1. 난류 흐름장에서의 DNA 의 마찰저항 감소특성

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Drag Reducing Characteristics of DNA in Turbulent Flow

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Introduction

Under certain conditions of turbulent flow, the phenomenon in which the drag of dilute polymer solution is drastically reduced by even minute amounts of suitable additives has been widely investigated for its wide range of applications (Kulicke et al., 1989; Brostow et al, 1999). This phenomenon implies that polymer solutions undergoing flow in a pipe require a lower pressure gradient to maintain the same flow rate. Consequently, a higher flow rate would be obtained for the same pressure gradient if such an additive were used. The various parameters such as polymer concentration, polymer molecular weight, temperature, Reynolds number (N_{Re}), and solvent quality are known to be the important factors of drag reduction (DR) (Kim et al., 2000; Sohn et al., 2001).

In this study, we chose a lambda DNA, which has one of the highest molecular weight among various DNAs in nature, as a successful candidate for drag reducing agent. DNA also has different molecular structure (helical structure) from conventional drag reducers (usually linear structures). We expected this configurational structure would show characteristic behavior, which could give more detail understanding about the drag-reducing phenomenon. Using calf-thymus DNA, Hand and Williams (1970) measured its drag reduction as a function of pH and observed that the less flexible helical conformation is preferable to the random coil for maximum drag reduction.

Theory

Considering the viscoelastic behavior of drag-reducing polymer solutions near a wall, Ruckenstein (1973) proposed that drag reduction is due to two effects of viscoelasticity: (1) Using a Maxwell model as the constitutive equation for a viscoelastic fluid, he showed that the instantaneous shear stress at the wall is smaller in the viscoelastic fluid than in a corresponding Newtonian fluid. (2) The replacement of the elements of liquid following short paths along the wall takes place as a result of turbulent fluctuations. In order to be replaced by other elements, an element moving along the wall must first relax its elastic stresses to enable viscous deformations required for its replacement to occur. This introduces a delay in the replacement process as compared to a Newtonian fluid. As the instantaneous shear stress at the wall decrease for increasing contact times with the wall, the average shear stress at the wall decreases.

In addition, an elastic theory of drag reduction was introduced to discuss the properties of homogeneous, isotropic three-dimensional turbulence in the presence of polymer additives without any wall effect (Tabor and de Gennes, 1986). The central idea of this "cascade theory," limited to linear flexible chains in a good solvent, is that polymer effects on small scales are not described by the viscosity but by the elastic modulus. The importance of an elastic property to describe the mechanism of drag reduction was also examined by Armstrong and Jhon (1984). Adopting a simple model to study both the turbulence and dissolved polymer molecules, they related the molecular dissipation to friction factors by constructing a self-consistent method.

With respect to mechanical molecular degradation (MMD), Brostow (1983) related macromolecular configurations in solution with drag reduction induced by polymers and MMD under flow. Zakin and Hunston (1978) monitored DR efficiency in a capillary tube, which is very sensitive to polymer molecular weight. In addition, Culter et al. (1975) indicated that much of the MMD occurs at the entrance of a capillary tube. To reduce the entrance effect, Horn and Merrill (1984) installed a conical funnel at the entrance of the tube from the feed solution reservoir.

The torque required to rotate the disk for pure solvent (T_S) at a given speed was measured first. The percent DR (%DR) was then calculated by measuring the corresponding torque required for a dilute polymer solution (T_P) at the same ω:

$$\% \, DR = \frac{T_s - T_P}{T_s} \times 100 \quad \text{(At a given } N_{Re}\text{)}. \tag{1}$$

Experimental

The rotating disk apparatus (RDA; Kim et al., 2001) was used to study both the DR efficiency and the transient behavior of DNA chains in a turbulent flow. Turbulence is produced for rotational Reynolds number (N_{Re}) $> 3 \times 10^5$ or, equivalently, rotational speed of the disk (ω) > 570 rpm$\times 2\pi$ (Schlichting, 1979). Here, $N_{Re} = \rho r^2 \omega / \mu$, where ρ is the fluid density, μ is the fluid viscosity, and r is the radius of the disk. The temperature of the system was maintained at (25 ± 0.5) °C. λ-DNA, purchased from Promega Corporation (US) with 48,502bp (32,300 kD) in size is a commonly used substrate in restriction enzyme activity assay. Drag reduction was performed in the buffer solution, which consists of 10mM tris-HCL (pH 7.8 at 25 ℃), 10mM NaCl and 1mM EDTA. Electrophoresis analysis was used to examine the base pare (bp) of the DNA after the sample was exposed to the turbulent flow.

Results and Discussion

Fig. 1 shows the %DR for 2.75 and 1.35 wppm of DNA as a function of time at relatively high Reynolds number ($N_{Re} \sim 1,000,000$). Lambda DNA showed relatively high drag reduction effect that increases with concentration. However, % DR decreased with time due to the degradation of DNA. Although lambda DNA degraded in high turbulent flow, the overall %DR efficiency was maintained for a long time, after it initially dropped. That characteristic behavior is the main difference from other kinds of drag reducing linearly long chain molecules. Usually, flexible long chain molecules degrade as soon as they are injected in high turbulent flow. The durability of the λ-DNA to high turbulence is assumed to originate

from the very strong helical structure of DNA molecules in proper condition.

For PEO in the same condition, DR efficiency decreased abruptly in a few minutes, and the decreasing behavior continued to reach zero DR efficiency. This means that, even though DNA molecules experienced degradation process in high turbulence, the residual short chain molecules still exist as a drag reducer in a strong turbulent flow. And, the short chain molecules no longer preceded degradation process in such specific condition.

To examine the maximum drag reducing condition, we conducted rotation speed sweep test (Fig. 2). The maximum drag efficiency was occurred at 1770rpm, which corresponds to Reynolds number, 908,000. The increase of %DR, until they reach to the critical speed, is a characteristic behavior of polymeric drag reducers. Usually the drag reducing phenomena is more effective in higher turbulent flow. So, this kind of behavior can be explained with the concept of high turbulent flow. Beyond this critical condition, polymer chains may start degradation by the excess energy generated by turbulent flow.
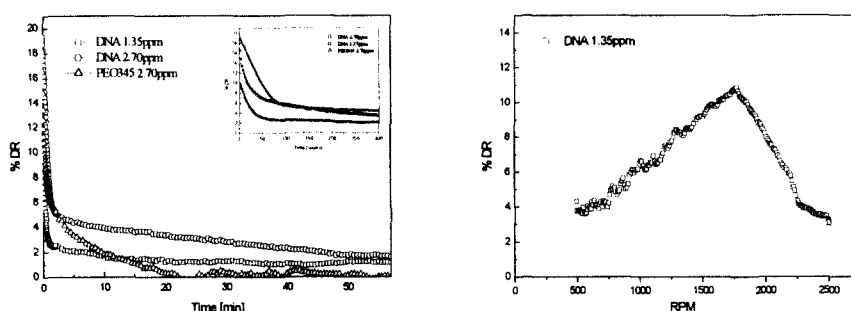

Fig. 1 The comparison of lambda DNA percent drag reduction with PEO345 ($M_w=5 \times 10^5$ g/mol) in long time scale (1hour) at 1,980 rpm ($N_{Re}=1 \times 10^6$), 25 $^\circ$C. (Left)

Fig. 2 The percent drag reduction versus rpm ($N_{Re}=2.5 \times 10^5 \sim 1.3 \times 10^6$) for 1.35 wppm lambda DNA in buffer solution at 25 $^\circ$C (continuous mode rpm sweep). (Right)

We selected the turbulent flow medium as buffer solution to preserve the helical structure of DNA. DNA, which is subjected in usual de-ionized water, decomposes to single strand, which can't show characteristic behavior of DNA. That kind of behavior usually called as 'melting of DNA'. In Fig. 3, DR efficiency decreased with time to zero efficiency, and also the initial DR effect also was smaller than that of buffer solution. The uncoiled chain of DNA was so weak to turbulence, so the chains exposed in turbulent flow followed the similar degradation mechanism of linear polymer, such as PEO.

Many researchers proposed the degradation mechanism of long chain molecules in turbulent flow. In their study, they showed the degradation usually occurred at the mid point of polymer using polydispersity index of polymer (Lee et al., 2002). The degradation of lambda DNA at 1980rpm ($N_{Re}\sim1,000,000$) was verified using electrophoresis method. In the Fig. 4, the first row represents 23.1kbp (kilo base pair). This result more definitely supports the previous theory that the overall degradation of polymer is mainly occurred in the half position of the polymer. And, 23.1kbp size DNA still showed very strong resistance to turbulent flow.
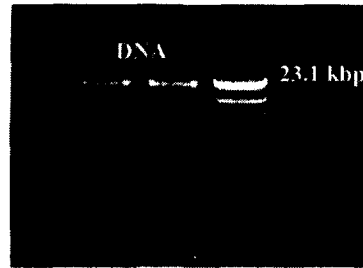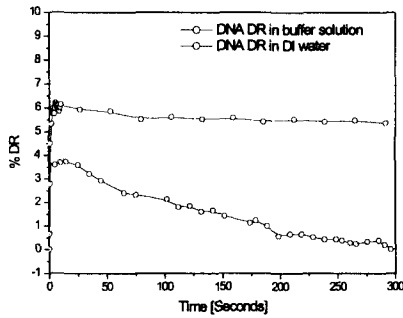
Fig. 3 The percent drag reduction versus time for 1.35 wppm lambda DNA in de-ionized water and buffer solution at 1,157 rpm ($N_{Re}=5.9\times10^5$), 25°C. (Left)

Fig. 4 The electrophoresis result of lambda DNA after degradation for 1 hour at 1,980 rpm, 25°C. (Right)

Conclusion

Drag reduction characteristics of DNA were observed to maintain with time due to the structural durability of the DNA in turbulent flow, and also compared to linear long chain polymer (PEO) system. The mechanical degradation at high Reynolds number for DNA in external flow was examined using electrophoresis method, showing that the mid-point degradation of long chain molecules occur in turbulent flow.

Acknowledgement

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