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Energy dissipation behaviors of a dispersed viscoelastic microsphere system

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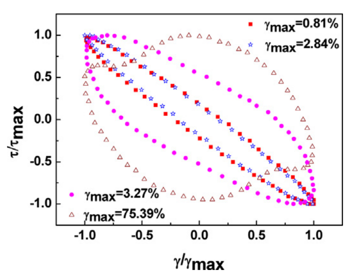
HIGHLIGHTS

- The prepared viscoelastic microspheres are spherical particles with particle size of 100.6 μm.
- The viscoelastic microspheres with 3-D network structure have good swelling capability.
- The dispersed system shows shear-thickening behavior under certain conditions.
- The energy dissipation behaviors of the dispersed system were studied in the energy point.

GRAPHICAL ABSTRACT



The energy dissipation behavior was indicated by the area enclosed by normalized LISSAJOUS.

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ABSTRACT

Dispersed viscoelastic microsphere systems have preliminarily been applied in oil fields with gratifying successes. In this paper, a type of viscoelastic microsphere system with an average particle size of 100.6 μm was synthesized by employing the inverse suspension polymerization. The synthesized viscoelastic microspheres could swell 25.42 times due to the three-dimension structure. The rheological properties of dispersed viscoelastic microsphere system were researched by dynamic strain amplitude scanning measurements and the energy dissipation behaviors were investigated through mathematical method. The results showed that the dispersed system exhibited "shear-thickening" behavior when the strain was greater than the critical strain at different fixed angular frequency. The area enclosed by LISSAJOUS curves or normalized LISSAJOUS curves increased with the increasing of the strain at fixed angular frequency. The relationship between the dissipated energy (E_d) and strain amplitude (γ_{max}) is: $E_d = K(\gamma_{max})^{\alpha}$. And the relationship between the dissipated energy exponent (α) and the fixed angular frequency(ω) is: $\alpha \propto \omega^{0.131\pm0.009}$. Therefore, as the strain increases, the clusters grow up gradually and block the flow of the system, which results in "shear-thickening" and the demand of additional energy.

1. Introduction

With the development of oil fields, water breakthrough among oil wells and water wells has become serious. In addition, the injected water does not work effectively, which results in a large amount of oil remaining in the reservoir. In order to increase the ultimate recovery of the reservoir, the in-depth flow direction needs to be changed [1–4]. Viscoelastic microspheres are a kind of water-swellable viscoelastic plugging agent, which are different from cross-linked polymer gels, and they are prepared based on the pore characteristics of the target layer [5]. Adverse effects on the treatment of wells caused by formation temperature, salinity,

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Table 1
Quality analysis of simulated formation water.

Ions	K^+/Na^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}	Total
Concentration (mg/L)	1519	27	29	994	7	2324	100	5000

shearing, adsorption, diluted formation water, chromatographic separation effect or other environmental factors can be reduced by using viscoelastic microspheres [6–8]. Viscoelastic microspheres that are bigger than the pore throat radius can also move through the porous media by deforming under pressure, which is conducive to broadening the motion range of the microsphere to improve the displacement effect.

Dispersed viscoelastic microsphere system is such a composite system that is composed of viscoelastic microspheres and polymer solution. The viscoelastic microsphere helps increase the viscoelasticity of the system and plug the high permeability channel and the polymer solution can suspend the viscoelastic microspheres to ensure the stability of the dispersed viscoelastic microsphere system. As a result, the water can go into the low permeability area and displace the remaining oil [9–12]. Currently, dispersed viscoelastic microsphere flooding technology has been successfully implemented in many oil fields in China because of the unique rheological properties of the dispersion system, e.g., the shear-thickening behavior under certain conditions. However, there have been only a few studies about the rheological properties of dispersed viscoelastic microsphere system until now. Although shear-thickening fluid has been studied experimentally, few investigations from the perspective of energy have been reported [13–15]. Recent researches related to shear-thickening fluids have enriched the understanding of the fluids' characterization with large amplitude oscillatory shear amplitude measurements techniques [16,17]. Large amplitude oscillatory shear tests are usually performed on strain-controlled rheometers with separated motor and transducer [16] to avoid inertial effects. Jiang et al. [18] studied the influence of particles on the mechanical performance of the poly(styrene-acrylic acid) based shear thickening fluid and proposed a possible mechanism for the shear thickening behavior. They found that the shear thickening effects were considerably affected by the surface charges and the particles' hardness, in which case they could be controlled by varying the monomer ratio of the precursor and the relative crosslink density.

Herein, viscoelastic microspheres were synthesized by employing the inverse suspension polymerization. The shear thickening behavior othe dispersed system under different dynamic shear rates was studied from the energy point, which was explained by the "cluster" theory [19]. Shear thickening behavior in colloidal suspensions relies on the formation of agglomerates of particles, known as clusters. The foundation of the cluster theory has been first exposed for spherical Brownian suspensions in function of the Peclet number [20]. Clusters have been observed by combining rheology and optical measurements [21] or small-angle neutron scattering [22]. This research provides theoretical support for further studies on the rheological properties of dispersed viscoelastic microsphere system and the mechanism of improving oil recovery.

2. Experimental

2.1. Materials

Acrylamide (AM, purity above 98.5%), ammonium persulfate (APS, purity above 98.0%), sodium carbonate ($NaCO_3$, purity above 96.0%) andSpan60 were all purchased from Sinopharm Chemical Reagent Co., Ltd. (China). *N,N′*-Methylenebisacrylamide (MBA, purity above 99.0%) was obtained from Tianjin Kemi'ou Chemical Reagent Co., Ltd. Anhydrous ethanol was obtained from Xilong Chemical Co., Ltd. Hydrolyzed polyacryamide (HPAM, Relative molecular mass 27.4×10^6) was supplied by Dagang oilfield (China). Aviation kerosene was purchased from the market. Deionized water was used for the preparation of all aqueous solutions.

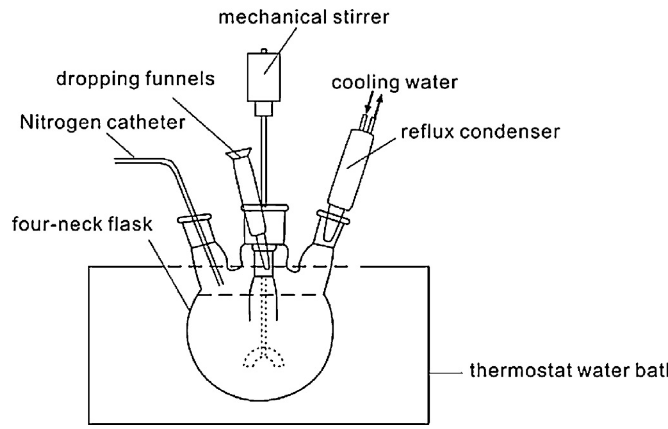

Fig. 1. The schematic diagram for inverse suspension polymerization.

The simulated formation water was used as the dispersed medium in this experiment, and the quality analysis of simulated formation water was shown in Table 1.

2.2. Methods

2.2.1. Preparation of viscoelastic microspheres

Fig. 1 is the schematic diagram of the inverse suspension polymerization used in this paper. The polymerization procedure was as follows [23]: typically, 0.60 g of Span 60 and 60.0 mL of aviation kerosene were added into a 250.0 mL four-necked flask equipped with a mechanical stirrer, a dropping funnel, a reflux condenser and a nitrogen catheter. Meanwhile, the mechanical stirrer started to work at a speed of 380 rpm under nitrogen atmosphere to make the dispersant dissolved. Then the mixed solution with AM, APS, MBA and $NaCO_3$ (6.00 g of AM, 0.26 g of APS, 0.30 g of MBA and 4.00 g of $NaCO_3$ dissolved in 20.00 g deionized water) was added drop wise into the oil phase at the speed of 5 mL/min. The temperature of the thermostat water bath was 69 °C after dripped off. After reacting for 6 h at the certain temperature above, the resulting product was washed several times with anhydrous ethanol and then dried at 80 °C for 48 h. Thus, viscoelastic microspheres were obtained.

2.2.1. Morphology and microstructure characterization

XSJ-2 optical microscope (Chongqing Optical Instrument Co., Ltd., China) was used to observe the morphology of viscoelastic microspheres before swelling.

A certain quantity of viscoelastic microspheres was dispersed in anhydrous ethanol solution. The distribution curve of particle size was characterized by Rize2006 laser particle size analyzer (Jinan Runzhi Technology Co., Ltd., China). D_{50} was used to express the average particle size of microspheres where D_{50} is the particle size of the cumulative distribution curve on probability of 50%.

ESEM images were obtained by FEI Quanta 200 FEG (FEI Company, Holland) to observe the microstructure of viscoelastic microspheres after swelling.