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SHORT COMMUNICATION

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# Universal drag reduction characteristics of saline water-soluble poly(ethylene oxide) in a rotating disk apparatus

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**Abstract** Polymer-induced turbulent drag reduction in a rotating disk apparatus was investigated using nonionic poly(ethylene oxide) (PEO) in a synthetic saline solution with novel application to ocean thermal energy conversion technology. A maximum total (skin friction plus form) drag reduction of 30% was obtained with 50 wppm of PEO with molecular weight $5.0 \times 10^6$. The concentration dependence of the percentage drag reduction for the PEO/saline solution system is found to fit Virk's empirical correlation, and a universal correlation for various molecular weights and Reynolds numbers is also presented. Furthermore, hydrodynamic volume fraction was introduced to correlate drag reduction efficiency with molecular parameters in this PEO/saline solution system.

**Key words** Drag reduction · Poly(ethylene oxide) · Hydrodynamic volume · Ocean thermal energy conversion · Rotating disk flow · Turbulence

## Introduction

The presence of very small amounts of high-molecular-weight polymeric substances in turbulent flow can cause drastic reduction of frictional drag [1]. This turbulent drag reduction (DR) phenomenon implies that pipe flow containing these polymer additives requires a lower pressure drop for a given flow rate. Applications of this phenomenon are found in various areas: transportation of crude oil in the Alaskan and Norwegian pipelines [2]; oil well fracturing operations [3]; closed-circuit pumping installations (e.g. central-heating systems [4, 5]); sewage systems to prevent overflow during heavy rain [6]; hydraulic transportation of solid particle suspensions [7]; increasing the output of the water jet during firefighting and in water supply and irrigation systems [4, 5]. Synthetic polymers, biopolymers [8] and surfactants [9] have been widely used as drag reducers. Among these, the most effective drag-reducing polymers, in general, possess a flexible linear structure with a very high molecular weight. A high-molecular-weight water-soluble poly(ethylene oxide) (PEO), which has been widely used as a drag reducer in aqueous systems, was adopted for our study.

Although DR was discovered half a century ago, a satisfactory theoretical interpretation is still not available [1]. Nonetheless, it is accepted that both the non-Newtonian rheological behavior of polymer solutions and the interaction between polymer molecules and turbulence are responsible for turbulent DR.

To study coupling between turbulence and dissolved polymer molecules, Armstrong and Jhon [10] related molecular dissipation to friction by constructing a self-consistent method, using a variant of the dumbbell model to describe the essence of the polymer molecules. It was found that the average size of a dissolved polymer molecule (i.e. radius of gyration of the polymer molecule) increases dramatically when exposed to turbulence, and they speculated that a polymer molecule could grow by a factor of 10 or more from its equilibrium conformation [11]. Furthermore, to explain the DR phenomenon, de Gennes and Tabor [12, 13] have proposed an energy cascade and scaling theory, which relates polymer length and deformation to turbulent energy dissipation. They suggest that friction reduction occurs primarily as a consequence of the elastic behavior of polymer molecules. Each polymer molecule (represented as a coil) behaves like a spring and, when deformed, stores part of its elastic energy. When the elastic energy of the molecule is equal to the kinetic energy of the turbulent disturbance, the disturbance is suppressed. A dispute still exists, however, as to whether the dominant DR mechanism occurs in the bulk flow or only at or near the system boundary [14].

In our study, we focus on the establishment of an empirical correlation for water-soluble PEO in synthetic seawater for the feasibility study of DR as applied to ocean thermal energy conversion (OTEC) technology. OTEC technology has recently been making headlines since it offers enormous potential for reducing our dependence on fossil fuels within the next decade through not only the production of electrical power, but also the utilization of cold water effluent for integrated applications [15]. Polymer-induced turbulent DR could be applied to OTEC cold water pipelines to reduce pumping power consumption. Recently, Kim et al. [16] studied DR and mechanical degradation of PEO in seawater for possible application to an OTEC system.

DR capability is primarily influenced by the molecular parameters of the dissolved polymer, such as molecular weight, aggregation, and chain flexibility. Virk et al. [17] observed the extent of DR induced by a homologous series of PEO in water flowing in a pipe and proposed a universal DR relationship, which was later simplified by Little [18]. The universal DR equation effectively correlates concentration, molecular weight, and flow geometry. Recently, Choi and Jhon [19] investigated the concentration dependence of DR for both PEO in water and polyisobutylene (PIB) in kerosene using a rotating disk apparatus (RDA), and correlations between polymer concentration, DR index, and viscosity-average molecular weight were obtained. The universal DR relationship has also been tested for a homologous series of PIB with two different solvent systems [20]. In this article, we not only investigate the DR efficiency of PEO in OTEC technology, but also investigate the universal characteristics of PEO in seawater using RDA.

## Experimental

While the salinity of seawater varies with location, the relative proportion of the major constituents in the ocean remains fairly constant; therefore, to synthesize artificial seawater for laboratory purposes, we dissolved 27.01 g NaCl, 10.44 g $MgCl_2 \cdot 6H_2O$, and 0.90 g KCl in 1 l deionized water to provide sufficient electrolytes, since the average salinity of the seawater is about 35 g dissolved salts in 1 l seawater. This synthetic seawater was then used as a solvent for our test. High-molecular-weight linear PEO was chosen because of its extremely high solubility in pure water and its excellent DR capabilities [19]. Four different molecular weight PEO samples, acquired from Scientific Polymer Products with weight-average molecular weights ($M_w$) ranging from $4.0 \times 10^5$ to $5.0 \times 10^6$ g/mol, were used.

The polymer solutions were prepared by dissolving an appropriate amount of PEO in seawater: PEO with $M_w$ $5.0 \times 10^6$ was dissolved directly in seawater; other PEO samples of differing molecular weights of polymers ($M_w$: $4.0 \times 10^5$, $9.0 \times 10^5$, and $4.0 \times 10^6$, respectively) were dissolved in deionized water during the stock solution preparation, since the backbones of PEO stick to the alkali ions dissolved in seawater [21–23] and precipitate at the bottom of the reservoir. A 0.5% (w/w) concentration of stock solution was prepared initially and was then diluted to the desired polymer concentration by direct injection into the turbulent seawater flow field. The RDA consists of a stainless steel disk (15.1-cm diameter, 0.32-cm thick) enclosed in a cylindrical thermostatically controlled container (16.3 cm inner diameter, 5.5 cm high) [24]. The rotational speed of the disk was maintained at a specific value ranging from 1200 to 2000 rpm, using a speed controller and a direct current motor [24], to produce turbulent flow at room temperature. In addition, turbulent flow is defined as a dimensionless parameter Reynolds number ($N_{Re}$) as follows:

$$N_{Re} = \frac{\rho R^2 \omega}{\mu} \ , \tag{1}$$

where $\rho$ and $\mu$ are the density and the viscosity of the fluid, $R$ is the radius of the disk, and $\omega$ is the rotational speed of the disk. Using the RDA, turbulence is produced for $N_{Re} > 3 \times 10^5$ [16], or equivalently 550 rpm for the rotational disk velocity in our RDA. Since DR occurs only in the turbulent region, all RDA measurements in our study were taken above 550 rpm.

The percentage DR (%DR) is obtained from Eq. (2) by measuring both the torque required to rotate the disk at a given speed in the pure seawater solvent ($T_O$) and the corresponding torque required to attain the same speed in the solvent with the added polymer ($T_P$),

$$\%DR = \frac{T_O - T_P}{T_O} \times 100 \ . \tag{2}$$

## Results and discussion

The PEO concentration dependence of DR in seawater was investigated by obtaining the concentration which yields the maximum DR. At low concentrations, drag reduction increases with increasing concentration, since the number of available drag reducers increases; however, as the concentration becomes relatively high, the solution viscosity increases, leading to an increase in the frictional drag. In general, when polymers are dissolved in a solvent, the viscosity of the solution increases with the polymer concentration; however, since DR is produced in the very low concentration regions (~ in wppm, parts per million by weight), carefully prepared solutions are needed for rheological measurements in the corresponding concentration range. Vlassopoulos and

Schowalter [25] measured the steady viscometric properties of dilute water-soluble polymer solutions using a stress-controlled rheometer and observed the shear-thinning behavior of dilute polymer solutions. Therefore, an optimum concentration exists at which the %DR has a maximum value. The dependence of %DR on polymer concentration at a rotation speed of 1,800 rpm for various molecular weights of PEO is shown in Fig. 1. The maximum DR in the seawater system is generally fairly broad, showing that at low concentrations of polymer solutions DR is greater for higher molecular weight polymers and that its maximum occurs at lower concentrations as the molecular weight is increased; however, for the high concentrations of PEO, the molecular weight dependence of the DR becomes negligible. That is, the maximum DR occurs at 50 wppm for higher molecular weight PEOs ($M_w = 4 \times 10^6$, $5 \times 10^6$), while it occurs at near 75 wppm for relatively lower molecular weight PEOs ($M_w = 4 \times 10^5$, $9 \times 10^5$). This can be compared to the DR data for PEO in pure deionized water [26], for which the concentration corresponding to the maximum DR decreases as the molecular weight of PEO increases.

This behavior of PEO in seawater in our study can thereby be explained by the fact that the alkali metal ions make a chilate complex with PEO molecules. Note that addition of low-molecular-weight molecules to the polymeric solutions including PEO has been widely studied by viscosity, surface tension, and conductivity for its applications, including studies on PEO–surfactant complex formation [27]. The addition of inorganic electrolyte generally promotes the formation of a complex between polymer and surfactants [27]. This type of aggregation pattern occurs when alkali ions are present in a polymer solution. We measured the intrinsic viscosities of PEO in distilled water and in seawater and observed that the intrinsic viscosity in seawater is lower than that in distilled water. The ion changes the polymer conformation and thereby alters the DR ability of the polymer. Hoyt [28] measured the effect of the ferric ion on the DR potential of polyacrylamides and concluded that the DR ability of the various polyacrylamides was strongly influenced by the ferric ion. His result also indicated that the immediate loss of DR capability is due to flocculation and, on a long-term basis, also to oxidative degradation. It has been reported that the DR performance of a polymer is related to its intrinsic viscosity, i.e. the DR efficiency increases with increasing intrinsic viscosity (or chain size in solution) [29, 30]. The intrinsic viscosity difference of PEO in distilled water and in seawater gradually increases with increasing molecular weight. Eichlberger et al. [30] observed that the intrinsic viscosity of PEO ($M_w = 5.0 \times 10^6$) in 1.0 M NaCl solution is 78% lower than that in distilled water.

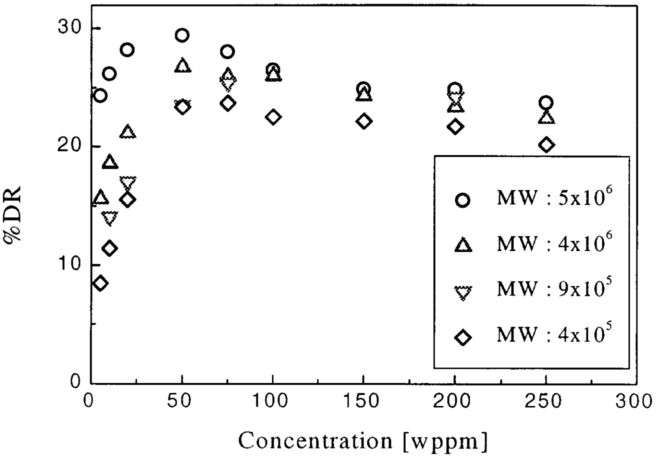

**Fig. 1** Percentage drag reduction (%*DR*) as a function of concentration for four different weight-average molecular weights (*MW*) of poly(ethylene oxide) (*PEO*) at a rotation speed of 1800 rpm ($N_{Re} = 9.7 \times 10^5$)

A maximum 30% DR is obtained with 50 wppm PEO with $M_w = 5.0 \times 10^6$. This relatively low value of the maximum DR in our study is a result of the external flow produced by our RDA, which measures the total drag (skin friction plus form drag). Skin friction drag is typically measured for an internal flow. By considering the difference in skin friction drag and the total drag in tube flow (inner flow) and rotating disk flow (outer flow), a maximum DR of 80% can be achieved in tube flow. With the RDA, DR induced by 50 wppm PEO in distilled water increases up to 25% at 2,800 rpm [26]; on the other hand, Eichelberger et al. [30] obtained almost 60% pressure drop recovery with the same molecular weight and concentration of PEO using the pipeline experimental system. Mumick et al. [31] also obtained a maximum 35% DR in the rotating disk rheometer with water-soluble polyampholytes. This shows that available DR efficiency in the RDA is approximately 35%, compared to more than 50% in pipe flow.

Choi and Jhon [19] introduced a three-parameter empirical relationship between %DR and concentration ($c$) expressed in wppm to provide a universal correlation for DR data. They modeled DR in the following simplified Padé from:

$$\mathrm{DR} = \frac{a_0 + a_1 c}{b_0 + b_1 c} \, , \qquad (3)$$

where $a_0 = 0$, $a_1 = [\mathrm{DR}]$, $b_0 = K$, and $b_1 = [\mathrm{DR}]/\mathrm{DR}_{\max} \equiv 1/[c]$.

The intrinsic DR, [DR], and the intrinsic concentration, [$c$], are defined as $[\mathrm{DR}] = \lim_{c \to 0} \mathrm{DR}/c$ and $[c] = \mathrm{DR}_{\max}/[\mathrm{DR}]$, respectively. Here, $\mathrm{DR}_{\max}$ is the maximum DR for a given polymer/solvent system. An adjustable parameter, $b_0$, defined as $K$, completes Eq. (3), as well as fitting the universal correlation for

DR; therefore, an empirical relationship in conventional form can be expressed as

$$\mathrm{DR} = \frac{c[\mathrm{DR}]}{K + c/[c]} \ . \tag{4}$$

Equation (4) can be rearranged to the following form

$$\frac{c}{\mathrm{DR}} = \frac{c}{\mathrm{DR}_{\max}} + \frac{K[c]}{\mathrm{DR}_{\max}} \ . \tag{5}$$

Equation (5) suggests that there exists a linear relationship between $c/\mathrm{DR}$ and $c$ up to the optimum concentration. This is valid for most drag-reducing polymers in both pipe and rotating disk flows. The linear correlation between polymer concentration and $c/\mathrm{DR}$ for four different molecular weights under a range of conditions close to the maximum DR is illustrated in Fig. 2. $\mathrm{DR}_{\max}$ can be obtained from the inverse of the slope, and the intercept yields $[c]$ multiplied by $\mathrm{DR}_{\max}/K$. The parameters $\mathrm{DR}_{\max}$ and $[c]$, which are characteristics of a given polymer compound, may provide a measure of the DR effectiveness and are thus useful quantities for laboratory characterization of drag-reducing polymers. For various polymer-solvent systems, more efficient DR materials [31] have a larger $\mathrm{DR}_{\max}$ and a smaller $[c]$. $[c]$ is found to be an extremely useful quantity for normalizing the DR data of different molecular weight compounds into one homologous series, such as PEO [19], PIB [20], and rodlike polysaccharide, xanthan gum [8]. $\mathrm{DR}_{\max}$ for PEO with $M_w = 5 \times 10^6$ is obtained as 30.18% from Eq. (5) and as 29.51% for PEO with $M_w = 4 \times 10^6$. These values are similar to the DR obtained at 50 wppm in Fig. 1. In addition, $\mathrm{DR}_{\max}$ becomes 28.43% for PEO with $M_w = 4 \times 10^5$and 29.65% for $M_w = 9 \times 10^5$, respectively; however, these are higher than the DR values, which occurred at 75 wppm as shown in Fig. 1. Thereby, we predict that the true maximum DR for the two PEO samples will be obtained between 75 and 100 wppm for these conditions.

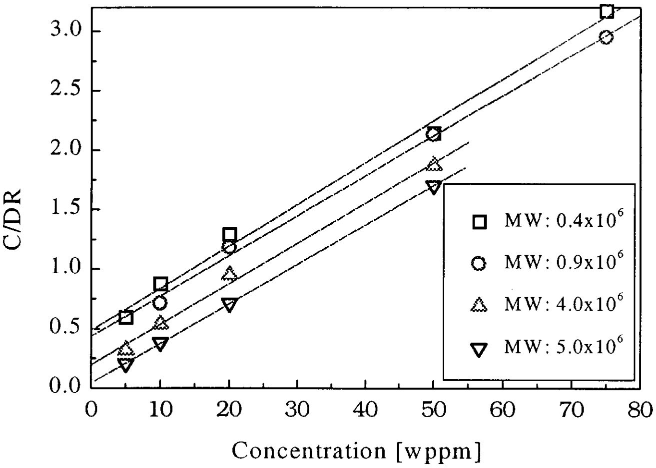

**Fig. 2** Concentration dependence of DR for the PEO–seawater system at 25 °C at a rotation speed of 1800 rpm ($N_{\mathrm{Re}} = 9.7 \times 10^5$)

Equation (4) is rearranged into the universal correlation for DR [8]:

$$\frac{\mathrm{DR}/c}{[\mathrm{DR}]} = \frac{1}{K + c/[c]} \ . \tag{6}$$

The constant $K$ in Eq. (6) is a characteristic of a particular polymer–solvent family and is independent of the molecular weight or flow geometry. Figure 3 clearly indicates that this universal characteristic of PEO in seawater is independent of molecular weight and Reynolds number or rotation speed by setting $K = 1$. Note that the numerical value of $K$ is observed to be 1 for the PEO–water system both in a pipe flow [32] and in an RDA [19].

Virk et al. [17] observed that DR effectiveness increases with concentration until the increased viscosity overwhelms the DR; therefore, $c$ has been recognized as one of the most critical quantities for interpreting the DR efficiency. It has been noted that $[\eta]c$ can be considered as a hypothetical pervaded volume fraction, where $[\eta]$ is the intrinsic viscosity. The onset of the concentrated region, where the overlap of polymer chains becomes significant, occurs at $[\eta]c = 1.08$ [33]. The hydrodynamic volume, $[\eta]c$, is a function of chemical structure, chain length, and interactions between polymer segments and solvent [34]. Experimental studies have shown that a number of molecular parameters (polymer molecular weight, hydrodynamic volume, aggregation, chain stiffness, and polymer/solvent system) influence DR behavior [35]; therefore, all systems were expected to obey a universal curve for DR when

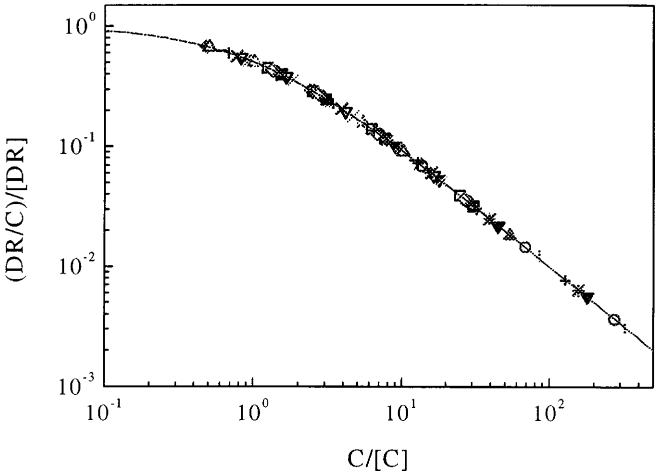

**Fig. 3** Universal DR curve, $(DR/c)[\mathrm{DR}]$ versus $c/[c]$ for PEO in seawater. *Rectangles*: $M_w = 4 \times 10^5$; *circles*: $M_w = 9 \times 10^5$; *triangles*: $M_w = 4 \times 10^6$; *diamonds*: $M_w = 5 \times 10^6$; *filled* ⊘: $N_{\mathrm{Re}} = 6.5 \times 10^5$; *open* ⊘: $N_{\mathrm{Re}} = 7.5 \times 10^5$; *dot center*: $N_{\mathrm{Re}} = 9.3 \times 10^5$; + *center*: $N_{\mathrm{Re}} = 9.7 \times 10^5$; – *center*: $N_{\mathrm{Re}} = 10.7 \times 10^5$

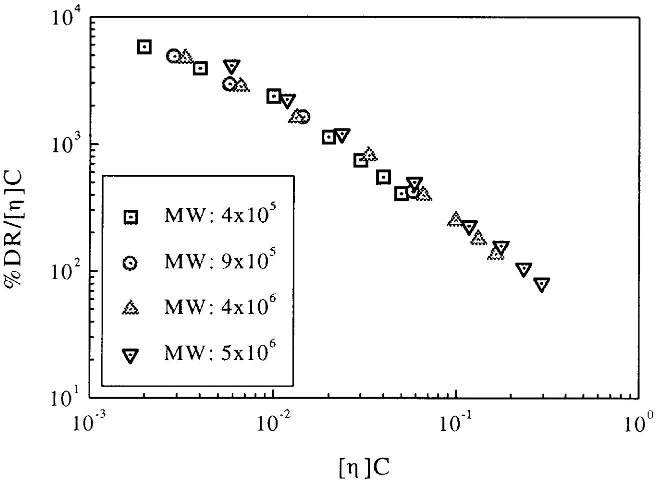

**Fig. 4** DR efficiency per volume fraction versus volume fraction for the PEO–seawater system for four different MWs at $N_{\mathrm{Re}} = 9.7 \times 10^5$

normalized by the hydrodynamic volume fraction of the polymer in solution [31, 35]. Motivated by Ryskin's analysis [36], we also obtained a measure of the relative DR efficiency at a given polymer volume fraction by normalizing %DR with $[\eta]c$. A plot of DR efficiency per volume fraction (%DR/$[\eta]c$) as a function of $[\eta]c$ for PEO in the RDA is shown in Fig. 4. The superimposed line with a slope of −1 represents the maximum DR envelope.

## Conclusions

We have investigated the DR efficiency of PEO in synthetic seawater using an RDA and found that the most effective DR is obtained near 50 wppm concentration for higher molecular weight PEO. The linear correlation between polymer concentration and $c$/DR is found in the RDA system. In addition, we constructed a universal correlation to characterize the DR of PEO in seawater and confirmed that the PEO–seawater system is similar to the PEO–pure water system, which is important in providing design criteria for OTEC technology.

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