난류장내에서의 마찰저항 감소에 대한 DNA 구조효과

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Effect of DNA Conformation on Drag Reduction in Turbulent Flow

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Introduction

Turbulent drag reduction (DR) is defined as a phenomenon in which turbulent drag of flowing medium is drastically reduced by even minute amounts of suitable additives, implying that such flowing system requires lower pressure gradient to maintain the same flow rate. It has been extensively investigated not only due to its wide range of applications (Brostow et al., 1999) but also due to its scientific interests (Sreenivasan et al., 2000). While a satisfactory explanation of DR still eludes fundamental and general interpretation on it (Ararouchene et al., 2002), it is well known that DR is controlled by various parameters such as polymer concentration, polymer molecular weight, temperature, Reynolds number (N_{Re}), and solvent quality (Kim et al., 2000). Among these factors, many of them are related to the conformation of the polymer in the solvent. In this study, we chose three different DNAs, which have different structural characteristics (monodisperse molecular weight (Mw), polydisperse Mw, and circular structure), as a successful drag reducing candidate for the investigation of structure effect on DR. Since DNAs have a different molecular structure (helical structure) compared to conventional flexible polymeric drag reducers (usually linear structure), we could expect this characteristic will make it possible to show more detailed understanding in DR experiment and analysis. For example, Hand and Williams (1970) measured drag reducing phenomena of calf-thymus DNA, as a function of pH and observed that the less flexible helical conformation is preferable to the random coil for maximum drag reduction. Recently Choi et al. (2002) also reported that double-stranded DNA is found as a good drag reducer when compared with linear flexible polymers such as PEO.

Theory

Among various efforts to explain the DR phenomena, Brostow (1983) developed a statistical-mechanical model adopting solvation numbers of macromolecular chains (Browstow et al. 1999). On the other hand, an elastic theory for DR was also introduced to discuss the properties of homogeneous, isotropic three-dimensional turbulence without any wall effect (Tabor et al. 1986). The importance of an elastic property to DR was also examined by Armstrong and Jhon (1984). Adopting a simple model for both the turbulence and dissolved polymer molecules, they related the molecular dissipation with friction factors by constructing a self-consistent method.

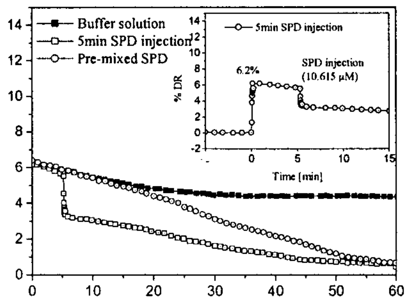
There are some advantages for choosing DNA in this study. First, DNA can be acquired in relatively high molecular weight with a perfect monodispersity, which is not easy to be obtained for any synthetic polymers. In addition, its molecular weight can be easily characterized using an electrophoresis. Second, the length of a fully stretched λ-DNA can be comparable to the microscales of the turbulent flow. Since the length of the polymers traditionally used in DR studies are much smaller than the microscales of the turbulence, the interaction between the polymer and the flow might be quite different. Finally, The structural feature of single, long duplex DNA exhibits a large discrete transition between elongated coil and compacted globule states in some specific condition (Takahashi et al., 1997). This chain-globule transition behavior of DNA with the addition of multivalent cation can give us the chance to investigate the detail mechanism of drag reducing phenomena and its molecular dynamics in turbulent flow. In addition, it is also possible to construct a specific form of DNA from biological technique such as circular form of λ-DNA. Based on those structural variations and conformational changes, turbulent DR phenomenon will be further discussed in conjunction with experimental results.

Experimental

Detail description for the rotating disk apparatus (RDA) can be found in the previous study (Kim et al., 2001). The temperature of the system was maintained at (25 ± 0.5) °C. λ-DNA (Promega Corporation, US) with 48,502bp (32,300 kD) in size was used as a model DNA. The coil-globule transition was manipulated by introducing polyamine (Spermidine (SPD), $C_7H_{19}N_3 \cdot 3HCl$, N-[3-Aminopropyl]-1,4-butanediamine, Sigma Chemical Co. US) solution into flowing medium containing DNA. For the comparison with monodispersed λ-DNA, polydispersed calf-thymus DNA (~75,761bp (~50,000kD), Sigma, USA) having higher molecular weight was introduced to the same turbulent flow field. On the other hand, circular form DNA (pRK290, plasmid, 20,000bp, Department of Biological Engineering, Inha University) through the biological treatment was also used in comparison with other forms of DNA. The resultant degradations of DNAs were confirmed via electrophoresis analysis.

Results and Discussion

Fig. 1 shows the %DR for 1.35 wppm of λ-DNA as a function of time at 1157rpm (Reynolds number, N_{Re}~590,000) with and without SPD. To identify the role of SPD in turbulent drag reduction of DNA, we differentiated SPD mixing procedure and compared the results with that of simple λ-DNA drag reducing phenomena. As far as the drag reduction of λ-DNA in buffer solution, we could find the relatively high drag reducing efficiency even at low DNA concentration (1.35 wppm). And also, the drag reduction was maintained for an hour with only slight decrease of efficiency (~1%) due to the minor degradation of DNA in turbulent flow. This kind of strong resistance of double strand DNA to turbulent flow was already investigated and the details were mentioned in our previous work (Choi et al., 2002). In de-ionized water, this double strand structure experiences the melting process, and results in disappearance of DR effect (Choi et al., 2002). Such effect also can be found in variation of pH (Hand and Williams, 1970). On the other hand, single and long duplex DNA chains exhibit a large discrete transition between elongated coil and compacted globule states in some specific condition (Takahashi et al., 1997). In biological systems, DNAs on the order of 10^2~10^4 μm long are usually packed in a narrow space on the order of only 0.1~1 μm. Various chemical species, such as histone proteins, metal cations, and polyamines are known to induce the compaction of long DNA chains. Among these, polyamines are widely spread in both prokaryote and eukaryote cells and possess various biological effects (Porter et al., 1983).



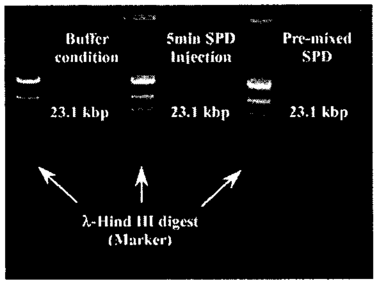


Fig. 1 The percent drag reduction versus time for 1.35 wppm lambda DNA in buffer solution at 1,157 rpm (N_{Re}=5.9×10^5), 25℃ (with (□,○) and without (■) SPD).

Fig. 2 The result of electrophoresis for λ-DNA after degradation for 1 hour at 1,157 rpm, 25℃ with and without SPD injection.

As a condensing agent, SPD in distilled water (10.615 μM) was prepared to be mixed before and after the injection of DNA into flow. The open symbols in Fig. 1 show the effects of SPD injection on DR of λ-DNA. The open circle represented the abrupt change of DR efficiency by SPD after 5 min of λ-DNA injection. SPD altered the conformation of DNA through the complexation of ionic structure. In the case of pre-mixed SPD system, we could find nearly the same initial %DR with buffer solution system (~6.2%). Soon after the compelxation started, the progressive decrease of DR effect was found, and finally reached to nearly same saturation %DR value of 5 min-injection case. In fact, the concentration of SPD to change abruptly the DR efficiency should be much higher than that of T4DNA in static condition (Takahashi et al., 1997). It might be the result of strong inhibition of turbulent flow in coil-globule transition of DNA. The possibilities of other factors, which can give rise to this result, except conformational change by SPD can be eliminated through the electrophoresis of degraded DNA as shown in Fig. 2. Fig. 2 shows that all DNAs, which experienced different processes, have the same molecular size, half-cut DNA (23.1 kbp). This means that the DNAs affected by SPD only experience the conformational change.

In the case of calf-thymus DNA (CT-DNA) having molecular weight distribution, the DR efficiency is much lower than λ-DNA. At 1.35 wppm, CT-DNA didn't show any measurable DR effect. And also, at much higher concentration (20.25 wppm~15 times higher than λ-DNA; 1.35 wppm), it showed lower value of DR effect (5.2%) than λ-DNA (10.2%) at same flow strength (1980 rpm). However, the values were nearly constant for an hour (~5%). It can be said that, contrary to monodisperse λ-DNA, the number CT-DNA molecules having effective chain length for DR is small at a same concentration (1.35 wppm). In addition, DNA chains having much higher molecular size are much susceptible to mechanical degradation in turbulent flow. This result was also verified through eletrophoresis, which showed the broad band near 9kbp size (maximum intensity). The maximum size of degraded CT-DNA was about

18kbp, which was smaller than the size of half-cut λ-DNA (23.1kbp).

On the other hand, we also examined the DR effect of circular DNA (pRK290, Inha University) at a specific condition (1980 rpm, 6.75 wppm in buffer solution). The size of pRK290 was 20 kbp in linear state. It was manipulated to circular form to give a specific conformation character for DNA DR study. Different from λ-DNA and CT-DNA cases, pRK290 didn't show any measurable DR effect. In the case of monodisperse λ-DNA (1.35 wppm), the saturation DR efficiency after 1 hour duration of turbulent flow reached to 2% at 1980 rpm. It was maintained by the half-cut λ-DNA (23.1 kbp). The relatively low but time independent DR efficiency (2.7%) for CT-DNA at the same flow condition (1980 rpm) was also found at 6.75 wppm. The resultant molecular size of CT-DNA corresponding to this DR efficiency decided from electrophoresis was about 20 kbp (18~23 kbp). Based on these results, we can conclude the reason why we couldn't find any DR effect using pRK290 is mainly reside on the conformation of DNA and its size. Usually the conformation of DNA in static state is supercoiled one. In addition, the circular form of DNA can enhance the supercoil structure more severely. It means that the size of pRK290 in circular form would be much smaller than its fully stretched state (10 kbp size).

Conclusion

Drag reduction characteristics of DNAs having different conformational characteristics were investigated under the turbulent flow condition. The induced coil-globule transition by polyamine altered the DR behavior of λ-DNA depending on the different mixing processes. Using CT-DNA, we could find the effect of polydisperse molecular size on DR. These results were compared with that of circular form DNA (pRK290).

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