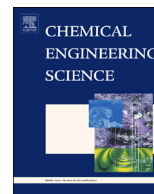




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# On the drag reduction effect and shear stability of improved acrylamide copolymers for enhanced hydraulic fracturing

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## HIGHLIGHTS

- NaAMPS content in the drag reducer backbone improves friction reduction.
- Drag reduction of NaAMPS copolymer was described with an empirical correlation.
- NaAMPS content does not affect polymer chains mechanical degradation.
- No limit to polymer mechanical degradation was detected.
- The most common correlation for polymer mechanical degradation does not apply.

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## ABSTRACT

Polymeric drag reducers, such as partially hydrolysed polyacrylamide (PHPAAm), are important chemical additives in hydraulic fracturing fluids as they can significantly decrease the frictional pressure drop in the casing (by up to 80%), resulting in an increase of the injection rate that can be delivered to the fracturing point. The incorporation of sodium 2-acrylamido-2-methylpropane sulphonic acid (NaAMPS) moieties into polyacrylamide (PAAm) can further improve the performance of fracturing fluids by addressing some compatibility issues related to the use of PHPAAm, e.g., the sensitivity to water salinity. In this study, three types of poly(acrylamide-co-NaAMPS) and pure PHPAAm were investigated with respect to polymer induced drag reduction and mechanical polymer degradation in turbulent pipe flow in a pressure-driven pipe flow facility. The test section comprised a horizontal 1" bore circular cross-section pipe. The facility was modified in order to allow long time/length experiments by automatically recirculating the polymer solution in a closed-loop through the test section. The presence of NaAMPS groups in the copolymer backbone is found to increase the ability of PHPAAm to reduce frictional drag while the vulnerability to mechanical degradation remains unaffected. The drag reduction of NaAMPS copolymer solutions can be described by a modified version of Virk's correlation (1967), extended to include the effect of Reynolds number. Polymer mechanical degradation is found to proceed until the friction reducer is almost ineffective in reducing drag. This phenomenon is in contrast with the most common correlation for polymer degradation, which predicts the existence of an asymptotic (but finite) limit to the reduced drag reduction.

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## 1. Introduction

Hydraulic fracturing techniques recently achieved resounding success in increasing fossil fuels extraction, particularly of shale gas, and will play a major role in growing non-OPEC production in

the near future (Energy Information Administration, 2013). Fracturing fluids typically comprise several additives to enhance their performance. Among these additives, polymers of acrylamide (AAm) have been extensively used in the oil and gas industry. Polyacrylamides are used in hydraulic fracturing applications to reduce the frictional resistance in turbulent pipe flow, an effect known as drag reduction, which was first described by Toms (1948). The net result of this effect is a decreased pressure drop inside the casing that decreases the pressure of the injected fluid

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at the wellhead for a fixed injection rate, or allows increased rate at the same wellhead pressure. These higher injection rates widen and extend the cracks present in the rocks that conduct gas in the wellbore.

It is expected that the extensive use of PAAm-based additives will be maintained if not increased in the near future; partially because PAAm copolymers can be also implemented in multiple applications, such as fluid loss control (Shenglai and Yuhuan, 2013), flooding (Vermolen et al., 2011), hydraulic fracturing treatments (Kot and Bismarck, 2010; Kot et al., 2012), and partially because the stricter legislations covering oil-based drilling will probably encourage the use of water-soluble additives.

Prior to the development of multiple hydraulic fracturing treatments in horizontal wells, fracturing fluids were typically composed of pure water with possibly 2% KCl or even lower amounts of KCl substitutes such as tetramethylammonium chloride. As a drag reducer for these fluids, PHPAAm gave acceptable results. However, the current industrial operations rely heavily on the use of reclaimed waters containing salts and this poses a challenge for PAAm based drag reducers. First, in the case of PHPAAm, a higher salt content can decrease the drag reduction by shielding the electrostatic charge along the polymer backbone and therefore reducing its hydrodynamic radius, which is directly related to the drag reducing power; see in this respect, for example, the study of Liberatore and co-workers (Liberatore et al., 2003; Liberatore and McHugh, 2005). Most important, at temperatures exceeding 60 °C PAAm undergoes hydrolysis resulting in the formation of acrylate groups. If the concentration of acrylate groups reaches a given threshold, in the presence of divalent ions, such as  $\text{Ca}^{2+}$ , insoluble salts are formed and PAAm loses its effectiveness in reducing drag (Seright et al., 2010).

Poly(AAm-co-NaAMPS) possess a better brine compatibility, being less sensitive to hydrolysis (Kelland, 2009) and, therefore, has the potential to be employed in a larger number of oil or gas fields. For this reason, a series of patents was filed relating to NaAMPS copolymers, in parallel to ongoing research studies (George and Gerke, 1985; Funkhouser and Norman, 2002). The benefits of the NaAMPS copolymers with respect to temperature stability and divalent metal tolerance are nowadays established. However, relatively few studies have focused on the ability of NaAMPS copolymers to reduce frictional drag. Studies of this kind were pioneered by McCormick and co-workers (McCormick et al., 1990; Mumick et al., 1994), who studied the influence of the molecular structure of four different AAm copolymers, with different degrees of hydrophobicity and ionic charge, on the level of measured drag reduction for Reynolds numbers ( $Re$ ) up to 30,000. More recently Shah and co-workers investigated the drag reduction of NaAMPS copolymers in straight and coiled tubing (Shah et al., 2006) and the effects of temperature and salinity on the measured level of drag reduction (Shah and Vyas, 2009). Apart from the insightful aforementioned studies, experimental data on the range of conditions encountered in the field (e.g. Reynolds numbers, polymer concentrations, NaAMPS contents) are still lacking. In addition, aspects such as resistance to mechanical degradation have not been investigated yet and require further attention. Obtaining such data on the drag reduction of NaAMPS copolymers is essential to assess the economic advantage of these friction reducers in terms of pumping cost and effect.

In the present experimental study we explore further the use of poly(AAm-co-AMPS) as drag reducing agent using a pressure-driven pipe flow facility with a relatively large pipe diameter and flow rates more closely simulating the conditions encountered in the field; data are reported at  $Re$  up to about 250,000. In particular we isolate and investigate the effect of NaAMPS content, polymer concentration and Reynolds number on drag reduction performance. A correlation is proposed to relate the drag reduction of

NaAMPS copolymers to concentration and  $Re$ . In addition, the experimental facility was modified to allow automatic recirculation of the polymer solution inside the test section thus offering the possibility of running the experiment multiple times. This modification allowed us to provide unique data on polymer mechanical degradation that is hereby used to study the long term shear stability of poly(AAm-co-NaAMPS) and PHPAAm. The results were also compared with the most common correlations for polymer degradation.

## 2. Experimental methods

### 2.1. Apparatus

Drag reduction was measured by means of a recirculating, pressure-driven pipe flow facility. An important feature of this facility, used for the first time in the present study, is that it was upgraded from being manually controlled to fully automated to allow for long term experiments. A detailed description of the manually driven pipe flow facility has been provided by Zadrazil (2011, 2012); here we limit ourselves to a brief presentation of the basic parts and functions of the apparatus.

Fig. 1 shows a schematic illustration of our drag reduction test facility. The rig is composed of two tanks (Tank I and II in Fig. 1), the main pipe test section and various measurement systems. Connections between each element are allowed by both pneumatic and manual valves (labelled by the letters “V” in the figure). Tank I (approximately 330 L) is used to prepare a polymer test solution at atmospheric pressure and is equipped with a low-speed impeller (approximately 60 rev/min) and a temperature sensor. It should be noted that the measurements were carried out at ambient temperature, i.e.,  $20 \pm 2$  °C. Tap water was provided from a connection to an outside network and the volume of water used was measured by a turbine flow meter (labelled “F<sub>rot</sub>” in Fig. 1). Once prepared, the polymer solutions were transferred to the second tank (Tank II), before being pushed through the main pipe test section. Tank II can be pressurised by a connection to a 6 bar laboratory compressed air supply and is equipped with measurement and control systems for water level and pressure.

Pipe flow is achieved by the pressure difference between Tank II and Tank I after the former is pressurised. The use of a pressurised tank instead of a centrifugal pump was preferred in order to minimise the mechanical degradation of the polymer chains prior to the test section (Den Toonder et al., 1995). Tank II is connected directly to the test section, which consists of a 1-in. ID stainless steel pipe. The length of the test section is 7.1 m. The relative roughness ( $k/D$ , where  $k$  is the absolute roughness and  $D$  is the inside pipe diameter) of the stainless steel pipe used in our work has been determined to be  $8.75 \cdot 10^{-4}$ , which is typical for this material. After the test section a plastic hose of larger diameter (1½-in) allows a return connection to Tank I, thus closing the recirculating flow loop.

A magneto-inductive flow meter (Sitrans F M Magflo MAG5000, Siemens) was used to non-intrusively measure the liquid flow rate. A series of pressure drop measurements were made along the test section by 6 membrane differential-pressure transducers (Deltabar S, Endress-Hauser). Specifically, the pressure drop was measured at set distances  $\Delta l$  from the test section inlet, with a reference tap at 1.76 m, and subsequent measurement taps at 1.96, 2.96, 3.96, 4.96, 5.96 and 6.96 m from the inlet.

### 2.2. Materials

Three copolymers of AAm and NaAMPS with the code names DP-OMC-1001, DP-OMC-1002 and DP-OMC-1007 having a weight

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