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저온 활용 시스템의 효율 제고를 위한 마찰 저항 감소 연구

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A Study on the Drag Reduction for Performance the Improvement of Low Temperature Utilization Systems

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요 약

본 연구에서는 회전원판 장치를 사용하여 난류 유동장에서의 고분자에 의해 유도되는 마찰저항 감소효과에 대하여 조사하였다. 해양온도차 발전에서 해수를 이동시키는 유동장은 난류상태로 이러한 난류계에 대하여 마찰저항 감소는 충분한 적용가치가 있다. 네가지의 분자량이 다른 PEO를 마찰저항 첨가제로, 실험실에서 제조한 인공해수를 용매로 사용하여 고분자의 분자량, 고분자의 농도와 원판의 회전속도와 같이 마찰저항 감소효과에 영향을 줄 수 있는 여러 인자들에 대해서 살펴보았다. 마찰저항 감소의 농도의존성은 Virk의 Universal correlation를 따르는 것을 확인하였다. 해수에서도 PEO와 용매간의 Universal 곡선이 증류수를 용매로 하였을 때와 동일함을 확인하였다.

Abstract

Drag reduction produced by the dilute solution of polymer under turbulent flow in a rotating disk apparatus (RDA) was investigated in this study for the purpose of potential application to the Ocean Thermal Energy Conversion (OTEC) system. Four different molecular weights of poly(ethylene oxide) (PEO) were used as drag reducing additives, and synthetic seawater was adopted as a solvent. Experiments were undertaken to observe the dependence of drag reduction on various factors such as polymer molecular weight, polymer concentration and the rotating speed of the disk. The concentration dependence on the drag reduction of this polymer system was shown to obey an empirical drag reduction equation of the Virk's universal correlation.

1. INTRODUCTION

The oceans are the biggest silo to collect the solar energy of the earth. They can provide an alternative energy source which is accessible to anyone. So, many of the major developed nations have conducted exploratory research and development, and then installed pilots and a few commercial plants. Most of this technology development involving tidal, wave, current, and salinity gradient energy systems have focused intensively on electricity production. OTEC (Ocean Thermal Energy Conversion) system is the one of techniques using the solar energy. Small-scale OTEC systems producing electrical power, nutrients for mariculture, and fresh water are ideal for expanding the economic potential of many islands and coastal communities. This OTEC process uses the temperature difference, induced by the solar energy absorbed and stored as heat in the surface layer of the ocean, to convert thermal energy to mechanical energy for the generation of electricity¹⁾. Cold water is, in general, found at depths of 800 meters. When the warm surface water temperature and cold deep water temperature differ by at least 20°C, an

OTEC system can produce net power. Tropical regions worldwide have a temperature difference of 20°C or greater throughout the year, thus providing an enormous potential for meeting the future energy needs of the world. Therefore, the OTEC technology is investigated in a greater depth recently because it offers a salient potential for reducing our dependence on fossil fuels within the next decade through the production of electrical power as well as the utilization of the cold water effluent for integrated applications.

In a number of practical situations of field flow, a large amount of energy losses due to friction occurs in a turbulent flow. However, it is well-known that the presence of very small amounts of high molecular weight polymeric substances can cause drastic reduction in the frictional drag of the liquids in the turbulent flow. This phenomenon implies that polymer solutions undergoing flow in pipe require a lower pressure gradient to maintain the same flow rate. A higher flow rate would be obtained for the same pressure gradient if such additives are used. Reduction in pump work when using this drag reduction (DR) additives was shown to be 70% in a full-scale test²⁾, which may lead to substantial cost savings

when electric power is expensive. Various areas of the technical application for this phenomenon can be found in the field of transport of crude oil³⁾, in fire fighting⁴⁾, in increasing the speed of boats, submarines and torpedo^{5,6)}, in water supply and irrigation system⁷⁾, in hydraulic transportation of solid particle suspensions^{8,9)}, and in cooling and heating circulation systems¹⁰⁾. The most effective drag reducing polymers, in general, possess a linear flexible structure and a very high molecular weight. Among various drag reducing polymers, a high molecular weight water soluble poly(ethylene oxide)(PEO), which has been widely used as a drag reducer in aqueous system, was selected in this study.

Although a mechanism of the drag reduction has been the subject of extensive researches, a complete and satisfactory explanation has not been reported. Nonetheless, it is generally accepted that the non-Newtonian rheological properties of polymer solution are responsible for the occurrence of the interaction between a polymer and turbulence to produce turbulent drag reduction. The understanding of turbulent drag reduction in dilute polymer solutions requires an investigation not only of the phenomena associated with turbulence itself but also of the dynamics of macromolecules in dilute solutions. Recently, de Gennes¹¹⁾ introduced an elastic theory of drag reduction to explain the properties of homogeneous, isotropic and three-dimensional turbulence without any wall effect, in the presence of polymer additives. The central idea of this 'cascade theory' is that polymer effects at small scales are not described by a viscosity, but by an elastic modulus.

It is well known that drag reduction is strongly

influenced by the molecular parameters of the dissolved polymer such as molecular weight of polymer and polymer concentration. Since the drag reduction is caused by the sum of contributions from individual polymer molecules, we measured the concentration dependence of drag reduction. The efficiency of drag reducing polymer additives, based upon a unit concentration at infinite dilution, was then determined by using a characteristic parameter, $DR_{max}/[C]$, where DR_{max} is the maximum percent drag reduction and $[C]$ is the intrinsic concentration. Through these analyses, the universal curve was established by previous researchers.¹²⁾ Virk et al.¹²⁾ investigated the relationship of the relative drag reduction/concentration versus the concentration for various molecular weights of PEO in water flowing through a pipe. They observed that the extent of drag reduction induced by homologous series of polymers in a given pipe is a universal function of concentration, flow rate, and molecular weight. Improving the form of Virk's drag reduction equation, Ting and Little¹³⁾ and other researchers studied the concentration dependence of drag reduction and found that a linear relationship exists between $DR_{max}/[C]$ and the molecular weight of the polymer. Furthermore, various parameters such as temperature, Reynolds number, and solvent quality are known to be another important factors of the drag reduction. Recently, Choi and Jhon¹⁴⁾ investigated that intrinsic drag reduction, intrinsic concentration, and universal drag reduction curve both for PEO in water and for polyisobutylene (PIB)-kerosene in an RDA agree well with those for PEO-water and for PIB-toluene in a pipe system, respectively. They also derived a three parameter relationship between

DR and C, using the Pad Pad 'e' form, which gives a universal curve.

In this study, we will not discuss a theoretical aspect of the origin of turbulent drag reduction but will focus our attention on some empirical correlation for water-soluble PEO in synthetic seawater using a rotating disk apparatus (RDA) for the potential application of this DR phenomenon to the OTEC.

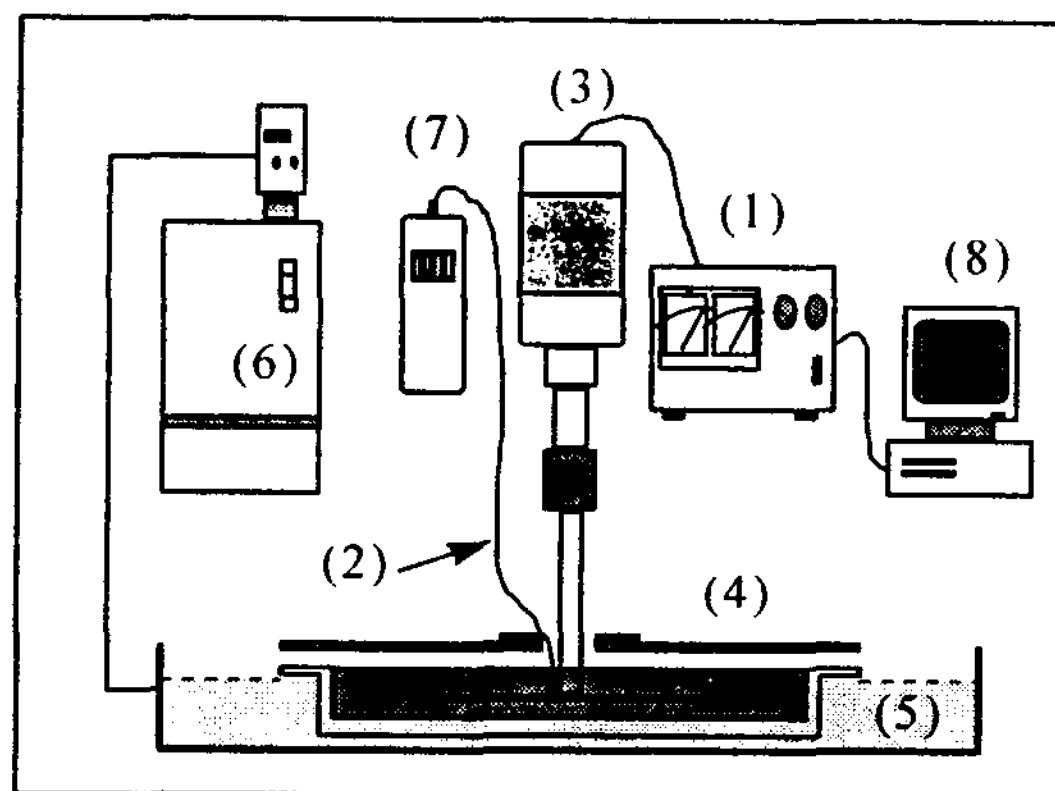
2. EXPERIMENTAL

Instead of using real seawater as a solvent in this study, we prepared the artificial seawater based on the fact that the average salinity of the seawater is about 35grams of dissolved salts per kilogram of seawater. While the salinity of seawater varies from place to place, the relative proportion of major constituents remains fairly constant. To make the artificial seawater, we dissolved 27.01g of NaCl, 10.44g of MgCl₂ · 6H₂O, and 0.90g of KCl in 1000g of deionized water to provide sufficient electrolytes. This synthetic seawater was then used as a solvent. Among drag reducing agents, high molecular weight linear PEO was chosen because of its extremely good solubility in pure water. Polymers were purchased from Scientific Polymer Products Inc. and the average molecular weight of PEO ranged from 4×10^5 to 5.0×10^6 g/mole.

Polymer solutions were obtained by dissolving an appropriate amount of PEO in seawater. A 0.5%(w/w) concentration of stock solution was initially prepared and then diluted to the required polymer concentration by injecting directly into the turbulent seawater flow field. The rotating disk

apparatus was the same as that previously reported.¹⁵⁾

A schematic diagram of the RDA is shown in Figure 1. It consists of a stainless steel disk whose dimensions are 10.1cm diameter × 0.32cm thickness, enclosed in a cylindrical thermostatically controlled container, which is made of stainless steel and whose dimensions are 16.3cm i.d. (inner diameter) × 5.5cm height. The volume of solution required to fill the entire container is about 1020cm³.



(1)Speed controller (2)Thermocouple (3)DC motor (4)Solution container
(5)Water bath (6)Water circulating system (7)Thermometer
(8)AD converter & PC

Fig. 1 Schematic diagram of rotating disk apparatus

The rotational velocity of the disk was maintained constant, using a speed controller (Cole Parmer Master Servodyne Unit) and a DC-varying speed motor, and the variable torque was measured by a multimeter. The temperature of the system was maintained at $25.0 \pm 0.5^\circ\text{C}$ by a constant temperature circulating apparatus, and the rotational velocity of the disk was measured by a digital

tachometer. A flow visualization experiment to determine whether the fluid was uniformly mixed after the addition of the stock solution was employed with the same apparatus used by Yang et al.¹⁶⁾ They observed complete mixing within several seconds and obtained reproducible results for each run.

The drag reduction efficiency was obtained by first measuring the torque required to rotate the disk at a given speed in the pure seawater solvent. By measuring the corresponding torque required to attain the same speed in the solvent with a polymer added, the percentage reduction is then calculated as follows :

$$DR(\%) = \frac{T_0 - T_p}{T_0} \times 100 \quad (1)$$

where T_0 is the torque in the pure solvent and T_p is the torque required when the polymer is added, that is, the torque in the dilute polymer solution.

In addition, the rotational Reynolds number N_{Re} is defined as

$$N_{Re} = \rho r^2 \omega / \mu \quad (2)$$

where ρ and μ are the density and the viscosity of the fluid, r is the radius of the disk, and ω is the rotational speed of the disk. Using the RDA, turbulence is produced for $N_{Re} > 3 \times 10^5$ or equivalently 1050rpm for the rotational disk velocity in our RDA.¹⁷⁾ Since the drag reduction phenomenon for the polymer occurs only in the turbulent region, all RDA measurements in this study were taken much above 1050rpm.

3. RESULTS AND DISCUSSION

The concentration dependence of drag reduction was studied at first to obtain the optimum concentration which gives the maximum drag reduction. Concentration effects on the drag reduction have been known to be determined by two competitive mechanisms. Initially, the drag reduction increases as the concentration increases due to the increase of the number of available drag reducers. However, as the concentration further increases, the solution viscosity increases, leading to the increase in the frictional drag. It was anticipated that the existence of a critical concentration at which the drag reduction has maximum value.

The dependence of percent drag reduction for various molecular weights of PEO as a function of polymer concentration at 1800 rpm is given in Fig. 2.

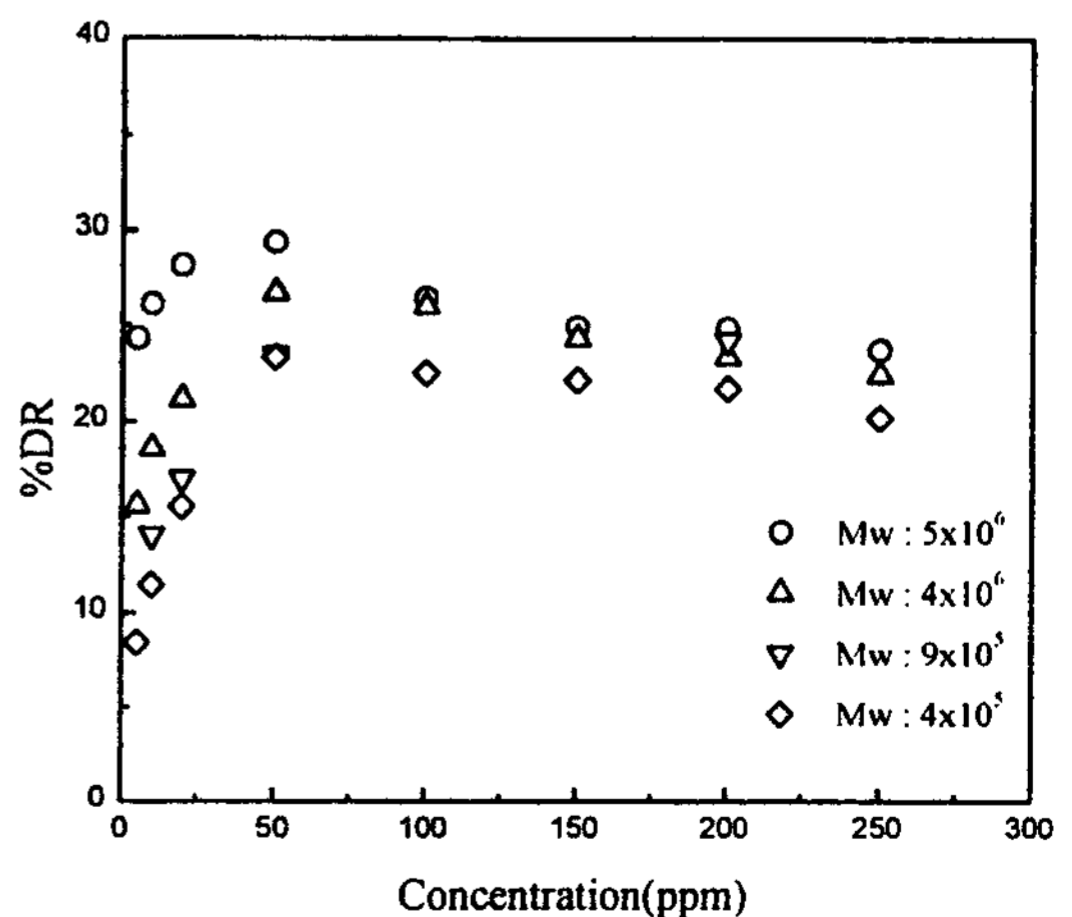


Fig. 2 Drag reduction of PEO with various molecular weight versus concentration at 25°C.

Maximum drag reduction in the seawater system occurs at the same concentration irrespective of the molecular weight of PEO. It can be compared with drag reduction result of PEO in the pure deionized water,^{15,16)} in which the concentration giving the maximum drag reduction has been shifted to lower value as the molecular weight of PEO increases. Hoyt¹⁸⁾ measured an effect of ferric ion on the drag reduction of polyacrylamides, and found that drag reduction ability of the various polyacrylamides was strongly affected by the ferric ion. His result also indicated that the immediate loss of drag reduction effect seemed to be due to flocculation and, on a longer term basis, also to oxidative degradation. The particular behavior of PEO in seawater in this study can be thereby explained from the possibility that the alkali metal ions make a chilate complex with PEO molecules. This kind of flocculation is believed to form when the alkali ion is presented in a polymer solution. It then alters the conformation of polymer and thereby does drag reduction ability.

In addition, to study the stability or mechanical degradation of polymer chains in a turbulent flow, we also measured drag reduction efficiency over a period of time. Figure 3 depicts the drag reduction obtained for various polymer concentrations as a function of time at the rotational speed of 1800rpm for various molecular weights of PEO. As shown in the figure, drag reductions decay as a function of time and then maintain stable values due to the degradation of polymer chains in a turbulent flow. As polymer chains degrade, they lose their ability of the drag reduction.

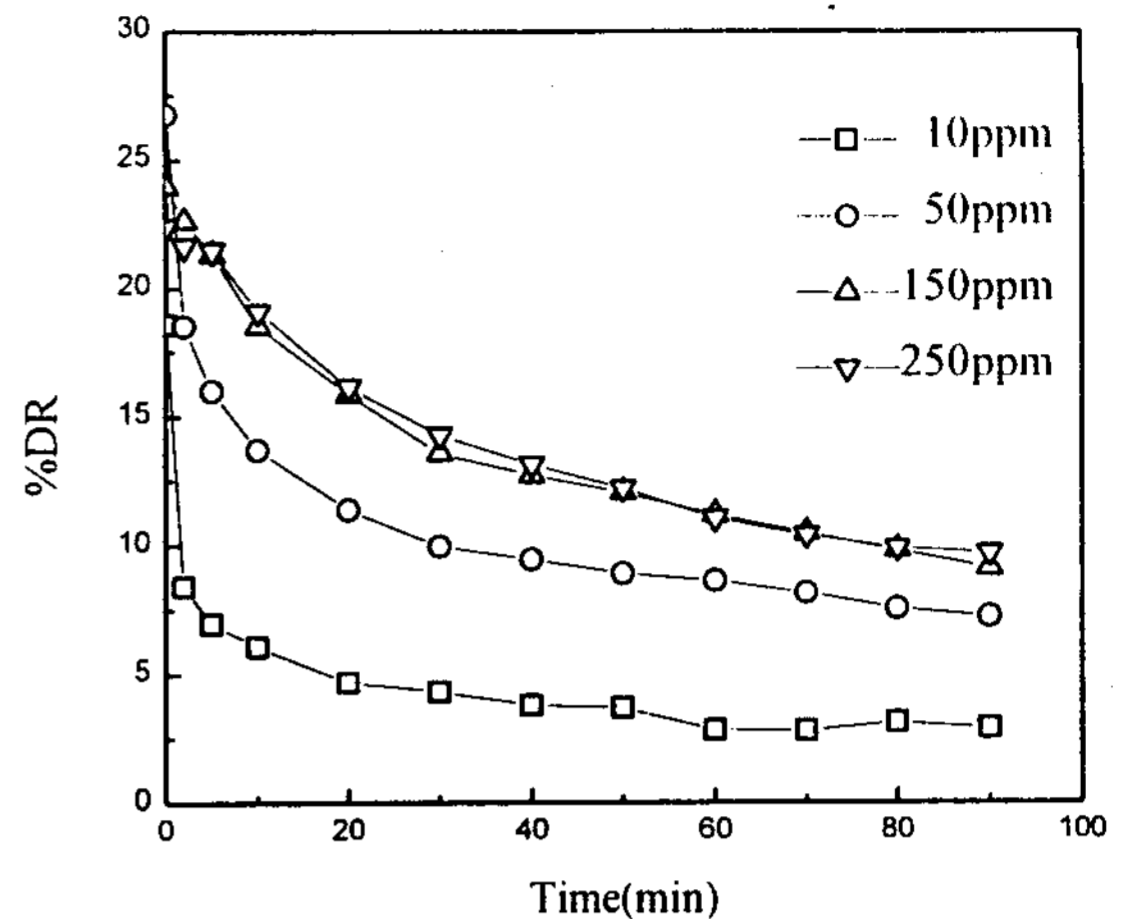


Fig. 3 Percent Drag reduction verse of PEO(Mw: 5×10^6) versus Time at various Polymer Concentrations.

Yang et al.¹⁶⁾ investigated the concentration dependence on drag reduction at 2800 rpm in a RDA. Their results showed that the polymer degradation occurs more rapidly with decreasing polymer concentration, which is consistent with the fact that at a low concentration of polymer solution, the number-average molecular weight decreases more rapidly.¹⁹⁾ However our study shows that the drag reduction effectiveness decreases more rapidly with increasing concentration. It indicates that the drag reduction is also strongly related to the Reynolds number.

On the other hand, to find an empirical relationship between the drag reduction and polymer solution properties, Choi and Jhon¹⁴⁾ introduced the three-parameter empirical relationship between the drag reduction (DR) and the concentration (C) to provide a universal correlation for the drag reduction data. To

interpret the drag reduction data, the empirical relationship, which accounts for the concentration dependence of drag reduction, takes the following form.

$$\frac{C}{DR} = \frac{[C]}{DR_{max}} + \frac{C}{DR_{max}} \quad (3)$$

where C, DR, DR_{max} and [C] are concentration in ppm, percent drag reduction, maximum drag reduction, and intrinsic concentration in ppm, respectively.

Furthermore, the intrinsic concentration is defined by

$$[C] = \frac{DR_{max}}{\lim_{C \rightarrow 0} DR/C} \quad (4)$$

The quantity in the denominator is the intrinsic drag reduction, which is a measure of the drag reduction per unit concentration at infinite dilution as follows :

$$\frac{DR}{DR_{max}} = \frac{C}{[C] + C} \quad (5)$$

$$\lim_{C \rightarrow 0} \frac{DR}{C} = \lim_{C \rightarrow 0} \frac{DR_{max}}{C + [C]} = \frac{DR_{max}}{[C]} \quad (6)$$

$$[DR] = \lim_{C \rightarrow 0} \frac{DR}{C} \quad (7)$$

The linear correlation between polymer concentration and C/DR for three different molecular weights in a range of conditions close to the maximum drag reduction is illustrated in Fig. 4. Figure 4 shows that eqn (3) can be

applied to drag-reducing polymer-seawater system in different geometry (e.g., RDA). The DR_{max} can be obtained from the reciprocal of the slope, and the intercept when it is multiplied by the DR_{max} yields the intrinsic concentration [C]. The parameters [C] and DR_{max}, being characteristics of a given polymer compound, may serve as a measure of the drag reduction effectiveness and thus are useful tools for laboratory characterization of drag reducing polymers.

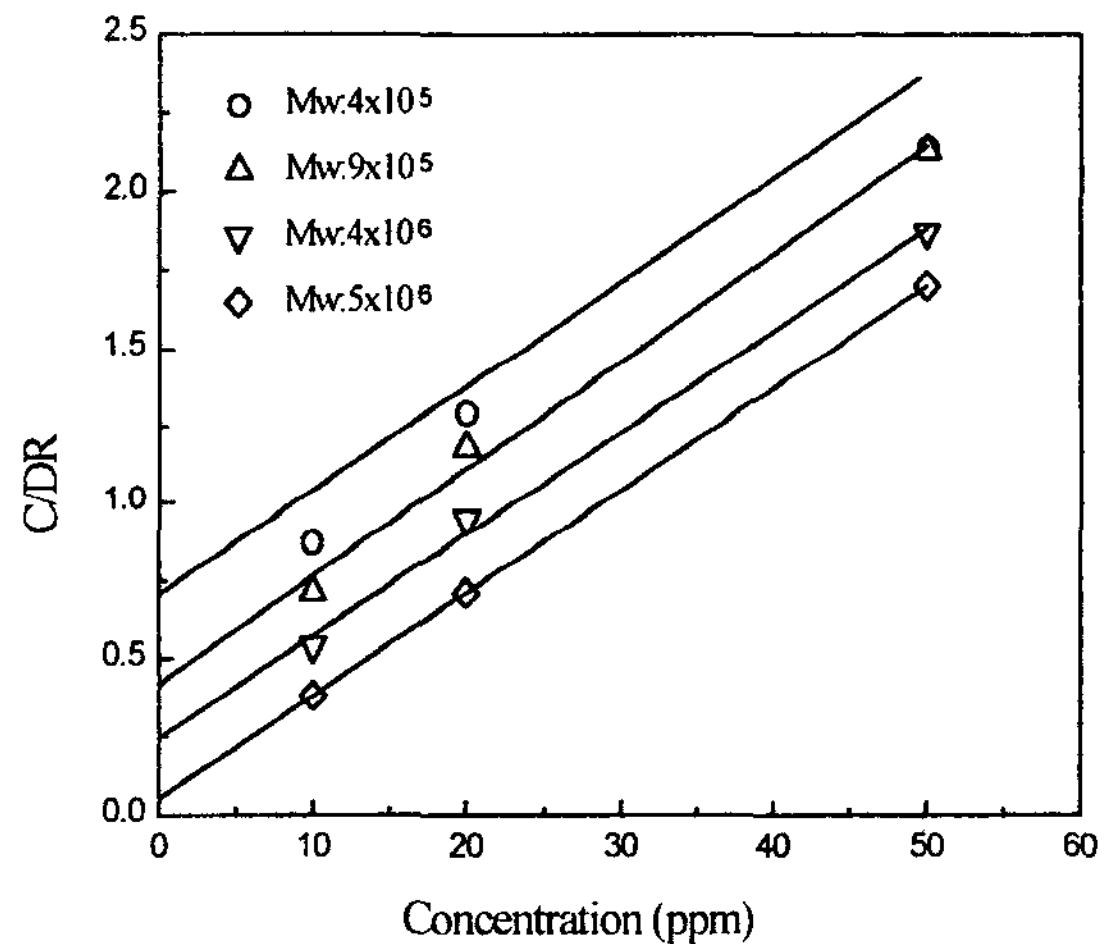


Fig. 4 Concentration dependence of drag reduction for PEO at 25°C in seawater.

The physical significance of these parameters becomes clear in eqn (6). Equation (6) can be simply obtained from eqn (5) in the case of zero concentration limit. This parameter, DR_{max}/[C], becomes a measure of the "efficiency" of the polymer additives on a unit concentration basis at infinite dilution. Figure 5 shows a correlation between this drag reduction "index" and the viscosity average molecular weight of polymer. The intercept value of $\bar{M}_v = 3.17 \times 10^5$

obtained from the least square method, suggests a cutoff point in polymer molecular weight below which no drag reduction takes place at this Reynolds number (4×10^5). This cutoff molecular weight is higher than that reported by Yang et al.⁵⁾ This difference in the cutoff molecular weights is believed to be related to the salinity in the solvent and different Reynolds number. Hunston and Zakin²⁰⁾ found that for various polymer-solvent systems, more efficient materials have a larger DR_{max} and smaller $[C]$, and both DR_{max} and $[C]$ are more favorable in a good solvent.

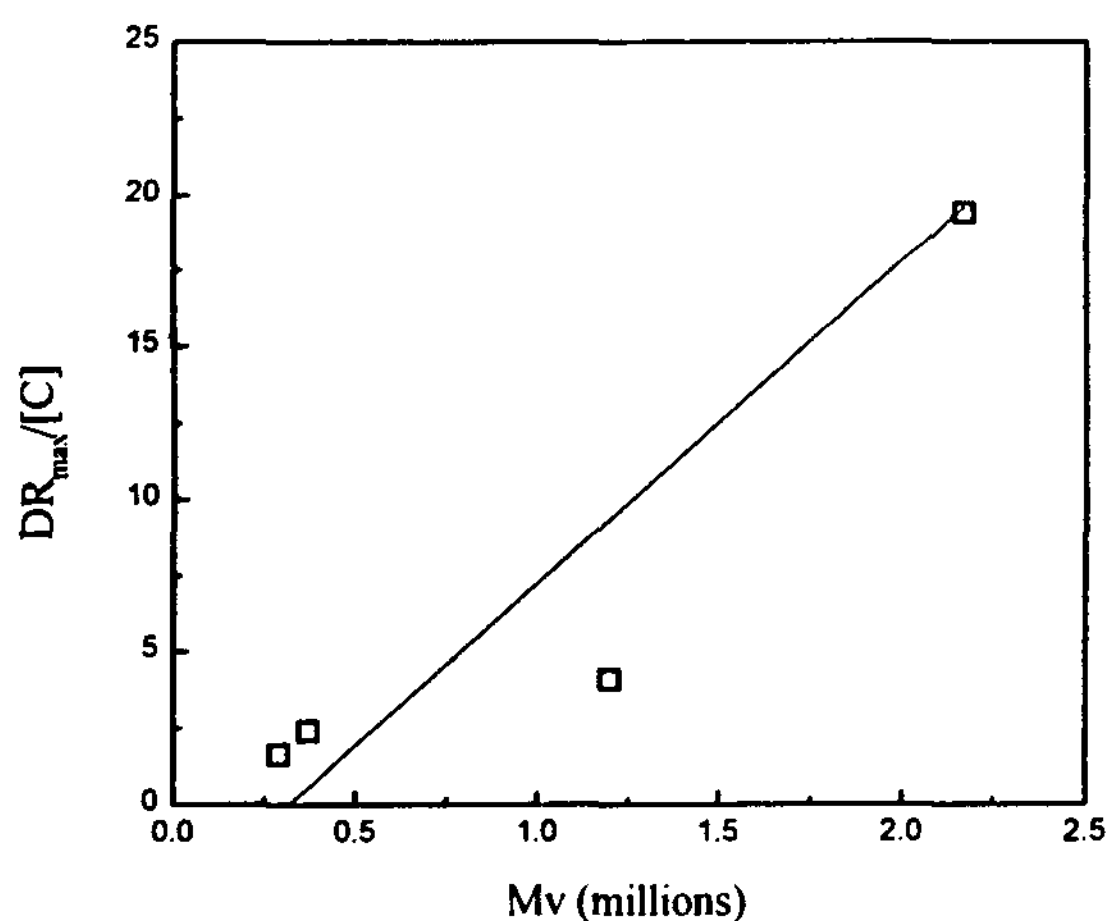


Fig. 5 Plot of $DR_{max}/[C]$ versus Viscosity average molecular weight for PEO in the seawater at 25°C.

Furthermore, $[C]$ was found to be extremely useful in normalizing the drag reduction data of different molecular weight as shown in Fig. 6. This figure describes that the intrinsic concentration can be used to normalize the data

obtained from our RDA. Little²¹⁾ moulded DR in the following universal correlation;

$$\frac{DR/C}{[DR]} = \frac{1}{K + C/[C]} \quad (8)$$

In addition, if $(DR/C)/[DR]$ and $C/[C]$ are defined as β and α , respectively, the universal curve is then formulated by the following form.

$$\beta = \frac{1}{(\alpha + K)} \quad (9)$$

The constant K in eqn (9) is a characteristic of a particular polymer family in a given solvent and does not depend on the molecular weight or flow geometry of the system. Figure 7 clearly indicates this universal characteristic of PEO in the seawater with $K = 1$, irrespective of the molecular weight.

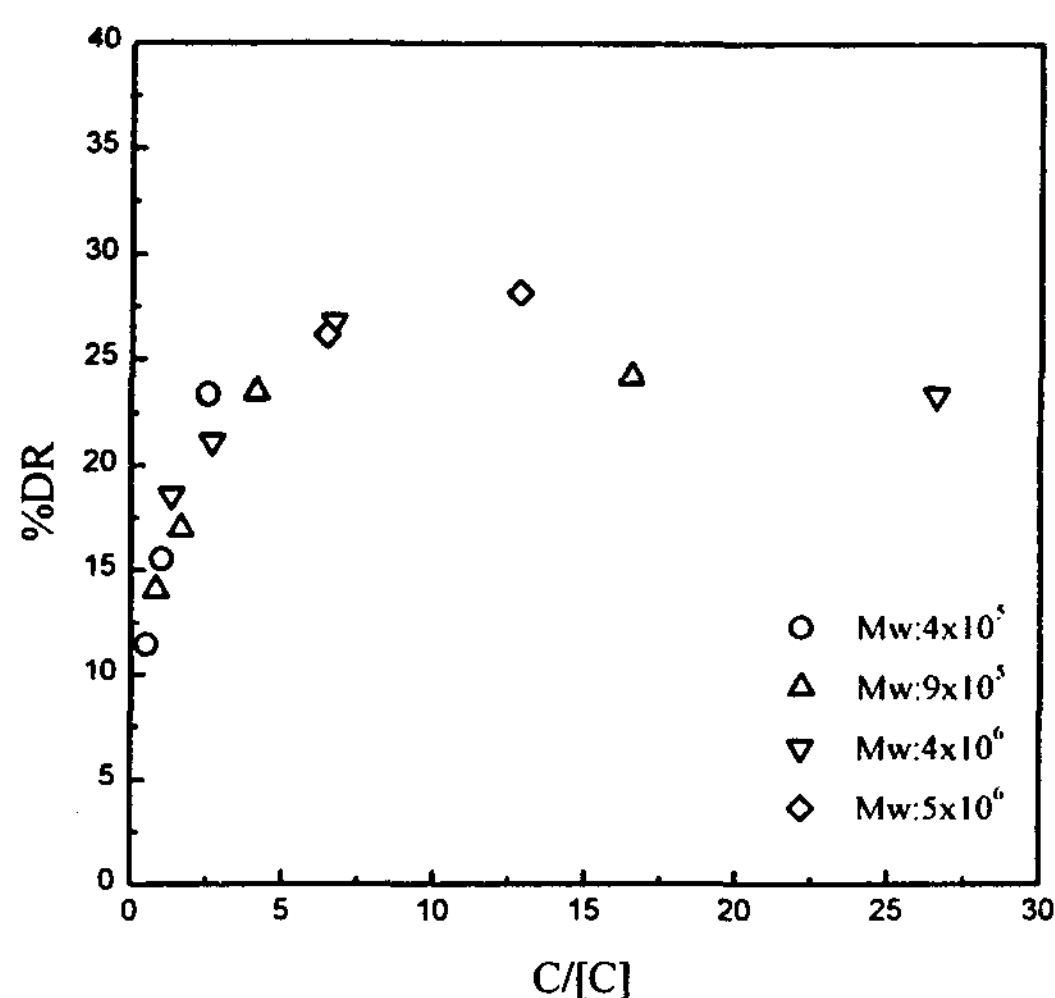


Fig. 6 Intrinsic concentration as a normalizing factor for PEO in seawater.

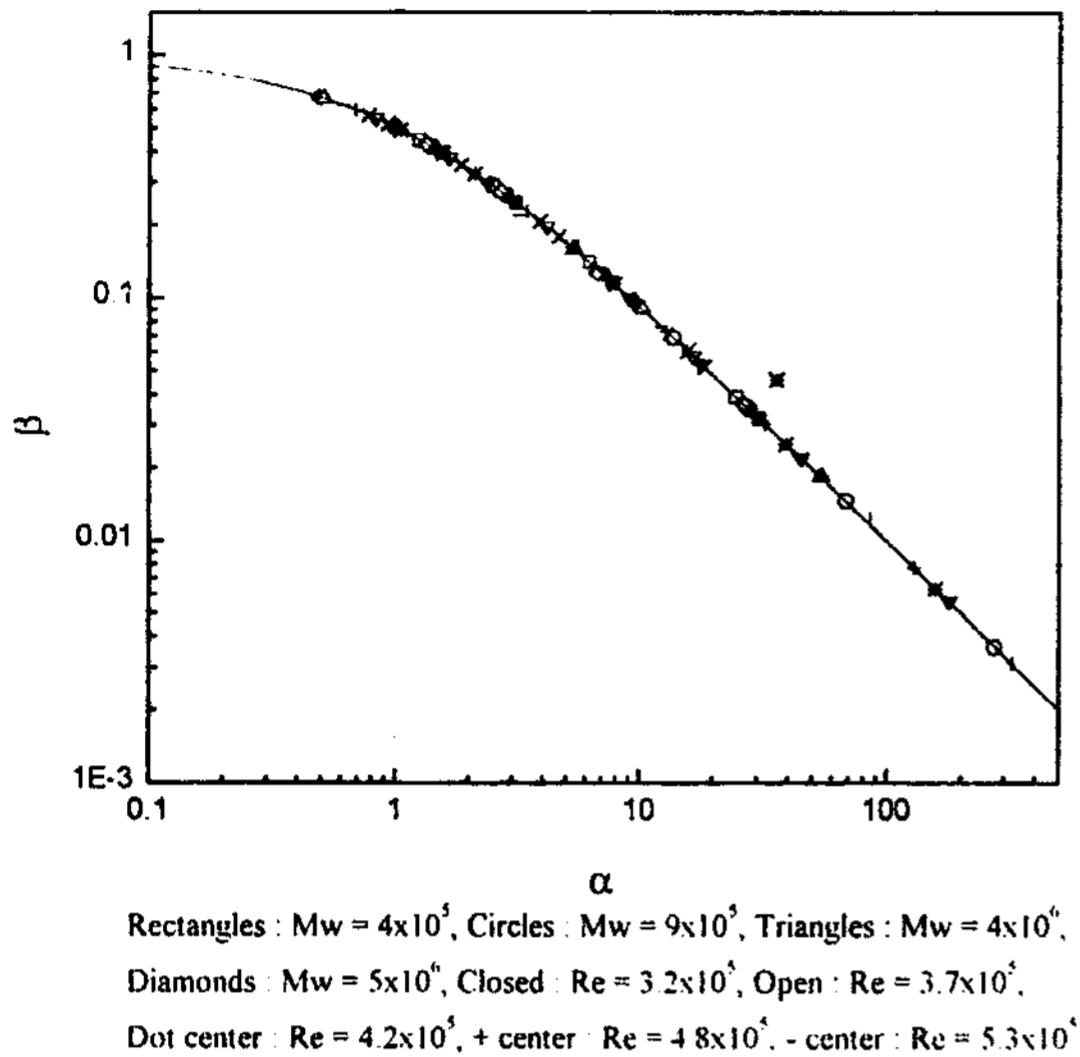


Fig. 7 Universal drag reduction curve, β vs. α for PEO in seawater. Figure 6

4. CONCLUSION

It is found that the drag reduction effect induced by polymer additives can be applied to the OTEC plant to save the pumping energy cost from this study. Effects of both concentration and molecular weight for a homologous series of PEO on drag reduction were thereby investigated in a RDA using the synthetic seawater as a solvent. The drag reduction increases with polymer concentration until a maximum is reached. The concentration required for DR_{max} was found to decrease with increasing molecular weight, and the molecular weight dependence becomes negligible above 100 wppm of PEO concentration. Linear correlation between polymer concentration and C/DR was obtained for this rotating disk geometry. In addition, correlation between drag reduction

index, DR_{max}/[C], and viscosity-average molecular weight was also found to be linear. When (DR/C)/[DR] and C/[C] are defined as β and α , respectively, it was possible to obtain a universal curve represented by $\beta = 1/(\alpha + 1)$ for PEO family in seawater.

ACKNOWLEDGMENT

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