

Experimental and mathematical modeling investigation on the dynamic viscoelasticity behavior of free liquid films prepared by alpha olefin sulfonate

Shuyan Chen^a, Hongjuan Liu^a, Youyi Zhu^b, Wenjun Li^c, Xiang Yan^a, Gehua Wang^a, Yujie Zhou^{a,*}, Jianan Zhang^{a,*}

^a Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China

^b State Key Laboratory of Enhanced Oil Recovery, Research Institute of Petroleum Exploration and Development, CNPC, Beijing 100083, China

^c Department of Chemistry and Chemical Engineering, University of Science and Technology Beijing, Beijing 100083, China

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ABSTRACT

The viscoelasticity behavior and corresponding mathematical models for free liquid films under dynamic conditions were investigated respectively. Systematic analysis of the effects of sinusoidal exciting frequency, surfactant concentration, inorganic salt, temperature and polymer additives on the viscoelasticity modulus of AOS (alpha olefin sulfonate) liquid films were performed in detail. Higher viscoelasticity modulus could be achieved for AOS liquid films at about the critical micelle concentration of AOS solution. Meanwhile, increasing the NaCl concentration increased both the values of the overall modulus (E) and elastic modulus (E') of AOS liquid films, while the values of viscous modulus (E'') decreased in the presence of NaCl. The values of E , E' and E'' of AOS liquid films decreased along with the increase of temperature. The viscoelasticity modulus of AOS liquid films improved significantly after the addition of polymer. Additionally, the experimental results indicated that the dynamic extensional viscoelasticity behavior of free liquid films could be simulated by A type standard linear and B type standard linear type model in the experiments.

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1. Introduction

Foam is a dispersed system in which gas is dispersed in the liquid phase in the form of small bubbles [1], wherein the gas and liquid are discontinuous phase and continuous phase, respectively. In recent years numerous researches on foam systems have been reported due to their wide applications in many fields including water-borne coatings, cosmetics, foodstuffs, mineral floatation, firefighting, enhanced oil recovery and so on [2–5]. In the view of thermochemistry, foam is an unstable system and the free energy of foam reduces along with the decrease of total surface area when the foam is broken, and thus the absolute equilibrium state of foam is impossible to be obtained [6]. There are many factors which affect the foam stability such as surface tension, Gibbs-Marangoni effect, surface charge of liquid film, apparent viscosity, solution viscosity, temperature, pressure as well as the distribution of bubble size [7–9]. As the fundamental structure of foam, the drainage and stability of liquid films play important roles in foam stability [10–12]. An understanding of how the film stretching, thinning and

rupturing, leading to the stability or instability, is critical to the stability of liquid films.

Surface rheological properties are believed to be among the main factors determining the dynamic behavior of foams. Numerous literatures have shown that the surface expansion viscoelasticity of bulk foaming solutions has an important influence on foam stability [13–16]. At present, the interface expansion methods containing grooving method [17], droplet (bubble) expansion technology [18], oscillation bubbles (droplet) method [19] and surface quasi-static light scattering [20] are commonly used to measure the surface expansion viscoelasticity modulus. It is worth noting that the surface expansion viscoelasticity is measured on the top layer of bulk solution, usually the thickness of top layer is more than ten or tens of millimeters in these experiments. While in real foam systems, the vast majority of foam area is occupied by the surface of thin liquid films, and the thickness of the solution between the two surfaces of thin films is usually only several hundred nanometers [21,22]. Due to the distinct thickness difference between thin films and bulk solution, the adsorption and desorption on the gas-liquid interface and the diffusion of surfactant molecules in the liquid films are significantly different from that in the bulk solution applied to the surface viscoelasticity measurements. Therefore, the viscoelasticity of free liquid films (foam thin films) should be more directly and

* Corresponding authors.

E-mail addresses: zhouyj@mail.tsinghua.edu.cn (Y. Zhou), zhangja@tsinghua.edu.cn (J. Zhang).

more closely related to the foam stability when compared to the surface expansion viscoelasticity of bulk solution [23]. An important aspect of studying the viscoelastic materials is to seek a physical relationship that reflects the mechanical properties of specific materials, that is, a so-called constitutive model. The rheological models of viscoelastic materials are mainly divided into two categories [24–27]. One is just for the phenomenological analysis of the data results of macroscopic rheological experiments, and does not involve the microscopic structure of a certain material to establish appropriate rheological models. This model is usually composed of a hypothetical viscoelastic material containing spring and dashpot. If the model can fit well with the obtained experimental viscoelasticity data, the constitutive equations of certain material can be calculated. Another one is microscopic rheological model which analyzes the dynamic behavior of materials from minimum infinitesimal unit. For the diluted polymer solution, a relatively reasonable method for the characterization of polymer molecule was initially assumed and its motion behavior in viscous medium was then deduced. Also the viscosity and elasticity parameters were predicted based on the molecular parameters. For a variety of dispersion systems, the rheological models are inferred from the microscopic information such as the scale of dispersion phase, distribution, geometry shape, interaction, and so on. Modern studies have shown that the two methods of establishing rheological models are equal with each other in many aspects [28].

In this research, the viscoelasticity behavior of liquid films under dynamic conditions was systematically examined using home-made FL10A extensional viscoelasticity apparatus. The effects of frequency, surfactant concentration, inorganic salt, temperature and polymer additives on the viscoelasticity of liquid films were investigated in a series of experiments. Based on the resultant experimental data, a tensile rheological model was proposed by phenomenological analysis method to study the extensional rheological behavior for free liquid films and the corresponding constitutive equations were established.

2. Experimental

2.1. Materials

The anion surfactant alpha olefin sulfonate (AOS, 92 wt%) was obtained from the RIPED (Research Institute of Petroleum Exploration and Development, Beijing, China) with the critical micelle concentration about 8.0×10^{-4} g/g. Sodium chloride (NaCl, 99 wt%) was provided by Sinopharm Chemical Reagent Co. Ltd., Beijing, China. The polymer applied in the experiments was the modified polyacrylamide (MPAM, $M_w = 900 \times 10^4$) which was also obtained from the RIPED. The chemical structure of MPAM was shown in Fig. 1. Deionized water was used in the following solution systems in all experiments. All chemical reagents were utilized as received without any further purification.

2.2. The viscoelasticity modulus of liquid films tests

Sinusoidal excitation and response method [29,30] was used to measure the dynamic tensile viscoelasticity modulus of liquid films. And the schematic of experimental apparatus and the experimental procedures

employed in this study were the same as those reported in our previous work [31]. In a sinusoidal oscillating system, viscoelasticity modulus is a complex quantity and has both a real component and an imaginary component, which could be expressed as the summation of elasticity and viscosity contribution:

$$E = E' + iE'' \quad (1)$$

Here, E is the overall modulus, E' is the real component (or elastic modulus), and E'' is the imaginary part (or viscous modulus).

The elastic modulus (E') can be thought of the energy stored in the system, and the viscous modulus (E'') can be considered as the loss energy caused by the diffusion of surfactant molecules between the bulk phase and the solution surface. The elastic and viscous modulus of liquid films under sinusoidal dynamic conditions can also be expressed in terms of the stress σ , the strain ε and phase angle δ , as follows:

$$E' = (\sigma_0/\varepsilon_0) \cos\delta \quad (2)$$

$$E'' = (\sigma_0/\varepsilon_0) \sin\delta \quad (3)$$

wherein, σ_0 was the maximum of stress; ε_0 was the maximum of strain, δ was phase-shift angle of the responses of stress and strain.

3. Modeling

The rheological model of extensional viscoelasticity behavior for free liquid films is one of the important parts for their viscoelasticity research. Phenomenological analysis method is applied to study the extensional rheological model of liquid films. The one-dimensional elastic solid is simulated with elastic element of spring and the one-dimensional viscous fluid is simulated with a damping element of dashpot. Elastic solids and viscous fluids represent the two extreme forms of the ideal mechanical model, respectively. For elastic solid materials, the stress is linearly related to the strain. Due to the natural configuration of elastic solids, the materials are deformed when the external force is loaded on the materials and the formed elastic strain energy will be stored in elastic materials; and the elastomer releases the stored elastic strain energy and there is no energy loss when the external force is unloaded on the elastic solids. While for the viscous fluid, it has no natural configuration and the system cannot be back to its original state when the external force is unloaded on the viscous fluid, and thus it will lose energy in the process. For viscoelasticity materials, they integrate the properties of elastic solid and viscous fluid, therefore the certain combinations of two basic elements including the elastic element (spring) and the damping element (dashpot) can be applied to simulate the rheological behavior of viscoelasticity materials.

However, the viscoelasticity materials are different from elastic solid and viscous fluid. The viscosity and elasticity behavior for a certain viscoelasticity material differ with each other remarkably. The transition zone between the elastic and viscous portions of the viscoelastic materials is very wide, resulting in different mechanical properties of the various viscoelastic materials. Thus different mathematic models should be applied to describe the dynamic stress and strain behavior for different materials. Four models including Maxwell model [32,33], Voigt-Kelvin model [34,35], A type standard linear model and B type standard linear model are commonly used to simulate the viscoelastic behavior for a certain viscoelasticity material [36–38].

3.1. Maxwell model

The schematic of Maxwell model using spring connected in series with dashpot was shown in Fig. 2. In the Maxwell model, the total stress is equal to the stress in a single component and the total strain is the sum of the strain in spring and dashpot. If the viscoelasticity of materials is in accordance with the Maxwell model, the following equations could

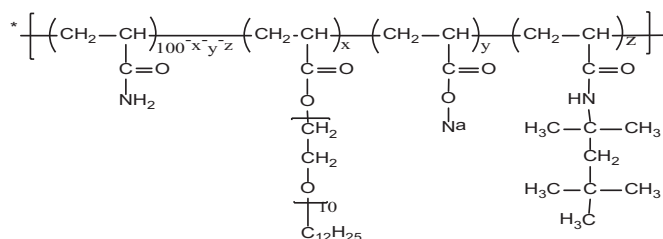


Fig. 1. The molecular structure of MPAM.

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