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Universal drag reduction characteristics of polyisobutylene in a rotating disk apparatus

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Abstract

Turbulent drag reduction (DR) in a rotating disk apparatus was examined for a homologous series of polyisobutylene (PIB) with two different solvent systems to investigate the effect of solvent on universal DR characteristics. The concentration dependence of DR for these systems obeys an empirical universal DR equation. A linear correlation between polymer concentration (*C*) and *C*/DR for different molecular weights of PIB was also obtained. The intrinsic concentration was found to be an extremely useful quantity in normalizing the DR data for a homologous series of PIB. The characteristic value, *K*, was found to depend upon the solvent system. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Drag reduction; Polyisobutylene; Rotating disk apparatus

1. Introduction

Introducing a minute amount o f flexible polymer into turbulent flows was known to reduce drag. Adding 10–50 ppm of a high molecular weight polymer to a turbulently flowing fluid in a pipe can achieve more than a 50% reduction of drag, implying that the energy cost necessary to move the fluid was reduced by a proportional amount [1]. Although a great deal of research was performed in this area, the physical mechanism behind drag reduction (DR) has not been clearly indentified [2]. However, it is generally accepted that the drag reduction is associated with the viscoelasticity of polymer solutions [3–5]. Drag reducing polymer systems in water-based systems were investigated extensively [6–8] in spite of their susceptibility to flow-induced degradation. However, very little was reported for comparable additives in hydrocarbon-based fluids [9]. Among oil-soluble polymers, polyisobutylene (PIB) [10] and polystyrene [11] were commonly used. PIB is the only polymer which has received any acceptance as a drag reducing additive for crude oil [10].

Drag reduction capability is primarily influenced by the molecular parameters of the dissolved polymer, such as molecular weight, aggregation, and chain flexibility. Virk et al. [12] observed the extent of drag reduction induced by a homologous series of polyethylene oxide (PEO) in water flowing in a pipe and constructed a universal drag reduction relationship, which was later simplified by Little [13]. The universal drag reduction equation was found to be independent of concentration, molecular weight, and flow geometry. These methods revealed that a linear relationship exists between characteristic parameters and molecular weight. Dschagarowa and Menning [14] also studied concentration and flow rate dependence for PIB systems of different molecular weight in pipe flow and obtained a universal drag reduction curve for intrinsic concentration and intrinsic drag reduction. Recently, Choi and Jhon [15] investigated the concentration dependence of drag reduction for both PEO in water and PIB in kerosene using a rotating disk apparatus (RDA). Correlations between polymer concentration, drag reduction index, and viscosity-average molecular weight were found.

The effects of PIB concentration on drag reduction for two different solvents and the characterization of an oil-soluble PIB drag reducer using the RDA is presented in this paper. PIB–cyclohexane and PIB–xylene solutions were investigated by adopting the universal correlation method and by comparing the results with previously studied systems of PIB–kerosene [16]. As only a few parts per million of polymer additives are involved in the

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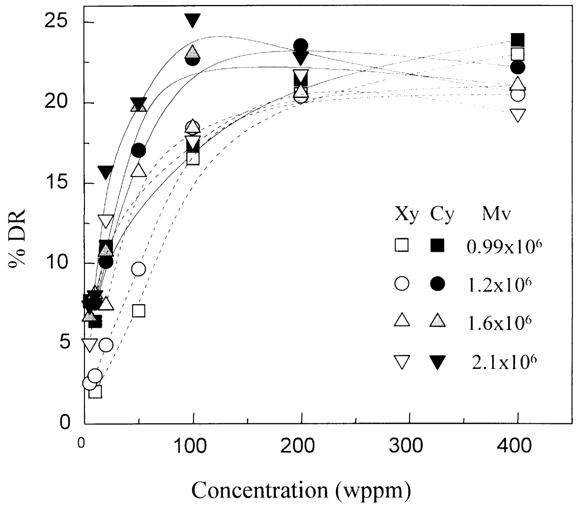

Fig. 1. Percent drag reduction versus concentration for four different molecular weights of PIB in cyclohexane (closed symbols) and xylene (open symbols). Molecular weights of 0.99, 1.2, 1.6, and 2.1 × 10^6 g/mol are represented by rectangles, circles, up-triangles, and down-triangles, respectively.

DR phenomenon, polymer–solvent interactions, rather than polymer–polymer interaction, play an important role in DR [17].

2. Experimental

Vistanex PIBs, highly paraffinic hydrocarbon polymers, are composed of terminally unsaturated, long straight-chain molecules are light-colored, ordorless, tasteless, and non-toxic. Four different grades of PIB (obtained from Exxon Chemical Americas: L-80, L-100, L-120 and L-140) based on molecular weight were used as drag reducers. The viscosity-average molecular weights reported by the manufacturer were 0.99, 1.2, 1.6, and 2.1 × 10^6 g/mol, respectively. Cyclohexane and xylene were used as solvents. Solubility parameters of these solvents are 16.8 $\mathrm{MPa}^{1/2}$ for cyclohexane and 18.0 $\mathrm{MPa}^{1/2}$ for xylene.

Stock polymer solutions of 5 wt% were prepared at room temperature by dissolving an appropriate amount of PIB into each solvent. To reduce mechanical degradation induced by stirring, mild agitation was applied to these polymer systems. The required amount of stock solutions was measured and directly injected into the turbulent flow field generated by the RDA.

Drag reduction measurements were performed using the same RDA as previously reported [15]. The RDA consists of a stainless steel disk, whose dimensions are 14.5 cm in diameter by 0.32 cm in thickness, enclosed in a cylindrical temperature-controlled container composed of stainless steel with dimensions 16.3 cm inner diameter by 5.5 cm height. An electric transducer was used to monitor the torque on the disk rotating at 1800 rpm, yielding a Reynolds number of 9.9 × 10^5.

Data were taken by measuring the torque required to rotate the disk at a fixed speed in each solvent and in a dilute polymer solution. The percent drag reduction was calculated by:

$$\mathrm{DR}(\%) = (1 - T_p/T_0) \times 100, \tag{1}$$

where T_p and T_0 are the torques required for the polymer solution and for the pure solvent, respectively.

3. Results and discussion

The DR effectiveness is related to polymer coil dimensions, which depend upon the chemical structure of the polymer and polymer–polymer and polymer–solvent interactions. It was shown that polymers reduce drag more effectively in good solvents rather than in poor solvents. McCormick et al. [7] studied a universal DR curve for several polymers having different structures and compositions by normalizing the hydrodynamic volume fraction of polymer in solution. Further, Virk et al. [12], Little [13], and Choi and Jhon [15] introduced a three-parameter empirical relationship between DR and concentration (C) to provide a universal correlation for drag reduction data. DR was cast as: $\mathrm{DR} = P(C)/Q(C)$, where $P(C)$ and $Q(C)$ are polynomials of C. DR was modelled in the following simplified Padè form:

$$\mathrm{DR} = \frac{a_0 + a_1 C}{b_0 + b_1 C}, \tag{2}$$

where $a_0 = 0$, $a_1 = [\mathrm{DR}]$, and $b_1 = [\mathrm{DR}]/\mathrm{DR}_{\max} \equiv 1/[C]$. Note that the Padè form fit DR data much better than a Taylor expansion with the same number of parameters. In addition, the intrinsic drag reduction [DR] and the intrinsic concentration $[C]$ are defined as $[\mathrm{DR}] = \lim_{C \to 0} \mathrm{DR}/C$ and$[C] = \mathrm{DR}_{\max}/[\mathrm{DR}]$, respectivley. Here $\mathrm{DR}_{\max}$ is the maximum percent DR for a given polymer solution. An additional parameter, b_0, assigned K, completes Eq. (2), as well as fits the universal correlation for DR. Therefore, an empirical relationship can be written as:

$$\mathrm{DR} = \frac{C[\mathrm{DR}]}{K + C/[C]} \qquad \textit{or} \qquad \frac{\mathrm{DR}/C}{[\mathrm{DR}]} = \frac{1}{K + C/[C]}. \tag{3}$$

To examine the drag reduction efficiency, one can rewrite Eq. (3) in the following form:

$$\frac{C}{\mathrm{DR}} = \frac{K[C]}{\mathrm{DR}_{\max}} + \frac{C}{\mathrm{DR}_{\max}}. \tag{4}$$

Eq. (4) shows that there is a linear relationship between C/DR and C up to the optimum concentration of each molecular weight. This is valid for most drag reducing polymers for flow in both a pipe [18] and rotating disk [15,16]. Further, by defining $(\mathrm{DR}/C)/[\mathrm{DR}]$ as β and $C/[C]$ as α, Eq. (3) can be simplified to:

$$\beta = 1/(\alpha + K). \tag{5}$$

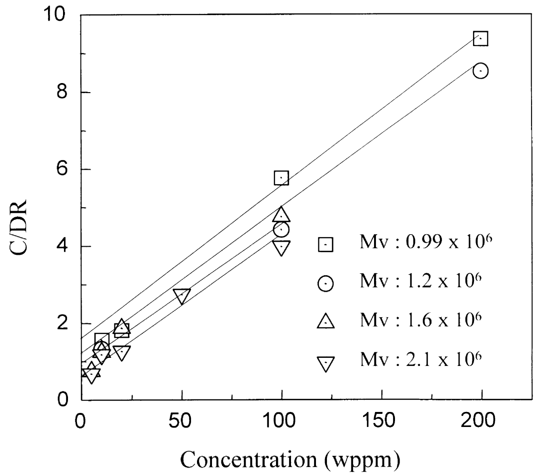

Fig. 2. DR versus concentration for four different molecular weight PIBs in cyclohexane.

Fig. 1 shows the dependence of percent drag reduction of four different molecular weights of PIB as a function of polymer concentration up to 400 wppm for two different solvent systems. The PIB–cyclohexane system yields better drag reduction in a lower concentration range compared to PIB–xylene. This indicates that the drag reduction is strongly dependent on the interaction between polymer and solvent. Values of maximum drag reduction vary with molecular weight of PIB in the two solvent systems.

The linear correlations between *C*/DR and the polymer concentration for four different molecular weights of PIB in cyclohexane and xylene in a range of conditions close to the maximum drag reduction are given in Figs. 2 and 3, respectively. Therefore, the plots of *C*/DR versus *C*, as represented in Eq. (4) can provide $\mathrm{DR}_{\max}$ from the reciprocal of the slope, and the intercept values generate[*C*]. The effect of concentration on drag reduction was investigated and revealed the existence of an optimal concentration at which the drag reduction was maximized [19,20].

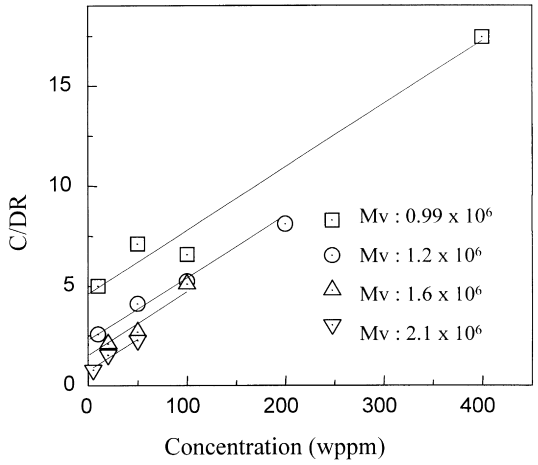

Fig. 3. DR versus concentration for four different molecular weight PIBs in xylene.

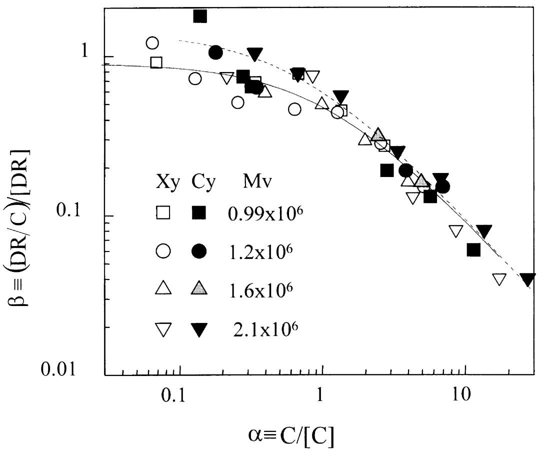

Fig. 4. Universal drag reduction curve, β versus α for PIB in cyclohexane (closed symbols) and xylene (open symbols). The solid line is the best fit for the PIB–xylene system, and the dotted line is the best fit for the PIB–cyclohexane system. Molecular weights of 0.99, 1.2, 1.6, and 2.1 × 10^6 g/mol are represented by rectangles, circles, up-triangles, and down-triangles, respectively.

Fig. 4 shows the universal characteristics for PIB in both cyclohexane and xylene, independent of the molecular weight and rotational velocity of the disk. This illustrates that (DR/*C*)/[DR] possesses a very strong universal correlation with *C*/[*C*], as shown in Eq. (3). It is known that single parameter *K* in Eq. (5) is dependent only on the given polymer–solvent system [15]. Different *K* values were determined for each polymer–solvent system; 0.7 for the PIB–cyclohexane system and 1.1 for the PIB–xylene system were obtained. A solid line in Fig. 4 represents the best fit of Eq. (5) for the PIB–xylene system, and a dotted line depicts that for the PIB–cyclohexane system. Using the obtained *K* values, $\mathrm{DR}_{\max}$, [*C*], and [DR] of PIB for both solvents were determined and are summerized in Table 1. From these results, it can be concluded that a universal plot is obtained with a single parameter *K*. The parameter *K* in Eq. (5) is characteristic of a specific polymer–solvent system and is independent of the molecular weight or flow geometry.

The differences in DR and *K* value of the PIB–cyclohexane and PIB–xylene systems stems from the difference in solubility parameters [15]. DR differences of polymer–solvent systems may be explained by the solubility

Table 1
Maximum drag reduction, intrinsic concentration, and intrinsic drag reduction of various PIB molecular weights in cyclohexane and xylene

		L-80	L-100	L-120	L-140
PIB–cyclohexane system	$\mathrm{DR}_{\max}$ (%)	21.5	23.5	22.2	23.9
	[*C*] (ppm)	49.3	40.9	29.1	21
	[DR]	0.44	0.57	0.76	1.14
PIB–xylene system	$\mathrm{DR}_{\max}$ (%)	31.6	32.3	31.9	31.8
	[*C*] (ppm)	131.7	69.9	45.5	21.2
	[DR]	0.24	0.46	0.70	1.50

parameter (δ) of each polymer–solvent pair [15]. $\delta_{\text{cyclohexane}}$ is closer to δ_{kerosene} than δ_{xylene}. The solubility parameters for PIB in cyclohexane, kerosene, and xylene are 16.8, 17.0, and 18.0 MPa$^{1/2}$, respectively. Thereby, coil dimensions of PIB in cyclohexane were larger than those of PIB in xylene. In addition, the solubility parameter of kerosene which is about 17 MPa$^{1/2}$, is obtained from the fact that the kerosene is composed mainly of *n*-dodecane and other chemicals such as trialkyl derivatives of benzene, napthalene, and 1-*n*-2-methyl-5,6,7,8-tetrahydronaphthalene.

Based on these facts, it is expected that values of the constant *K* increase in the sequence of cyclohexane, kerosene and xylene. However, as was discussed in Ref. [8], the parameter *K* should be adopted in Eq. (2) through $b_0 = K$. Nonetheless, in a previous study, *K* was introduced in a final form of the universal correlation as given in Eq. (10) of Ref [15], instead of using Eq. (2). Therefore, error in obtaining *K* was introduced for the PIB–kerosene system [15,16]. Previous data for the PIB–kerosene system was replotted in Fig. 4 in order to obatin the dependence of *K* on solvent quality by carefully examining the region of $C/[C] < 1$. The new *K* value is then obtained as 1.0 for the PIB–kerosene system in RDA instead of 0.4 as given in Ref. [15]. Therefore, by adopting the new *K* value of 1.0 for PIB–kerosene, it can be concluded that *K* values of three different solvents for PIB are: 0.7 for cyclohexane, 1.0 for kerosene, and 1.1 for xylene. δ's also occur in an increasing sequence.

In addition, it was interpreted by Dschagarowa and Menning [14] that DR depends on the mobility of the main polymer chain as well as on the dimensions of macromolecules. Thereby, determinative factors of DR are not only the dimensions of polymer coils, but also their ability of deformation and orientation in the flow [4,14]. To clarify this point, especially, for the dependence of *K* on the dimensions of polymer coils, we also measured intrinsic viscosities of the PIBs in each solvent using an Ubbelohde viscometer, as the dimension of the polymer coil is related to intrinsic viscosity and found that $[\eta]_{\text{cyclohexane}} > [\eta]_{\text{kerosene}} > [\eta]_{\text{xylene}}$ for all four different grades of PIB. This sequence corresponds to the *K* values, indicating that *K* values increase with decreasing the intrinsic viscosity. On the contrary, to investigate the dependence of DR on deformation and orientation of the polymer chain, it is suggested to study DR for different shear stress by changing Reynolds number. More studies on this argument are underway.

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