



## Full Length Article

# Investigation of effect of surfactants on the hydrophobicity of low rank coal by sliding time measurements



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## ABSTRACT

In this paper, effect of surfactants on the hydrophobicity of low rank coal particles by sliding time measurements was investigated. X-ray photoelectron spectrometer (XPS) analysis indicated that the surfaces of low rank coal particle consisted of many hydrophilic functional groups. It was observed that the sliding time of low rank coal particles in 2-ethyl hexanol solution was the shortest than that of low rank coal particles in dodecyl amine hydrochloride (DAH) and sodium dodecyl sulfate (SDS) solutions. Moreover, the maximum touching angle ( $\theta_T$ ) of low rank coal particles observed in  $10^{-2}$  mol/L of 2-ethyl hexanol solution was about  $80^\circ$ , which was the greatest than that of low rank coal particles, about  $39^\circ$  in  $10^{-3}$  mol/L of DAH and  $35^\circ$  in  $10^{-4}$  mol/L of SDS solutions, respectively. Therefore, the sliding time results indicated that the hydrophobicity of low rank coal was enhanced by 2-ethyl hexanol and DAH and reduced by SDS. However, it was noted that the hydrophobicity of low rank coal was depressed when the DAH concentration increased to  $10^{-2}$  mol/L. The flotation performances were consistent with the results of sliding time measurements. Therefore, effect of surfactants on the hydrophobicity of low rank coal particles can be characterized by sliding time measurements.

## 1. Introduction

In the Shendong Coalfield in Shanxi province of China, there are many low rank coal beds produced [1,2]. It is difficult to obtain a high yield or combustible matter recovery of low rank coal with physical separation and traditional flotation method using oily collectors, such as kerosene, diesel and fuel oil combined with frother, because the surfaces of low rank coal particles was oxidized [3–5]. Moreover, oxidized surfaces of low rank coal with abundant oxygenated functional groups such as hydroxyl, carbonyl and carboxyl, generally reduce the hydrophobicity and easily form hydrogen bonds with water molecules in the flotation process.

Therefore, in order to improve the flotation performance of low rank coal, the surface modification method by chemical reagents [6,7] and oxygen-containing functional group reduction on the coal surface [8–10], were investigated. Harris et al. [11] demonstrated that the flotation performances of both laboratory-oxidized and naturally weathered coals were improved using the nonionic surfactants while it is difficult to float oxidized coal with dodecane only. Recently, Jia et al. [12] considered that a series of non-ionic surfactants, tetrahydrofuryl butyrate, was more effective collectors than traditional oily collector dodecane for both oxidized and unoxidized coal flotation. It was

because that the various functional groups in the nonionic surfactants interact with the oxygenated sites on the coal surface, orient the hydrocarbon chain to the water and spread on the surface more readily than dodecane, thereby enhancing flotation performance of oxidized coal [11,13]. Aplan [13] found ionic reagents (tributyl phosphate, carboxylic acids, and amines) with collector function obtained a high yield or combustible matter recovery of low rank oxidized coals. Sis et al. [14] observed that the ionic fatty acids as collector obtained a better flotation selectivity than nonionic reagent. Vamvuka and Agri-diotis [15] reported that cationic surfactants were more conducive to enhancing the hydrophobicity of lignite than anionic and nonionic surfactants. Within a certain range, the cationic dodecyl amine (DDA) as a collector played a greater significance on the flotation response of the lignite than that of kerosene but its flotation selectivity for ash reduction was not obvious [16]. Flotation results also indicated that dodecylammonium was adsorbed with the polar groups from the negatively charged carbonaceous and mineral matter on the surface of a low-rank bituminous coal, which increased the hydrophobicity of weathered coal [17]. The interaction between surfactants and coal surfaces investigated by many researchers can be adopted to explain the hydrophobicity enhancement of low rank coal surface. The non-ionic surfactants with oxygenated functional groups, as the collector,

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markedly enhance the hydrophobicity of lower rank and oxidized coals by hydrogen bonding with surface oxygenated sites and through hydrophobic bonding of the hydrocarbon chain of the collector with hydrophobic carbonaceous sites on the coal surface [12]. The cationic adsorption on the negatively charged sites of low rank and oxidized coal surfaces due to electrostatic attraction significantly improves the hydrophobicity [15–17]. As a result of both hydrogen bonding from the anionic surfactant's polar group and hydrophobic bonding phenomenon with non polar groups, the kerosene has a strong tendency to spread on the coal surface [18–20]. Therefore, the hydrophobicity of low rank and oxidized coal surfaces are greatly enhanced.

The fundamental process of flotation is overwhelmingly dependent on the sliding time or induction time. Therefore, the induction time between mineral particles and air bubbles was investigated by the induction time setup [21,22]. It indicated that the induction time between the bitumen particle bed and the air bubble decreased with the extent of air bubble compression increase [21]. Therefore, it demonstrated that a greater extent of air bubble compression would drive the thin liquid film to drain away quickly between the bitumen particle bed and the air bubble, which is consistent with the results of theoretical simulation [23]. However, impact interaction with a greater extent of air bubble deformation is ineffective for adhesion of mineral particles to the bubble surface in the real flotation environment [24]. Therefore, to characterize the effect of surfactants on the hydrophobicity of low rank coal, the sliding time between the low rank coal particle and a moving bubble was investigated. It indicates that two types of the interaction between particles and bubbles are confirmed in flotation process: (i) impact or collision interaction and (ii) sliding interaction [24,25]. The sliding interaction between a particle and a bubble in the flotation process was shown in Fig. 1, which was calculated as the time needed for the particle sliding from the touching point at the start touching angle ( $\theta_T$ ) of the bubble surface to the bottom of the bubble [26]. Meanwhile, the effect of surfactants on the flotation performance of low rank coal was also studied. In this paper, the sliding time obtained from high speed camera was adopted to characterize the real collision process. A homemade flotation column was used for flotation studies.

## 2. Experimental

### 2.1. Materials

Experimental samples of low rank coal were collected from a coal preparation plant in Shanxi province of China. In order to eliminate the

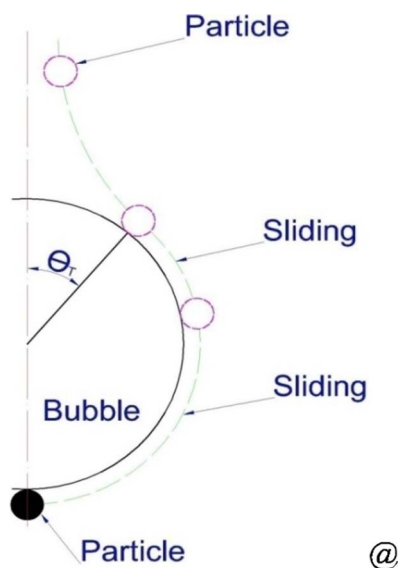


Fig. 1. A schematic of sliding interaction between a particle and a bubble in flotation.

**Table 1**  
Proximate analysis of low rank coal sample (air dried, wt%).

Mad (%)	Vad (%)	FCad (%)	Aad (%)
6.07	38.79	53.23	1.91

heterogeneity effect on the sliding time measurements, low rank coal bulk were separated firstly by density. The density fraction of  $< 1.3 \text{ g/cm}^3$  was used as experimental samples, which were crushed by a single toggle jaw crusher. After that crushed low rank coal samples were then screened and the size fraction of  $-0.500 \text{ mm}$  particle size fraction was followed by grinding process. Grinding process was carried out in a laboratory dry rod mill. Grinding times were set at 5 min.

After grinding step, the particle materials were wet screened through  $0.250 \text{ mm}$  sieve to obtain coal samples  $0.500\text{--}0.250 \text{ mm}$  in size fraction for sliding time and flotation measurements. Moreover, the sliding time is strongly particle size dependent [27]. So, all the experimental samples were obtained from the size fraction of  $0.500\text{--}0.250 \text{ mm}$  particles at the air dry basis after the crush process. Proximate analysis results of low rank coal samples were shown in Table 1, where Mad is the moisture content, Vad the volatile matter content, FCad the fixed carbon content, and Aad is the ash content. Analytical grade 2-ethyl hexanol, dodecyl amine hydrochloride (DAH), and sodium dodecyl sulfate (SDS) were purchased from Aladdin, China.

### 2.2. XPS measurement

To investigate the heterogeneity effect on the low rank coal surface, experimental samples with  $0.500\text{--}0.250 \text{ mm}$  size fraction for XPS analyses were conducted at  $25^\circ\text{C}$  in extreme vacuum (UHV) environment with a solid surface analysis set (ESCALAB 250Xi, America). The peak fitting of data processing was analysed by the XPS peak fit software [28,29]. The surface binding energies of solid particles were modified by the C1s hydrocarbon ( $-\text{CH}_2-\text{CH}_2-$  bond) binding energy at  $284.8 \text{ eV}$ .

### 2.3. Sliding time measurements

The device photograph for sliding time measurement is shown in Fig. 2. Inside the column cell, a capillary connected with the microinjector through a soft tube at the bottom was designed and the sliding time of low rank coal particle was recorded by a high speed camera. The frame number of high-speed camera was set to 750 per second. So, interval time of consecutive photos is  $1.33 \text{ ms}$ . The inner diameter of

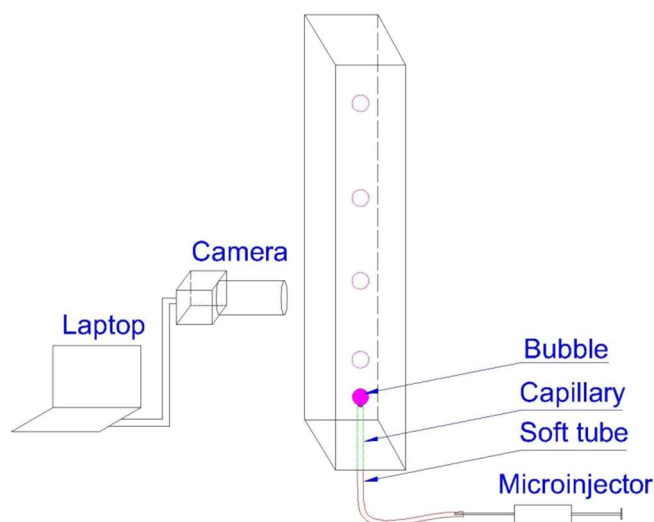


Fig. 2. A schematic of the measurement setup of sliding time.

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