Nonlinear rheological behavior of concentrated Xanthan Gum solutions in steady shear flow fields

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Introduction

The unique rheological properties induced by xanthan gum have prompted its industrial success and are responsible for its wide-spread use in various applications. The rheological behavior of xanthan gum reflects the ordered conformation and consequent intermolecular interactions usually adopted in aqueous solutions [1]. Likewise other biopolymeric materials, rheological studies of this polysaccharide can provide a lot of significant informations with regard to [2] : (a) quality control of either raw materials or final products; (b) process engineering; (c) optimization of formulations on the basis of the relationships between micro-structure and physical properties; and (d) objective texture analysis of commercial products.

It was realized from our rigorous literature survey that, while there exists a reasonably substantial amount of literature published on the rheological properties of dilute and semi-dilute (or moderately concentrated) xanthan gum solutions prepared from aqueous media, only a little attention has been given to the rheology of concentrated solutions of xanthan gum, even though these systems are far more important from an industrial point of view [3,4].

The objective of the present study is to systematically investigate the nonlinear rheological behavior of concentrated xanthan gum solutions in steady shear flow fields. Using a strain-controlled rheometer, the steady shear flow properties of aqueous xanthan gum solutions with different concentrations were measured over a wide range of shear rates.

Experimental section

The xanthan gum sample used in this study is a commercially available product supplied from the Sigma-Aldrich Corporation (St. Louis, MO, USA). The weight average molecular weight of our xanthan gum is approximately estimated to be 2×10^6 g/mol [5], even though its values reported in the literature are very diverse [6].

In this work, xathan gum solutions with concentrations of 1, 2, 3, and 4 wt% were prepared by slowly adding the required amount of polymer powder weighed using an electronic balance into a known volume of gently agitated medium (dust-free distilled water) filled in a glass container, which was maintained at room temperature with constant stirring using a magnetic bar for 24 hr. During stirring, the top of a glass container was sealed up with an air-tight film to prevent an evaporation of a medium.

Then, a propeller–type variable-speed homogenizer was used to provide a further necessary agitation of xanthan gum solutions. The agitation was continued for 3~5 hr

with a rotational speed of 300 rpm until the polymer was perfectly dissolved and the solutions were lump-free. In order to complete the hydration of the polymer, the prepared solutions were kept at rest at room temperature for more than 12 hr prior to conducting the rheological measurements.

The steady shear flow properties of prepared xanthan gum solutions were measured using a strain-controlled rheometer [Advanced Rheometric Expansion System (ARES), Rheometric Scientific, Piscataway, NJ, USA] equipped with a parallel-plate fixture with a radius of 12.5 mm and a gap size of 2.0 mm. All measurements were performed at a fixed temperature of 20 ℃ over a wide range of shear rates from 0.025 to 500 1/s with a logarithmically increasing scale.

Before the xanthan gum solution was loaded, the two plates were covered with sandpaper in order to remove a wall slippage between the test material and the plates. In all measurements, a fresh sample solution was used and rested for 20 min after loading to allow material relaxation and temperature equilibration.

Results and discussion

Fig. 1 shows the flow curves (representation of the shear stress as a function of shear rate) for aqueous xanthan gum solutions with different concentrations. For all xanthan gum solutions, the shear stress tends to level off and approach a limiting constant value as a decrease in shear rate towards zero at low range of shear rates, indicating that these polymer systems exhibit a finite magnitude of yield stress.

These results are more dramatically observed when plotting the steady shear viscosity as a function of shear stress rather than shear rate, as demonstrated in Fig. 2. Two distinctive regions are clearly seen for each xanthan gum solution : (1) the existing region of a yield stress reflected by a viscosity that continues to rise at relatively lower range of shear stresses; and (2) the shear-thinning region where the viscosity is substantially decreased with increasing shear stress.
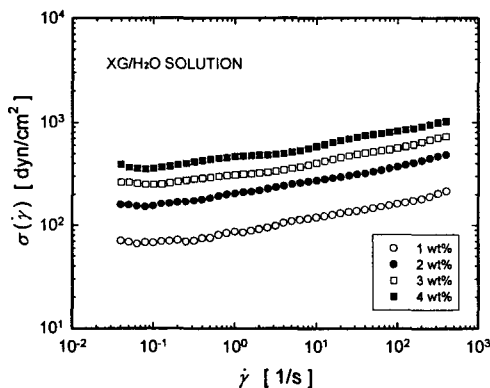

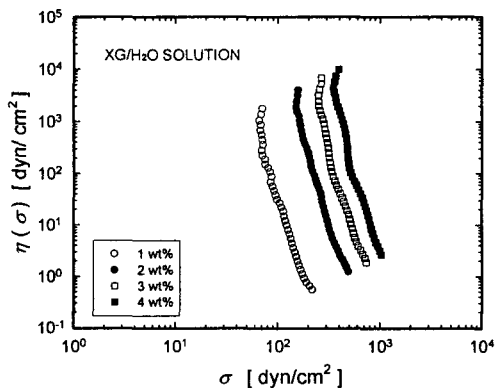Fig. 1. Flow curves for aqueous xanthan gum solutions with different concentrations.

Fig. 2. Steady shear viscosity as a function of shear stress for aqueous xanthan gum solutions with different concentrations.

The appearance of a yield stress for xanthan gum solutions may come from the fact that a large number of hydrogen bonds in the helix structure results in a stable configuration that can show a resistance to flow [7].

Fig. 3 shows the shear rate dependence of the steady shear viscosity for aqueous xanthan gum solutions with different concentrations. While the Newtonian viscosity region is not observed at low shear rates, the steady shear viscosity of all solutions is sharply decreased as an increase in shear rate, demonstrating that these systems exhibit a marked non-Newtonian shear-thinning behavior.

The shear rate dependence of steady shear viscosity seems to be well described by a well-known power-law (or Ostwald-de Waele) equation expressed as follows :

$$\eta(\dot{\gamma}) = K\dot{\gamma}^{\,n-1} \tag{1}$$

where $\eta(\dot{\gamma})$ is the shear rate-dependent viscosity, $\dot{\gamma}$ is the shear rate, K is the consistency index, and n is the flow behavior index.

The values of the power-law parameters obtained by a linear regression analysis along with those of the determination coefficients are tabulated in Table 1. As expected, the fits of the experimentally measured data to the power-law equation represent quite well the viscous behavior of all concentrated xanthan gum solutions. It is also clear that, while the consistency index is increased with concentration as a consequence of the expected development of a stronger structure, the flow behavior index is gradually decreased with concentration, indicating a progressive increase in shear-thinning nature.

Fig. 4 shows the shear rate dependence of the primary normal stress difference for aqueous xanthan gum solutions with different concentrations. It is clear that these systems exhibit quite important elastic flow properties in steady shear flow fields. As expected, the primary normal stress difference is gradually increased as an increase in xanthan gum concentration in a given shear rate range.
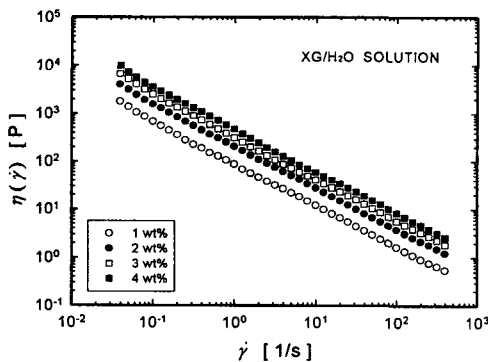

Fig. 3. Shear rate dependence of steady shear viscosity for aqueous xanthan gum solutions with different concentrations.

Table. 1. Calculated power law parameters for aqueous xanthan gum solutions with different concentrations.

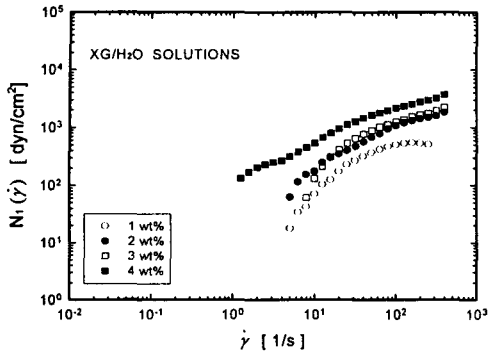| Concentation	K $(P{\cdot}s^{n-1})$	n (-)	R^2
1 wt%	85.5159	0.1401	0.9997
2 wt%	201.430	0.1334	0.9999
3 wt%	310.382	0.1299	0.9996
4 wt%	455.168	0.1275	0.9996

Fig. 4. Shear rate dependence of primary normal stress difference for aqueous xanthan gum solutions with different concentrations.
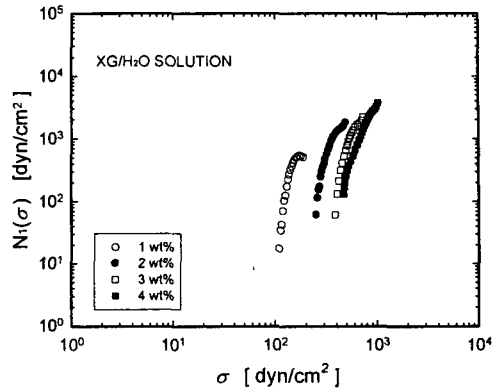
Fig. 5. Primary normal stress difference as a function of shear stress for aqueous xanthan gum solutions with different concentrations.

An elastic behavior of concentrated xanthan gum solutions is more interestingly observed when plotting the primary normal stress difference as a function of shear stress rather than shear rate, as illustrated in Fig. 5.

These elastic flow properties of xanthan gum solutions may be quite significant for many industrial applications such as food, pharmaceutical, and cosmetic manufacturing processes.

References

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