DNA Dynamics under Turbulent Flow

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Introduction

Turbulent drag reduction (DR) is defined as the very striking phenomenon in which turbulent drag of flowing medium is drastically reduced by even minute amounts of suitable additives [1, 2]. While a satisfactory explanation of DR still eludes fundamental and general interpretation on it [3] due to a coupled mechanism of both turbulence [4] and polymer dynamics, it is well known that the DR is governed by various parameters such as polymer concentration, polymer molecular weight, temperature, Reynolds number (N_{Re}), and solvent quality [5]. In addition, intrinsic structural characteristics are also playing crucial roles in controlling and evaluating the fundamental features of DR phenomena [6].

In this study, we choose DNA of both λ-DNA and CT-DNA, of which the CT-DNA possesses different structural characteristics of polydispersity and higher molecular weight compared with monodisperse λ-DNA, as a successsful drag reducing candidate for the investigation of structural effect on the DR. Since DNAs have a unique molecular helical structure compared to conventional linear flexible polymeric drag reducers, we could expect this characteristic will make it possible to show more detailed understanding in the DR experiment and analysis [7]. Some noticeable advantages of choosing DNA as an additive for the DR are the followings. First, high MW DNA with perfect monodispersity can be easily obtained and characterized by the use of electrophoresis. Second, the length of a fully stretched DNA can be comparable to the microscales of turbulent flows. Finally, the structural feature of single, long duplex DNA exhibits a large discrete transition between elongated coil and compacted globule states in some specific conditions [8].

Experimental

Concentrated stock solution of the DNA was separately injected into a buffer solution in rotating disk apparatus. Detailed descriptions for the RDA can be found in our previous study [9]. For the comparison with the previous results from monodispersed λ-DNA [6], polydispersed calf-thymus DNA (CT-DNA, ~75,761bp (~50,000kD)) having higher molecular weight was introduced to the same turbulent flow field. Furthermore, to better characterize the degradation feature of DNA in turbulent flow, we also conducted DR experiment using polydisperse synthetic polymer; polyacrylamide (PAAM). As a conventional drag reducing polymer, high molecular weight water-soluble PAAM (Mw 1.8×10^7) was selected for the comparison. The %DR was then obtained as a function of time. 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 [9].

Results and discussion

Figure 1 shows %DR of the CT-DNA for two different CT-DNA concentrations (6.75 and 20.25 wppm) as a function of time at relatively high Reynolds number (N_{Re}~1,000,000; 1,980rpm).

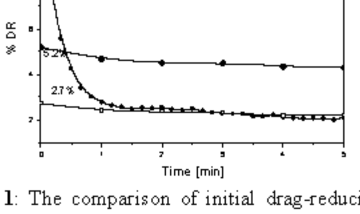

Figure 1: The comparison of initial drag-reducing efficiency of calf-thymus DNA with λ-DNA for different concentrations at 25°C

Although CT-DNA degraded initially, the overall DR efficiency was maintained for an hour. However, when compared to λ-DNA, CT-DNA did not seem to show any measurable DR effect at a very low DNA concentration with similar conditions in our previous experiment of λ-DNA (1.35 wppm and 1980 rpm), despite the higher molecular weight of the CT-DNA. The difference can be explained based on polydisperse molecular weight characteristics of the CT-DNA. At the concentration of 6.75 wppm, the CT-DNA showed 2.7 % of DR effect which is nearly constant for one hour but somewhat small. In this case, such constant DR efficiency does not imply that there is no mechanical degradation in the system. Based on the higher molecular weight of CT-DNA and the analysis of λ-DNA under turbulent flow condition [6], it might be reasonable to assume that major mechanical degradations of the CT-DNA intensively occurred right after the injection of CT-DNA into turbulent flow just in a few second.

Based on the higher molecular weight of CT-DNA and the analysis of λ-DNA under turbulent flow condition [6], it might be reasonable to assume that major mechanical degradations of the CT-DNA intensively occurred right after the injection of CT-DNA into turbulent flow just in a few second. This assumption is supported by the result of electrophoresis. As far as this half-cut phenomenon is concerned based on thermally activated bond scission model [10], molecular degradation in an elongational flow field proceeds as a two-stage process; molecular stretching and fracture [11]. In this process, scission of the extended conformation always occurs near the midpoint, where the stress in the molecule reaches a maximum value [12]. Regarding the critical condition of molecular degradation, they [10] also explained that the critical strain rate for fracture is related to the contour length and molecular weight of a polymer chain in an inverse square mode, indicating that a polymer chain, after its first mechanical degradation, will need a much higher strain rate for its second generation scission. In a sufficiently strong turbulent flow, multi-generation degradation process can occur. Nonetheless, this model strongly supports the single step half-cut degradation process of both CT-DNA and λ -DNA, if the critical strain rate for half-cut of both CT-DNA and λ-DNA is much higher than the flow field.

A drag reduction experiment was also conducted with a linear flexible polymer (PAAM) to compare its long term durability with that of both CT-DNA and λ-DNA. The mechanical degradation behavior was totally different from that of DNA. Although it showed much higher DR efficiency, the DR effect eventually diminished to zero effect within five minutes.

Conclusions

From both DR efficiency and a mechanical degradation under turbulence, DNA chains having much higher molecular size than that of λ-DNA were observed to be more susceptible to mechanical degradation in a turbulent flow. This result was verified via electrophoresis. Furthermore, the coil to globule phase transition of DNA was also investigated under a turbulent flow [13].

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