.0	

Grafted Guargum (Gm_3)–Grafted Xanthangum (XGm_3) Mixture

The grafted copolymers of xanthangum and guargum show higher drag reduction effectiveness and biodegradation resistance. Hence their mixtures were studied at the total concentration of 100 ppm, and the results are shown in Figure 9. Here in comparison with PGG–PXG, the fall of the drag reduction from pure samples on both extremes is not so rapid; otherwise, the overall behavior is almost the same. In this case as well, the drag reduction caused by the mixture is less than the additive value of the drag reduction caused by the constituent polymers (Table VI).

Purified Xanthangum (PXG)–Grafted Xanthangum (XGm_3) Mixtures

The purified xanthangum–grafted xanthangum mixtures were studied at the total concentration of 100 ppm at Re = 14,000; the results are depicted in Figure 10. Here the variations of viscosity and drag reduction vs. composition are linear. As in the case of Gm_3–PGG, it is seen that the drag reduction caused by mixture is less than the additive value of the drag reduction caused by the constituent polymers (Table VII).

Purified Xanthangum (PXG)–Grafted Guargum (Gm_3) Mixtures

The drag reductions by these mixtures have been studied at the total concentration at 100 ppm. The results are plotted in Figure 11. Here again, in conformity with the previous case, a linear variation of viscosity and drag reduction with composition have been obtained. Table VIII shows that the drag reduction caused by the mixture is less than the additive value of the drag reduction caused by the constituent polymers.

Polyacrylamide (PAM)–Purified Xanthangum (PXG) Mixtures

The mixtures of PAM–PXG have been studied at total concentrations of 20 ppm. The experimental results are plotted in Figure 12. In this case, the drag reduction caused by the mixture is less than the additive value of drag reduction caused by the constituent polymers (Table IX).

Polyacrylamide (PAM)–Grafted Xanthangum (XGm_3) Mixtures

PAM–XGm_3 mixtures were studied at total concentrations of 20 ppm. The studies were carried out at Re = 14,000. Figure 13 depicts the variation of
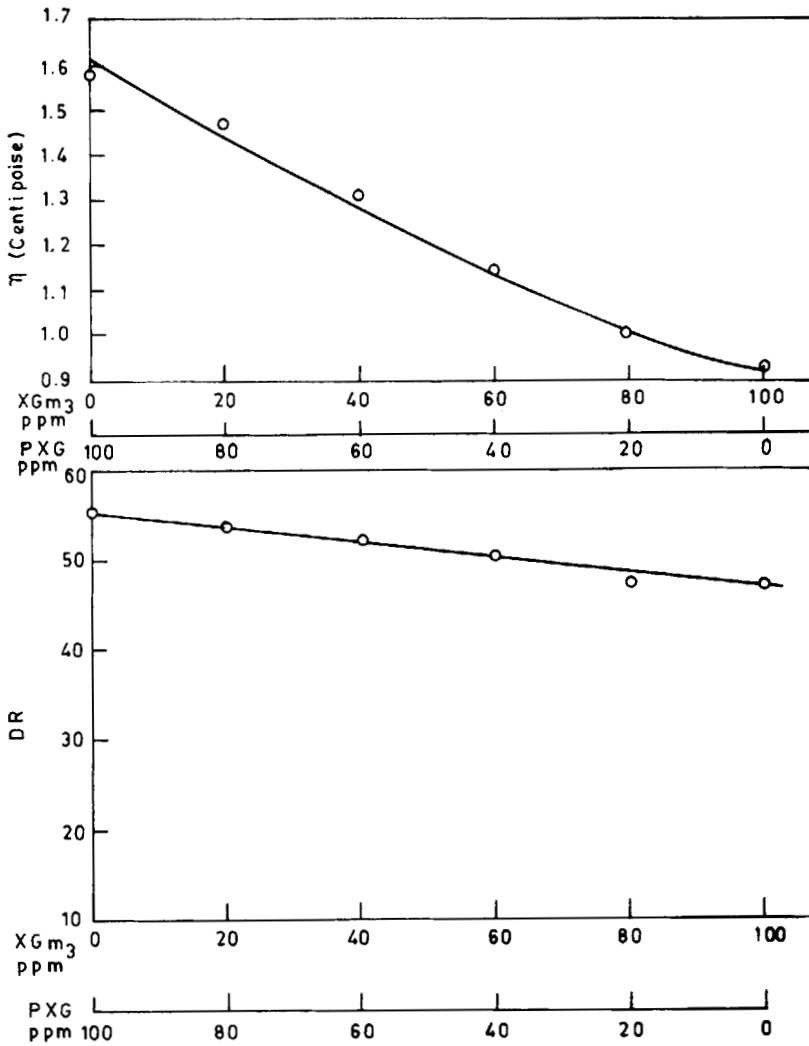
Fig. 10. Absolute viscosity and DR vs. composition of mixtures of purified xanthangum and graft copolymer of xanthangum at total concentration of 100 ppm and Reynolds number 14,000.

TABLE VII
Drag Reduction Effectiveness in PXG + XGm_3 Mixtures

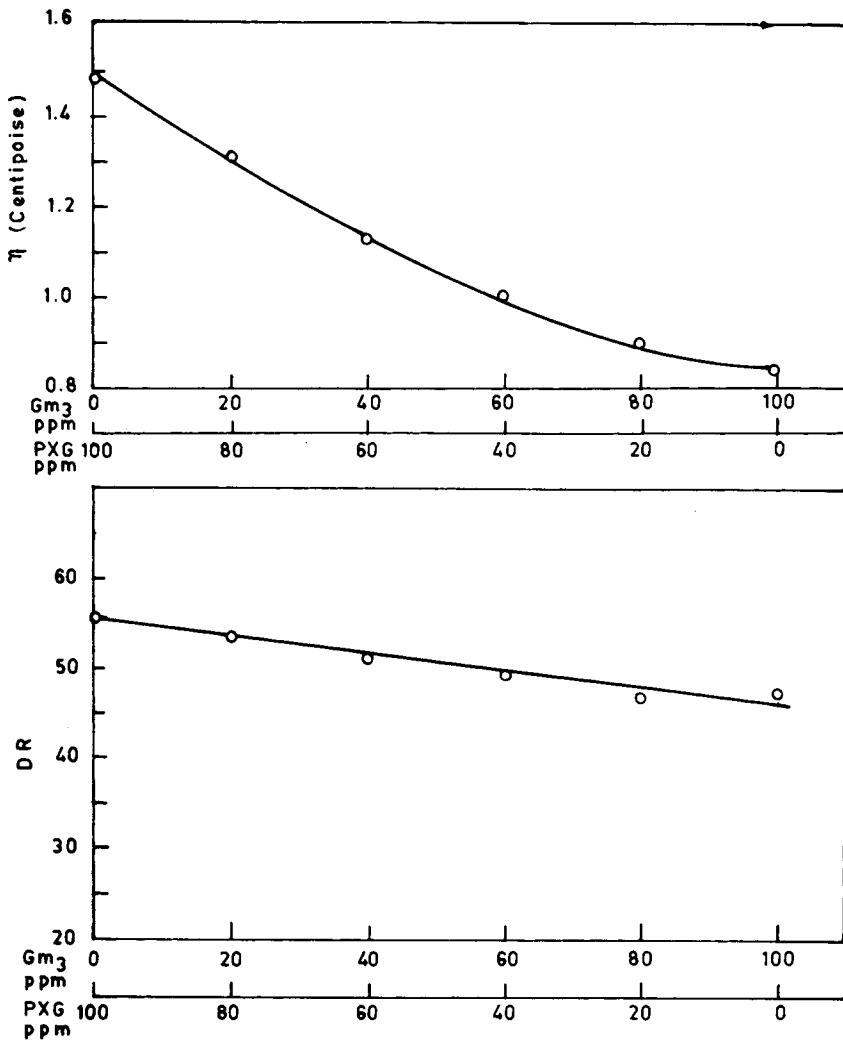| Concv of PXG (ppm)	Concn of XGm_3	DR % by PXG	DR % by XGm_3	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
100	0	55.50	0.00	55.50	55.50	
80	20	49.66	20.66	70.33	55.75	54.38
60	40	43.66	31.33	73.00	52.50	54.50
40	60	34.00	37.33	71.33	50.50	51.77
20	80	20.33	42.00	62.33	49.00	48.18
0	100	0.00	46.50	46.50	46.50	

Fig. 11.   Absolute viscosity and DR vs. composition of mixtures of graft copolymer of guargum and purified xanthangum at total concentration of 100 ppm and Reynolds number 14,000.

TABLE VIII
Drag Reduction Effectiveness in PXG + Gm_3 Mixtures

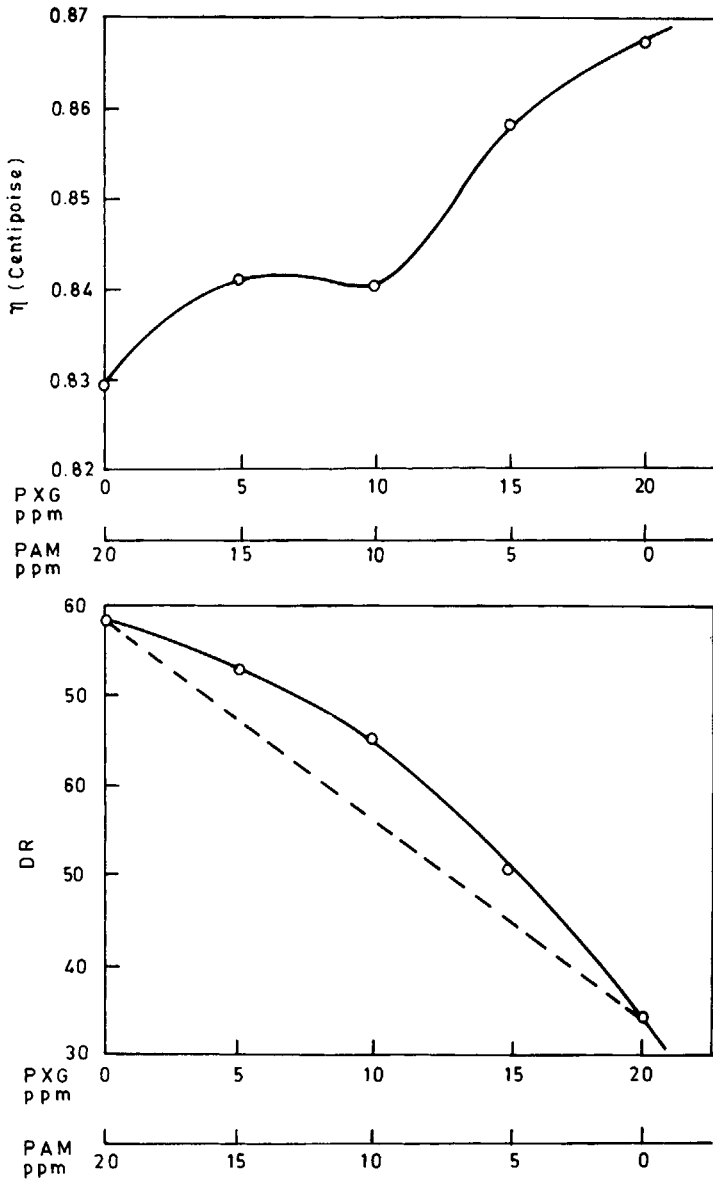| Concn of PXG (ppm)	Concn of Gm_3 (ppm)	DR % by PXG	DR % by Gm_3	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
100	0	55.50	0.00	55.50	55.50	
80	20	49.66	21.33	71.00	53.50	52.72
60	40	43.66	31.50	75.17	51.75	51.89
40	60	34.00	38.50	72.50	49.50	49.79
20	80	20.33	44.00	64.00	47.50	47.99
0	100	0.00	47.40	47.40	47.40	

Fig. 12.   Absolute viscosity and DR vs. composition of mixtures of polyacrylamide and purified xanthangum at total concentration of 20 ppm and Reynolds number 14,000.

drag reduction percentage vs. composition in case of the PAM–XGm$_3$ mixture. In this case as well, the drag reduction caused by the mixture is less than the additive value of the drag reduction caused by the constituent polymers (Table X).

The general features of the drag reduction caused by the polymer–polymer mixtures are described below.

1. In most of the cases, the drag reduction caused by mixtures shows a positive deviation from the linearly additive straight line. This effect is more

TABLE IX
Drag Reduction Effectiveness in PXG + PAM Mixture

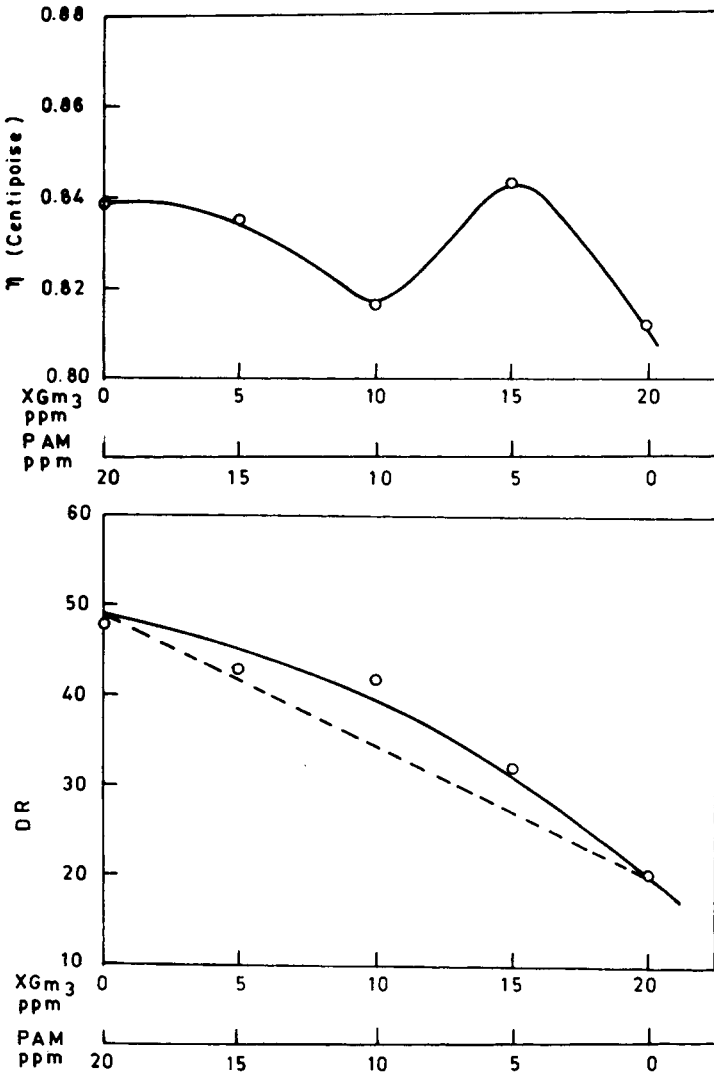| Concn of XGm$_3$ (ppm)	Concn of PAM (ppm)	DR % by XGm$_3$	DR % by PAM	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
20	0	14.00	0	14.00	14.0	
15	5	11.66	27	38.66	30.5	29.12
10	10	8.33	45	53.33	45.0	44.89
5	15	4.33	53	57.33	53.0	54.46
0	20	0.00	58	58.00	58.0	

Fig. 13.   Absolute viscosity and DR vs. composition of mixtures of polyacrylamide and graft copolymer of xanthangum at total concentration of 20 ppm and Reynolds number 14,000.

TABLE X
Drag Reduction Effectiveness in XGm_3 + PAM Mixtures

Concn of XGm_3 (ppm)	Concn of PAM (ppm)	DR % by XGm_3	DR % by PAM	Additive DR %	Expt DR (mol %)	Calcd DR (mol %)
20	0	20.00	0.0	20.00	20.0	
15	5	16.66	18.0	34.66	30.5	30.55
10	10	11.33	30.5	41.83	39.0	38.98
5	15	6.66	39.0	45.66	44.5	44.47
0	20	0.00	48.0	48.00	48.0	

prominent when the drag reductions caused by both the constituents differ appreciably; e.g., in the mixtures where the drag reduction caused by the constituent polymers does not differ appreciably, there is almost no deviation from the linearly additive straight line. The only exceptions are the mixtures of XGm_4–PGG at a total concentration of 100 ppm and PAM–Gm_3 at a total-concentration of 20 ppm. In the latter mixture, the measurements were extended to a limited composition at a concentration of 100 ppm where the drag reduction by the mixture does not exceed the measuring limits of the instrument used. It has been found that the drag reduction in this case too has positive deviation from the additive straight line. Thus only one true exception exists. The calculated values of drag reduction by eq. (2) in terms of the drag reductions of pure components by the method of Reddy and Singh[8] are close to experimental values in all cases.

2. In most of the cases, the drag reduction caused by the mixtures is higher than the DR caused by either of the constituent polymers; however, the drag reduction caused by the mixture is less than the sum of the drag reductions caused by both the constituents at their respective concentrations in the mixture. The difference between the drag reduction caused by the mixture and the sum of the drag reduction caused by the constituents of the mixture is larger when constituent polymers caused high drag reduction, which is evident in the mixtures of PAM–PGG or mixtures of PAM–PXG. But in other mixtures when the drag reductions caused by the constituent polymers are of the same order and of lower magnitude, the drag reduction caused by the mixture and the sum of the drag reduction caused by the constituent polymers do not differ much. The first case refers also to the situations where drag reductions caused by the constituent polymers at their respective concentrations are approaching the maximum limit.

3. There is no evidence of synergism in these mixtures at low concentrations and Reynolds number. There is only positive deviation from the linearly additive straight line, which is due to the fact that, in the cases of constituent polymers, the drag reduction vs. concentration profiles are not linear.

4. In the present mixtures, the PGG, PXG, and graft copolymers of guargum and xanthangum have been used. The PGG and PXG give higher drag reduction than commercial samples. The graft copolymers of guargum and xanthangum show higher drag reduction effectiveness and biodegradation resistance. However, in various mixtures studied in the present investigation, there is not any discernable molecular effect on the drag reduction character-

istics of the mixtures. The total concentrations of the mixtures, studied by previous workers,[3–5,7,8] were almost at least one order higher than the present case, and in most of the cases Re was also higher.

5. The positive deviation from the linearly additive straight line and synergism in drag reduction by the mixture have been attributed to the change in the coil dimensions due to the copresence of molecules of both the polymers in the solution and to the rigidity of the polymers. Reddy and Singh[8] observed that the synergism also increases with the Re in most of the mixtures studied by them. In the present case, the solutions are extremely dilute, the concentration being one order lower and the Re is also lower. Though the positive deviation from linearly additive line is observed for some cases, synergism is not obtained. Hence it appears that the synergism is due to the presence of interaction among the polymer molecules, which influences the extension of the molecules. This interaction gets more intensified at higher flow rate and concentrations. But one fact is clear from the present results: that when both the constituent molecules are rigid, the difference between the drag reduction caused by the mixture and the sum of the drag reduction caused by the constituent polymers is lesser, in comparison with the difference which exists when one of the constituent polymers is flexible like PAM.

6. The guargum and xanthangum are respectively obtained from renewable sources, i.e., from agriculture crop and culture medium of some bacteria. Though they are less efficient drag reducing agent than PAM, but are more shear-resistant and cheaper. In grafting with PAM, guargum and xanthangum become fairly biodegradation-resistant as well. PAM is highly shear degradable. By taking a larger proportion of PGG, PXG, or their grafted copolymer in the mixtures with PAM, a fairly stable combination is obtained having reasonable drag reduction ability, because a very small (5 ppm of PAM) quantity of PAM enhances the drag reduction ability of the mixtures with these polymers considerably.

CONCLUSIONS

The following conclusions may be drawn by the present extensive investigation on drag reduction caused by polymer–polymer mixtures.

The drag reduction and synergism in drag reduction are functions of concentration and flow rate. Synergism in drag reduction is caused by a mixture when both the constituents are rigid and cause the same order of drag reduction individually.

The synergism may be obtained in many other mixtures at higher concentration at which the drag reduction studies cannot be made by the turbulent flow rheometer used in the present study. In the future, a study is highly desirable to obtain the critical concentrations at which the onset of synergism in drag reduction caused by mixtures starts appearing.

Grafting PAM chains on guargum and xanthangum also cause the chain scission of the backbone molecules. Resulting graft copolymers are only more shear stable than the parent molecules when their molecular weights are higher. It is apparent from the present study that grafting also incorporates flexibility in the molecules, which hampers the synergistic effects in causing drag reduction, when one of the constituents is the graft copolymer. Hence a

detailed study on the drag reduction caused by the graft copolymers and their mixtures with various degrees of grafting and variation of synthesis parameters of graft copolymerization will be pertinent.

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