



# Mechanical degradation of water-soluble acrylamide copolymer under a turbulent flow: Effect of molecular weight and temperature



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## ARTICLE INFO

### Article history:

Received 31 May 2015

Received in revised form 21 September 2015

Accepted 26 September 2015

Available online 9 October 2015

### Keywords:

Polymer degradation

Drag reduction

Turbulent flow

Copolymer

## ABSTRACT

An experimental study of the turbulent drag reduction (DR) performance of water-soluble poly(acrylamide-co-acrylic acid) copolymers with two different molecular weights in a rotating disk apparatus is reported. The DR efficiency of very dilute polymer solutions was measured to relate their DR activity to molecular parameters, such as molecular weight, concentration, temperature, and rotational speed of the disk. Experimental results show that polymers with high molecular weights and high concentrations exhibit a persistent DR activity to mechanical degradation under a turbulent flow.

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## Introduction

The skin frictional drag of a turbulent flow can be remarkably and actively decreased owing to the employment of tiny amounts of additives, such as flexible polymeric chain molecules [1–3] and colloidal surfactants, compared to non-additive passive drag reduction (DR) systems [4]. Among various active drag-reducing materials, linear, long-chain, flexible, and high molecular weight polymers are known to be the most effective drag reducers. Due to the pronounced effect of polymers on the turbulent DR, many commercial and scientific applications have been reported, including those relevant to crude-oil pipelines [5], irrigation systems [6], firefighting [7], and biomedicine [8].

Various theories and mechanisms on turbulent DR have been reported. Specifically an elastic theory of the turbulent DR was introduced to discuss the properties of homogeneous and isotropic three-dimensional turbulence in the presence of polymer additives without any wall effects using a cascade theory [9]. The central idea of this 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 for the description of the DR mechanism was also examined by adopting a simple model to study both the turbulence

and dissolved polymer molecules [10]. On the other hand, the turbulent DR was also interpreted using a model in terms of the solvation of polymer chains, and the formation of relatively stable domains, in which the domains partly suppressed the vortex formation and act as energy sinks [11]. It was also found that the flexibility of the polymers helps the domain formation, and that higher molecular weights help to resist turbulence eddies in a better manner. Note that these mechanisms are further related to the idea of polymer threads proposed by Bewersdorff [12], confirming that the central thread provides DR, which is almost equivalent to premixed solutions of the same total polymer concentration flowing in the pipe [13]. Despite the existence of many available theories, note that a full understanding of this theory is still lacking.

Nonetheless, in terms of the experimental drag-reducing polymers, water-soluble poly(ethylene oxide) PEO [14,15], polyacrylamide (PAAM) [16,17], and commercial polysaccharides with high molecular weight were extensively used in aqueous systems, while nonpolar drag reducers, such as polyisobutylene (PIB) and polystyrene (PS), have been used in hydrocarbon-based fluids [18]. Various parameters, including polymer concentration, polymer molecular weight, temperature, Reynolds number, and solvents [14,19], have been found to strongly influence the DR efficacy.

Although the polymers are considered as the most effective drag reducers, they are less resistant to high mechanical shears – such as those generated by pumps – and under turbulent flows

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with high shear and extensional rates. The molecular degradation of the polymers can be caused by skin friction [20] and is very sensitive to temperature variations [6]. Recently, to reduce the polymer susceptibility to bond scission, graft copolymers have attracted much attention. The PAAM grafted on polysaccharides – with a varying number and length of grafted chains [21] – was found to be more stable under shears than linear PAAM [22]. In addition, the copolymers with a small portion of hydrophobic moieties [23] were also investigated and the persistent DR efficiency due to the intermolecular interaction was identified.

In this study, the copolymer of poly(acrylamide-co-acrylic acid) [poly(AM-co-AA)] was chosen as a drag reducer to investigate the influences of various parameters, such as molecular weight, concentration, temperature, and rotational speed, on its turbulent DR in a rotating disk apparatus.

## Experimental

The motor assembly with the motor and loader that was used to operate the disk consists of a servo motor, which can be operated up to a maximum rotational speed of 3000 revolutions per minute (rpm) at a very high rotational acceleration [19]. The rotational speed and motor power control are determined by the loader. The loaded torque on the disk is detected using a rotary shaft torque sensor. It can measure the torque from 0 to 200 oz in. accurately. One shaft of the torque sensor is coupled to the motor using a steel coupling, and the other is joined directly to the hollow disk shaft to monitor the torque. In order to examine the DR efficiency, torque was measured by a rotating disk apparatus (RDA) in which a disk rotates at uniformly set speeds. The vessel of the apparatus was made of stainless steel, and its dimension was 15.9 cm in diameter and 5.6 cm in depth. The disk was also made of stainless steel with dimensions of 14.5 cm in diameter and 0.3 cm in thickness. The volume of the solution required to fill the entire container was approximately 1020 cm<sup>3</sup>. While the rotational velocity of the disk was controlled by a speed controller (Cole Parmer Master Servodyne Unit), the variable torque was measured by a multimeter. The temperature of the system was maintained by a constant temperature circulating apparatus at 25 °C with an error range of 0.5 °C unless the dependence on the temperature was at 40 °C and 80 °C. The rotational velocity of the disk was confirmed by a digital tachometer. However, the temperature increased initially by a few degrees when the rotational speed was increased from 0 rpm to the set value. Therefore, we operated the setting temperature to be lower than the experimental temperature, making sure that the polymer was injected into the chamber at the appropriate temperature of either 40 °C or 80 °C.

Turbulent flows occur in the RDA when  $N_{Re}$  is larger than  $3 \times 10^5$  ( $\omega > 570$  rpm) [24]. Here,  $N_{Re}$  is defined as:

$$N_{Re} = \frac{\rho r^2 \omega}{\mu} \quad (1)$$

where  $\rho$  is the fluid density,  $\mu$  is the fluid viscosity,  $r$  is the radius of the disk, and  $\omega$  is the angular velocity [rad/s,  $2\pi \times$  (revolution per minutes)/60]. Since the DR phenomenon of the polymer occurs only in the turbulent region, all the experiments in this study were undertaken at rotational speeds above this critical rotational velocity of the disk. It can be also noted that a cylindrical double gap rheometer device has also been recently introduced to study polymeric turbulent DR [25,26].

Stock solutions of high molecular weight poly(AM-co-AA) ( $M_w = 5 \times 10^6$  g/mole and  $1.5 \times 10^7$  g/mole, Sigma–Aldrich, USA) at 0.5 wt% were prepared in advance with mild stirring for one week at room temperature, using de-ionized water as a solvent. A desired amount of stock solution for a specific polymer

concentration of the DR measurement was subsequently injected into the RDA for the actual turbulent DR study. Note that the test of the molecular weight was conducted using two different molecular weight copolymers only due to its limit on the commercial availability, and the DR data of  $M_w = 5 \times 10^6$  g/mole was adopted from our previous work for the reanalysis [27].

The percentage DR (%DR) was then obtained as a function of time by injecting measured quantities of stock solution directly into the turbulent flow field generated by the RDA. To obtain the DR efficiency of the rotating disk apparatus, the torque that was required to rotate the disk in the pure solution at a given speed was measured first. The percent DR was then calculated by measuring – at the same speed – the corresponding torque that was required in the solution with the added polymer, as follows:

$$\%DR(t) = \left( \frac{T_s - T_p(t)}{T_s} \right) \times 100 \quad (2)$$

where  $T_s$  is the torque of the pure solvent and  $T_p$  is the torque of the polymer dilute solution. Unless the rpm was mentioned, the DR test was performed at 1980 rpm, which is corresponding to about  $N_{Re} = 1 \times 10^6$ .

Furthermore, the shear viscosity of the polymer solution with 50 wppm poly(AM-co-AA) ( $M_w = 1.5 \times 10^7$  g/mole) was examined using a rotational rheometer (Physica, MCR300, Germany) with a Couette cell geometry (DG 26.7) at different temperatures (25, 40 and 80 °C). The steady shear viscosity was measured as a function of shear rate in the range of 0.01–100 s<sup>-1</sup>.

## Results and discussion

Fig. 1 shows the shear viscosity as a function of three different temperatures (25, 40, and 80 °C) for 50 wppm of poly(AM-co-AA). Severe shear-thinning behavior was clearly observed for this copolymer solution ( $M_w = 1.5 \times 10^7$  g/mole) [28]. It is also confirmed that the shear viscosity decreased with increasing temperature as a function shear rate. And the approximate shear rate in the DR test condition could be estimated using diameter and thickness of the disk in our RDA geometry and a rotational speed of revolutions per minute (rpm) of 1980 rpm with a shear rate of about 570 s<sup>-1</sup>. The infinite shear viscosity of the polymer solution thereby could be considered as a polymer solution viscosity for estimating the rotational Reynold number. Furthermore, the overlap concentration could be also estimated to be 200 ppm based on PAAM of  $M_w = 1.8 \times 10^7$  g/mole [29]. Therefore our

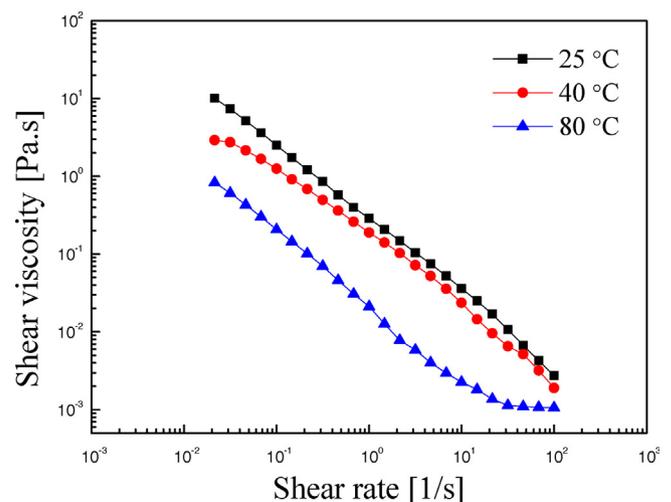


Fig. 1. Shear viscosity as a function of shear rate for different temperatures of poly(AM-co-AA) ( $M_w = 1.5 \times 10^7$  g/mole) solution at a concentration of 50 wppm.

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