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Effect of partially hydrolyzed polyacrylamide on the solution and foam properties of sodium alcohol ether sulfate

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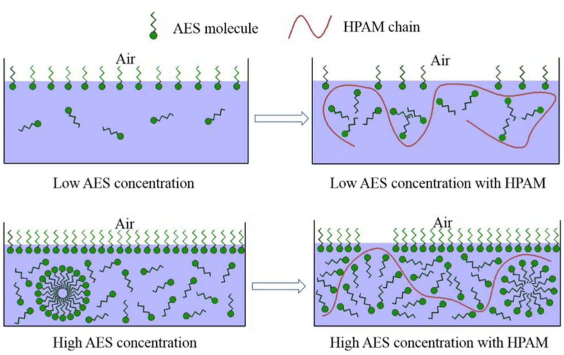
GRAPHICAL ABSTRACT



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ABSTRACT

The solution and foam properties of systems composed of sodium alcohol ether sulfate (AES) and partially hydrolyzed polyacrylamide (HPAM) at different concentrations were investigated. The addition of HPAM could increase the surface tension of AES solutions caused by the decrease of surfactant adsorption density at the air-water surface. The viscosity of the AES/HPAM systems were determined by the HPAM concentration. With the increase in AES concentration, the foam generation time and bubble size first decreased and then reached a plateau, while the initial liquid volume of the foam increased first and then reached a plateau. The inflection occurred at an AES concentration of 0.1 wt%, which is higher than the critical micelle concentration (CMC). This is because the air-water surface area increased dramatically during foam generation, which makes surfactant surface density unsaturated at the CMC. Only a higher surfactant concentration could maintain the saturation of surface adsorption density. The addition of HPAM could improve the foamability and enlarge the bubble size at low AES concentrations, because the increased bulk viscosity and the hydrogen bonds between AES molecules and HPAM chains stabilized bubble films and reduced the breakdown of large bubbles. The increase of HPAM concentration would always improve the liquid-carrying capacity and decrease the drainage rate of the foam. These findings indicate that it is possible to use low concentrations of foaming agents and improve foam properties by adding water-soluble polymer in field applications.

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1. Introduction

Aqueous foam is a gas-liquid dispersion system in which gas is separated by liquid film to form many small bubbles. It is broadly used in many engineering applications, such as oil recovery, mineral flotation, and fire fighting [1–4]. In coal mines, aqueous foam also plays an important role in fire control and dust suppression [5,6]. Mine fires caused by the spontaneous combustion of coal have destroyed a large quantity of coal resources and have led to accidents. Many fire-fighting materials have been invented, such as melamine-phenol-formaldehyde resin microcapsules [7], chemical inhibitor [8], hydrogels [9,10], paste foam [11], and inorganic solid foam [12,13]. These materials can suppress the spontaneous coal combustion and aid the control of fires in underground coal mines. For large-scale coal fires in open-pit mines, aqueous foam has been proven to be a very effective material for extinguishing fires with large area in field applications [14]. During the coal mining process, large amounts of dust are generated during the cutting of rock and coal, which can cause dust explosion and pneumoconiosis [15,16]. Respirable dust with a diameter less than 5 μm is known to cause the greatest harm to miners' health, because it can be suspended in the air for a long time and is easily inhaled into the respiratory system. In China, 6000 cases die of pneumoconiosis every year [17]. Compared with the most commonly used water spray technology, aqueous foam has a much higher dust-removing efficiency for respirable dust and thus can create a safe working environment for coal miners [18,19].

The properties of aqueous foam greatly affect the fire-fighting performance and dust suppression efficiency. The expansion ratio is an important parameter for fire-fighting foam, and it is related to the foamability of extinguishing agents. Foam with low expansion ratio has good wetting properties and can be directly sprayed onto fire. High-expansion foam, on the other hand, can adhere to vertical surfaces and fill a large fire space in a short time [20]. In dust control technology using foam, high foamability of foaming agents is expected. Such agents can generate more foam at a lower foaming agent concentration and reduce the economic cost of this technology. Foam with high liquid content can improve its spray distance and cover range of dust source, which are helpful for suppressing dust [21]. Bubbles with small size are not easy to rupture during the flow and spray process of foam. A study has shown that a bubble size in the range of 100–200 μm is optimal [22]. Therefore, studying the foam properties of the foaming agent solution is of great significance, as it can provide guidance for fire fighting and dust control technologies using aqueous foam.

The foam properties are closely related to the adding concentration and the composition of the foaming agent. In field applications, the concentration of foaming agents used in fire fighting and dust control technologies is relatively high, resulting in high economic cost. For example, the extinguishing agent is used at the concentration of 3% [3,4], and the concentration of foaming agent for dust control is 2–3% [23]. At present, surfactant/water-soluble-polymer systems are widely studied, and the polymers have been found to significantly change the solution and foam properties [24]. Deng et al. [25] investigated the foam properties of a solution of an anionic surfactant, sodium alcohol ether sulfate (AES), and the polymer exopolysaccharide (EPS). Their results show that both the foamability and foam stability of the solution were improved greatly by the formation of hydrogen bonds between AES and EPS at the interfaces. Zhang et al. [26] studied the effect of bovine serum albumin (BSA) on the foam and interfacial properties of Tween 20 solution. They found that BSA lowered the foam drainage rate and enhanced the foam stability. Xu et al. [27] reported that the water-soluble polymer welan gum increased the surface tension of AES solution because of the competitive adsorption at the air-water surface and the diffusion resistance caused by hydrogen bonding and van der Waals force. The foaming ability and foam stability were higher than those of the single system, and a synergistic effect was present. These findings motivated us to study the effects of water-soluble polymers on solution and foam properties of surfactant solutions, in order to improve the foam properties and lower the adding concentration of foaming agents that could be used for fire fighting and dust control technologies in coal mines.

In this work, the surfactant AES was chosen due to its good foaming performance. HPAM was also selected because it is a cheap and easily available polymer that is widely used in petroleum industry to improve the stability of foam [28,29]. In our experiments, the water-soluble polymer HPAM was added to the AES solution to form surfactant-polymer systems at different concentrations. The surface tension and bulk viscosity of the AES/HPAM solution were measured, and the foam properties foamability, liquid-carrying capacity of foam, drainage rate, and bubble size were tested. The relationship between solution properties and foam properties were analyzed in detail.

2. Experimental

2.1. Materials

AES (70 wt% solution, purity ≥99%) with a formula of CH_3-$(CH_2)_m$-$(OCH_2CH_2)_n$-SO_4Na (m = 11–13, n = 2 or 3) was purchased from Qingdao Yousuo Chemical Technology Co., Ltd.. HPAM (purity ≥99%) with a molecular weight of $400 \times 10^4\,g\,mol^{-1}$, was provided by Xinbang Environmental Protection Technology Co., Ltd.. The water used in all experiments was distilled twice. The solution containing HPAM polymer was stirred for 24 h with a magnetic stirrer so that the polymer was fully dissolved. All measurements were performed at 25 °C.

2.2. Surface tension measurement

The surface tension of the surfactant-polymer solution was measured on a JYW-200B surface tension meter through the platinum ring method. The average value of the surface tension was obtained from three measurements for each solution. Before every measurement, the platinum ring was cleaned with distilled water and then dried over an alcohol lamp.

2.3. Viscosity measurement

The viscosity of various solutions was measured with an NDJ-5S digital viscometer. In all measurements, a #0 cylinder rotor was used and the rotation speed was set at 60 rpm. Every solution was measured three times to obtain an average value. Before proceeding to the next measurement, the rotor was cleaned with distilled water, and then the water on the rotor was wiped with filter paper.

2.4. Measurement of foam properties

Foam properties were measured by using a Foamscan analyzer (Teclis Scientific, France). The schematic for this instrument is described in our previous publication [30]. At the bottom of the transparent vertical glass tube is a sample cell. Before each experiment, a certain volume of surfactant solution is injected into the sample cell. Subsequently, gas is dispersed into the solution through a porous glass plate to generate foam. The foam volume in the glass tube is monitored through an optical camera. Five electrodes are positioned at different heights in the glass tube, and the liquid volume of the foam is measured by the conductivity method. Images of the bubbles are recorded with a CCD camera, and the bubble size can be analyzed with cell size analysis (CSA) software.

In all experiments, 40 mL of the test solution was injected into the sample cell, and the gas flow of dry air was set at $50\,mL\,min^{-1}$. A # P3 porous glass plate with an average pore diameter of 16–40 μm was used. The blowing of dry air was terminated immediately when a foam volume of 200 mL was reached. From the beginning of foam generation,