



Full Length Article

Reducing quartz entrainment in fine coal flotation by polyaluminum chloride

Long Liang^{a,*}, Jiakun Tan^a, Biao Li^b, Guangyuan Xie^a

^a Key Laboratory of Coal Processing and Efficient Utilization of Ministry of Education, School of Chemical Engineering and Technology, China University of Mining and Technology, Xuzhou 221116, China

^b Mining and Minerals Engineering Department, Virginia Tech, Blacksburg, VA 24060, United States

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ABSTRACT

Flotation tests using artificial mixtures of clean coal and quartz were conducted with and without the presence of sodium hexametaphosphate (SHMP) to study the effect of polyaluminum chloride (PAC) on quartz entrainment in fine coal flotation. Comparisons of flotation results show that the degree of quartz entrainment was greatly reduced using a suitable amount (e.g., 20 mg/L) of PAC in the absence of SHMP, however, significant changes of PAC on quartz entrainment did not appear in the presence of SHMP. The possible mechanisms responsible for the reduced quartz entrainment using PAC in fine coal flotation were investigated by particle size distribution measurements, zeta potential measurements, and interaction force calculations. Analysis of particle size distribution results reveals that when SHMP was not added, quartz particles were selectively aggregated with the addition of 20 mg/L PAC and the aggregation of quartz or coal particles was negligible at a high PAC dosage (e.g., 50 mg/L). Meanwhile, the aggregation of quartz particles induced by PAC was eliminated with the presence of SHMP. The electrostatic double layer repulsive force between quartz particles was calculated using the Deryaguin-Landau-Verwey-Overbeek (DLVO) theory with incorporating the results of zeta potential measurements. At 20 mg/L of PAC, the negative surface charge of quartz particle was neutralized and the electrostatic double layer repulsive force between quartz particles reached the minimum. These findings might be reasons of the aggregation of quartz particles and therefore reduce the quartz entrainment in fine coal flotation.

1. Introduction

Gangue entrainment is the main reason that results in the deterioration of flotation concentrate grade. The gangue entrainment problem in coal flotation has become more severe since the proportion of fine and ultrafine particles in coal flotation feed increases greatly with the popularization of mechanical mining and heavy medium cyclone separation technologies. Since China has adopted much stricter environmental regulations, the production of high quality clean coal has become a major challenge faced by the coal flotation industry today. Reducing the entrainment of fine and ultrafine gangue minerals seems to be a promising approach to improving the grade of clean coal, although, studies reported that it is very difficult to deal with [1–3].

In recent years, a number of studies have been conducted to improve the quality of flotation clean coal. Jiang et al. [4] and Peng et al. [5] applied inclined plates in the flotation column to increase the segregation rate between the rising bubbles and descending liquid by which both the capacity and the separation efficiency of the flotation

column increased. Ni et al. [6] designed an unconventional flotation column by adopting the mechanism of gravity sedimentation into flotation. They found that the ash of clean coal obtained with the new column was reduced by 1.17% compared with the conventional flotation column. The successes in improving clean coal quality also have been achieved by the development of new compound collector to promote fine particle recovery [7], the uses of ultrasonic [8], and high intensity conditioning to realize surface cleaning [9]. Recently, two liquid flotation, for example the Hydrophobic-Hydrophilic Separation (HHS) technology, has been developed to remove the gangue minerals by dispersing coal in hydrocarbon phase [10,11]. The entrainment of gangue minerals such as quartz, kaolinite, and montmorillonite in fine coal flotation has been recognized since the beginning of employing flotation. However, research effort has been mainly focused on developing new processes to improve the clean coal quality as above-mentioned. On the other hand, various studies have also been carried out to understand the gangue entrainment. A comprehensive review paper by Wang et al. [12] summarized the effect of major contributing

* Corresponding author.

E-mail address: lianglong1218@sina.com (L. Liang).

factors on entrainment, the methods for quantifying entrainment, and the models of gangue entrainment. Wiese et al. [13] proposed that the shape of particles had influence on entrainment, it was found that the particles of a flaky shape would be more easily entrained than those of a spherical shape. Recently, Sheni et al. [14] investigated thoroughly the effects of pulp chemistry on entrainment, which included pulp potential, pH, dissolved oxygen, and ionic strength, and found that only the pulp potential had significant influence on entrainment. Although a number of methods as to how to mitigate gangue entrainment have been put forward, the report on their practical application is scarce.

It is well recognized that there is a positive correlation between the gangue entrainment and water recovery. As to fine coal flotation, researches on reducing gangue entrainment were mainly focused on enhancing the water drainage in froth by increasing the froth height [15] and the use of bias water [4,16] to reduce water recovery. The effectiveness of these methods largely depends on whether the gangue particles are extremely fine, and whether the motion path of fine particles is exactly the same as the water flow. That is to say, the commonly used methods on gangue entrainment reduction might not be effective when the gangue mineral particles are selectively aggregated. Successful use of selective aggregation to mitigate the entrainment of gangue has been frequently reported in the flotation of metalliferous ores [17–19]. However, attempt on reducing gangue entrainment by selective aggregation has rarely been given in fine coal flotation. It might be attributed that the hydrophobic coal will be preferably aggregated when an organic polymer is used [20–22]. Thus, it will be of interest to explore an effective method on how to reduce gangue entrainment in coal flotation by selective aggregation without deteriorating of the recovery of coal.

In the present work, a model system (mixtures of fine clean coal and quartz particles) was used to study the gangue entrainment in fine coal flotation. Polyaluminum chloride (PAC), a low-cost and commonly used inorganic polyelectrolyte, was chosen to aggregate quartz particles. The effect of PAC on quartz entrainment was investigated through determining clean coal ash and water recovery, and also analyzed through measurements of aggregation degree of particles and zeta potential, and calculations of interaction energy.

2. Experimental

2.1. Materials

The quartz particles with a top size of 125 μm were purchased from Wanquan Co. Ltd, China. X-ray diffraction (XRD) analysis in Fig. 1 shows that only a trace amount of muscovite was found in the sample.

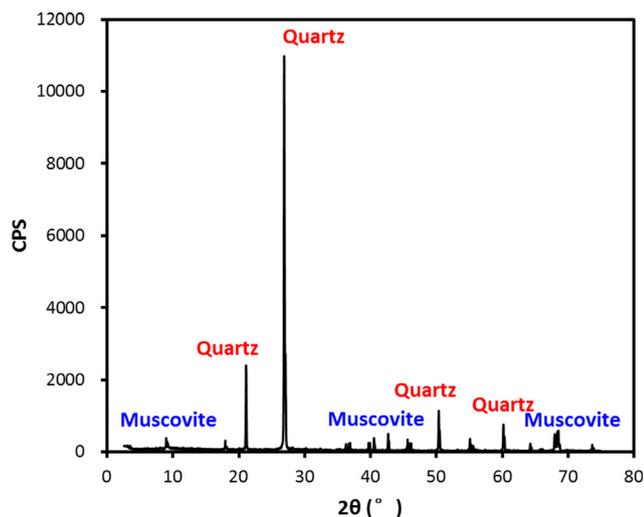


Fig. 1. X-ray diffraction results of quartz sample.

Table 1
Proximate and ultimate analysis of the clean bituminous coal sample.

Proximate analysis (dry basis)			Ultimate analysis (dry-ash-free basis)				
Ash content (%)	Volatile matter (%)	Fixed carbon (%)	C (%)	H (%)	N (%)	O (%)	S (%)
6.25	48.93	44.82	81.56	5.11	1.66	11.12	0.55

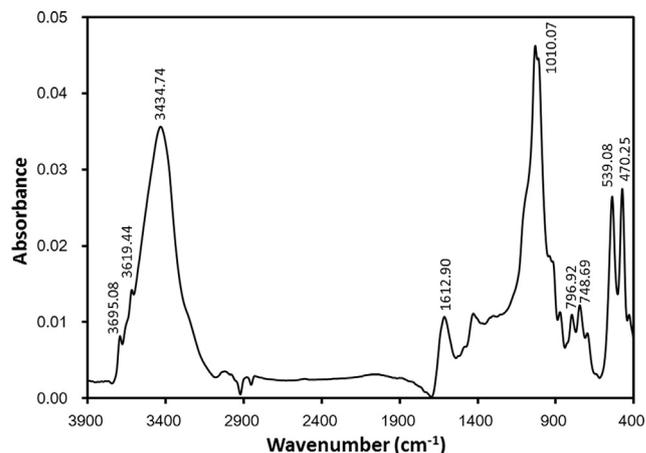


Fig. 2. FTIR spectrum of the clean coal sample.

Therefore, the quartz sample was used without further purification. A clean bituminous coal sample was collected from a coal mine in Shandong province, China. The coal sample was firstly crushed and ground to $-250\ \mu\text{m}$. Then, the $-1.4\ \text{g}/\text{cm}^3$ density fraction was collected and used in flotation tests, particle size distribution and zeta potential measurements. Table 1 presents the results of proximate and ultimate analysis of the clean coal sample used in this study. As shown, the ash content of the clean coal is 6.25% (dry basis). The FTIR spectrum of the clean coal sample is shown in Fig. 2. There were no obvious peaks at $1100\ \text{cm}^{-1}$ or $1750\ \text{cm}^{-1}$ which respectively originated from the symmetric stretching of Si–O–Si linkages and the asymmetric stretching of the Si–O–Si systems [23]. The FTIR measurements validated that quartz was not present in the clean coal sample.

The PAC of 0.5–0.7 basicity from Sinopharm Chemical Reagent Co. Ltd, China was used as received. A 1% by weight PAC solution was aged for 24 h before use. Sodium hexametaphosphate (SHMP) of analytical grade (Sinopharm Chemical Reagent Co. Ltd, China) was used as a dispersant. Kerosene and 2-octanol were used as the collector and frother, respectively. These two reagents are the conventional flotation reagents used in the coal preparation plant where the coal sample was obtained. Sodium hydroxide (NaCl) of analytical grade was used as a background electrolyte. All the experiments were conducted in the presence of 1 mM NaCl. Deionized water with a resistivity of $18.2\ \text{M}\Omega\text{-cm}$ (Watson, Ltd.) was used for preparation of reagent solutions and flotation tests.

2.2. Flotation experiments

The flotation experiments were conducted using a XFD laboratory mechanical flotation machine with a 1.5 L cell. In each test, a mixture of 25 g clean coal and 25 g quartz was placed in the cell containing 1.5 L of 1 mM NaCl solution and agitated for 4 min at 1800 rpm. After, the slurry was first conditioned with PAC (predetermined dosages) for 4 min, then kerosene (40 mg/L) for 2 min with each reagent addition. Frother (2-octanol, 10 mg/L) was added last followed by 1 min of conditioning. For the tests using dispersant, 2 g/L SHMP was added prior to the addition of PAC followed by 2 min conditioning. During all

flotation tests, the superficial gas velocity was maintained at 0.69 cm/s while the froth was scraped every 5 s over a period of 3 min. The flotation tests were repeated once under the same condition. The wet and dry weights of froth products in each test were recorded to calculate the water recovery. A series of float-and-sink tests was conducted on the froth products obtained from each flotation test using an organic liquid mixture of a 1.6 g/cm³ density to separate the quartz from clean coal. The results were used to determine coal recovery, quartz recovery, and quartz entrainment (the mass of quartz in unit volume of water) in the froth product by following equations:

$$\text{Coal Recovery} = \frac{MC_C}{MC_F} \times 100\% \quad (1)$$

$$\text{Quartz Recovery} = \frac{MQ_C}{MQ_F} \times 100\% \quad (2)$$

$$\text{Water Recovery} = \frac{MW_C}{MW_F} \times 100\% \quad (3)$$

$$\text{Quartz Entrainment} = \frac{MQ_C \times \rho_W}{MW_C} \quad (4)$$

where MC_C , MQ_C , MW_C , MC_F , MQ_F , and MW_F refer to the mass of coal, quartz, and water in the flotation concentrate and in the flotation feed, respectively, ρ_W refers to the density of water with the value of $1 \times 10^3 \text{ kg/m}^3$.

2.3. Particle size distribution measurements

The Focused Beam Reflectance Measurement (FBRM G400, Mettler Toledo, Switzerland) technique was used to obtain the particle size distribution of quartz and coal samples. Compared to other size measurement techniques, it has the advantage of avoiding the breakage of the aggregates during the measurement since the sampling process was not necessary here. In each test, 1 g quartz or clean coal particles were dispersed in 200 mL of 1 mM NaCl solution and agitated for 20 min at 500 rpm using a magnetic agitator. The size distribution measurement was then conducted after reducing the agitation speed to 150 rpm. For the measurement on the particles treated with PAC, a pre-determined dosage of PAC was added to the abovementioned fully dispersed suspension in 4 min after the measurement, and the particle size distribution was plotted after 1 min conditioning with the addition of PAC. The size measurement tests were repeated once under the same condition and the averaged results with an error less than 5% were reported in this study.

2.4. Zeta potential measurements

5 g quartz or clean coal sample was first dispersed in 100 mL of 1 mM NaCl solution and agitated at 500 rpm for 4 min by a means of magnetic agitator. Then the suspension was agitated for another 5 min after the addition of a pre-determined dosage of PAC. After the agitation, the suspension was kept standing for 12 h to allow coarse particles to settle. 20 mL supernatant was taken out using a pipette to conduct the zeta potential measurement (ZetaPALS, Brookhaven, US). Five measurements were performed under each condition, and the average zeta potential was reported in this study with the standard deviation less than 3 mV.

3. Results and discussion

3.1. Flotation results

The results of effects of PAC on the ash content and yield of froth product in the absence and presence of SHMP are presented in Fig. 3(A) and (B), respectively. As shown in Fig. 3(A), when SHMP was not used, the ash content of froth product decreased significantly from 10.35% to

8.14% with the addition of 10 mg/L PAC. An evident negative linear relationship between PAC concentration and froth product ash content was observed with varying PAC concentration in the range of 20–50 mg/L. At 50 mg/L of PAC, the ash content of froth product was 6.69% which was very close to that of the clean coal feed. On the other hand, the yield of froth product gradually decreased with the increase of PAC concentration in a mild manner compared with the changes of ash content.

In the presence of 2 g/L SHMP, as shown in Fig. 3(B), the ash content of froth products obtained using various PAC concentrations remained stable around 8.50%, which was much higher than that of the clean coal feed, indicating that quartz entrainment became more significant in the addition of SHMP. As to the yield of froth product, it remained around 44% when PAC concentration was in the range of 0–20 mg/L, and decreased to 38.60% as PAC concentration increased to 50 mg/L.

Comparisons of Fig. 3(A) and (B) show that the quality of flotation clean coal could be improved with the use of PAC in the absence of SHMP, and the effect of PAC on the ash rejection was not observed in the presence of SHMP. Extensively discusses on the effects of PAC will be given in the following section. It is also found that the yield of the flotation clean coal decreased significantly at a high dosage of PAC (e.g., 50 mg/L). Therefore, a recommended dosage of PAC would be in the range of 10–20 mg/L with the comprehensive consideration of both the quality and recovery of the clean coal.

To better understand the flotation performance, coal and quartz were separated from the froth product. Fig. 4 presents the recoveries of coal and quartz as a function of PAC concentrations. As can be seen in Fig. 4(A), when SHMP was not added, the quartz recovery was 37.40% in the absence of PAC and it steadily reduced to 26.78% as PAC concentration increased to 50 mg/L. Meanwhile, the coal recovery remained stable around 53% when PAC concentration was low, but it quickly dropped to 30% as PAC concentration further increased from 30 mg/L to 50 mg/L. When 2 g/L SHMP was present, a complete change in the pattern of effect of PAC on the quartz recovery was seen in Fig. 4(B), the quartz recovery slightly increased from 31.29% to 34.33% as the increase of PAC concentration. However, the variation of coal recovery to the PAC concentration was similar to those obtained in the absence of SHMP except for a smaller reducing trend.

Fig. 5 shows the effects of PAC on water recovery and quartz entrainment in froth in the absence and presence of SHMP. As shown in Fig. 5(A), when SHMP was not used, the water recovery first increased from 7.33% to 9.74% at PAC concentration of 20 mg/L, then decreased to 5.70% as PAC concentration further increased to 50 mg/L. However, the quartz entrainment showed a completely opposite trend. The quartz entrainment first decreased from 85 g/L to 54 g/L as PAC concentration increased from 0 to 20 mg/L, then increased to 78 g/L at PAC concentration of 50 mg/L. This means that the maximum reduction of quartz entrainment was achieved at PAC concentration of 20 mg/L, although the quartz recovery and the clean coal ash content were not the lowest. It is also found that the water recovery reached the maximum at PAC concentration of 20 mg/L, thus the quartz recovered in the froth phase per unit volume of water was the lowest. It is worth noting that the quartz recovery did not increase with water recovery when PAC concentration was lower than 20 mg/L, which was contradictory with the classical models that gangue recovery changes proportionally with water recovery [24,25]. This difference may be attributed to the aggregation of quartz particles induced by the presence of a small amount of PAC, which was not considered in the classical models. Gong et al. [26] and Liu and Peng [27] conducted the collectorless flotation of quartz with the addition of polymers, such as polyethylene oxide, and they also found that the quartz recovery decreased when the polymer was added. However, the water recovery did not increase when the polymer was added in their work. Compared to their work, the major difference in this work is that we used the hydrophobic coal particles in addition to the hydrophilic quartz particles.

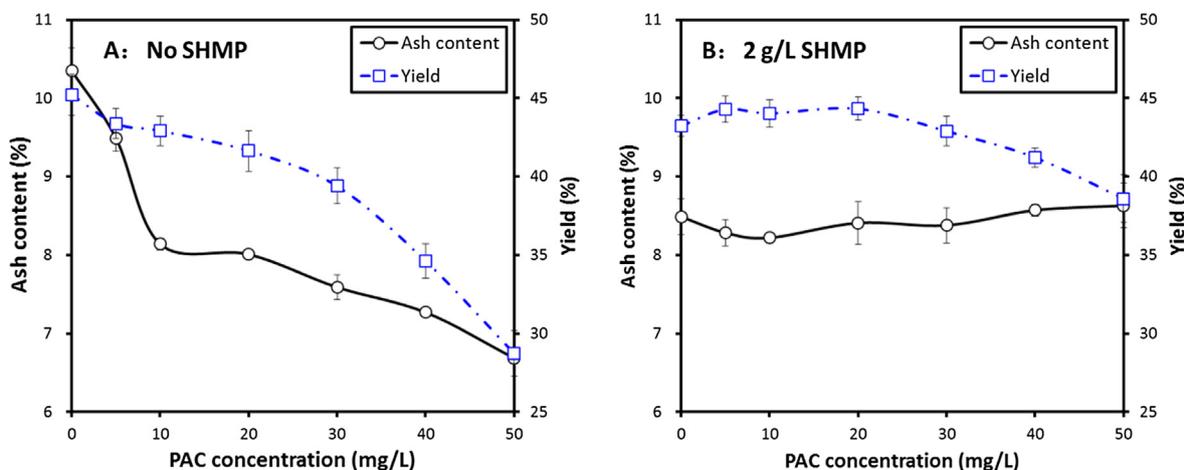


Fig. 3. Effects of PAC on the ash content and yield of the flotation froth product (A: without SHMP, B: with 2 g/L SHMP).

It, therefore, can infer that PAC may also have effect on the hydrophobicity of coal or froth structure.

As shown in Fig. 5(B), when 2 g/L SHMP was added, the water recovery decreased with the increase of PAC concentration, while the opposite trend showed for quartz entrainment. It suggests that the mitigation of quartz entrainment induced by PAC shown in Fig. 5(A) was eliminated by the presence of SHMP. It is also noted that the amounts of quartz entrained into the froth in the presence of 2 g/L SHMP were much larger than those obtained without SHMP. Therefore, PAC should not be used together with dispersant in order to reduce gangue entrainment.

3.2. Particle size distribution results

Fig. 6 and Table 2 show the measurement results of the particle size distributions using various amount of PAC in the absence of SHMP. It is clearly shown that the quartz particles became coarser with the addition of 20 mg/L PAC with an increase of the mean particle size from 63.67 μm to 78.96 μm. Additionally, the volume percentage of particles coarser than 50 μm and 100 μm increased from 64.28% to 72.78% and from 11.99% to 27.99%, respectively.

However, when PAC of 50 mg/L was added, the pattern of particle size distribution was very similar to that obtained without PAC and only a slight increase was observed in terms of the mean particle size and the volume percentage of particles coarser than 50 μm and 100 μm. These results indicate that the aggregation of quartz particles appeared at PAC of 20 mg/L but not at PAC of 50 mg/L. This finding is in line

with those results obtained by other researchers [28,29]. When cationic polyelectrolyte is used to aggregate negative charged particles, there is an optimum polyelectrolyte dosage to attain charge neutralization. Aggregation of particles is significant at this optimum dosage. However, with higher cationic polyelectrolyte dosage, the particles become positive charged and disperse in water again. It is also noted that the aggregation of quartz particles induced by PAC in this work was less significant than that achieved by polyethylene oxide reported in other literature [26,27]. This is because the molecular weight of polyethylene oxide was in millions but the molecular weight of PAC was only in thousands. It was reported in our previous work [30] that the hydrophobic coal and hydrophilic gangue minerals were simultaneously aggregated by polyethylene oxide when SHMP was not added, and the hydrophobic coal was prior to be aggregated by polyethylene oxide than the hydrophilic gangue minerals when SHMP was present. Therefore, polyethylene oxide was not used in this work because it is not favorable for quality improvement of the flotation clean coal.

Fig. 7 and Table 3 show the measurement results of the particle size distributions using various amount of PAC in the presence of SHMP. The particle size distribution did not change significantly no matter how much PAC was added. That is to say, the aggregation of quartz particles did not occur. This may be because SHMP prevented the adsorption of the cations dissociated from PAC on quartz surfaces, which will be discussed in the following section. A series of particle size distribution measurements was also conducted on coal with varying amount of PAC in the absence and presence of SHMP with the results presented in Fig. 8. Distinguishable differences were not found when

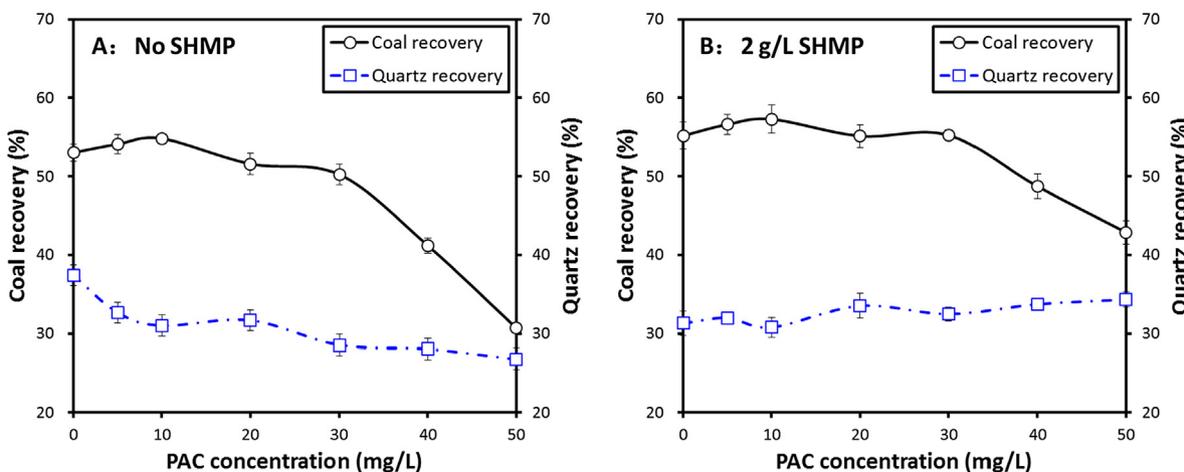


Fig. 4. Effects of PAC on the recoveries of coal and quartz (A: without SHMP, B: with 2 g/L SHMP).

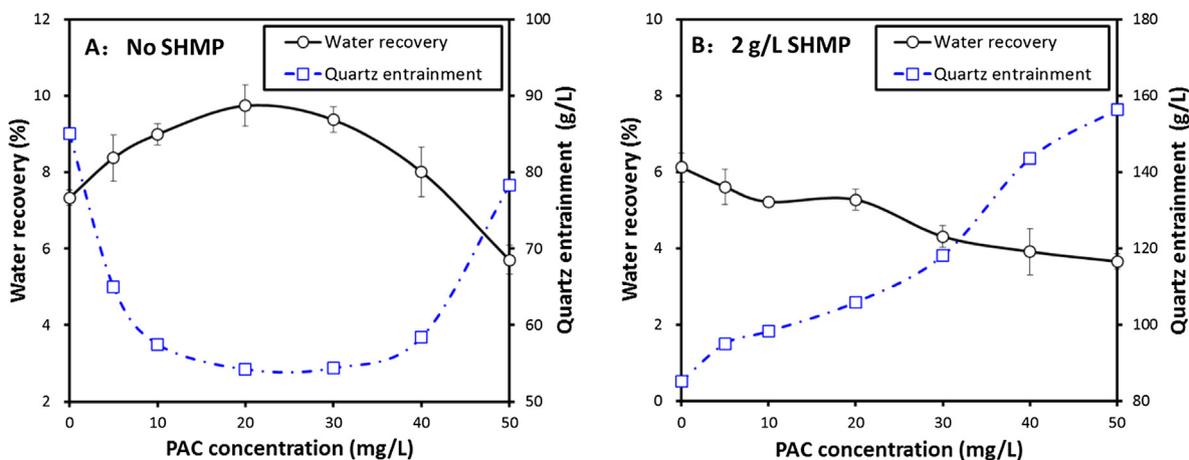


Fig. 5. Effects of PAC on the water recovery and quartz entrainment in the froth (A: without SHMP, B: with 2 g/L SHMP).

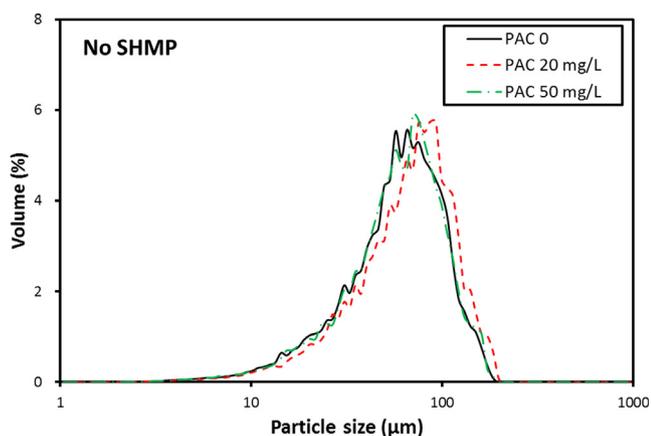


Fig. 6. Particle size distributions of quartz at different PAC concentrations in the absence of SHMP.

Table 2

Characterization of particle size distributions of quartz at different PAC concentrations in the absence SHMP.

PAC concentration (mg/L)	Mean particle size (μm)	Volume percentage of particle > 50 μm (%)	Volume percentage of particle > 100 μm (%)
0	63.67	64.28	11.99
20	78.96	72.78	27.99
50	65.55	66.18	12.84

PAC was added to the coal suspension, no matter whether SHMP was present or not. Consequently, it could be inferred that PAC would not induce the aggregation of hydrophobic coal particles in the tested range of 0 to 50 mg/L.

3.3. Zeta potential results

Zeta potentials of quartz and coal particles in deionized water with a background electrolyte of 1 mM NaCl were measured. As shown in Fig. 9, the zeta potentials of coal and quartz particles were negative over the tested pH range from 4 to 9, therefore, an aggregation of coal or quartz particles at neutral pH would not be expected theoretically. As the pH increased from 4 to 9, the zeta potential of quartz steadily decreased from -19 to -54 mV, while the zeta potential of coal also decreased from -17 to -46 mV. It is seen that the point of zero charge (pzc) for quartz was less than 4, which is consistent with those reported in the literature [31,32]. It is observed that the zeta potential difference

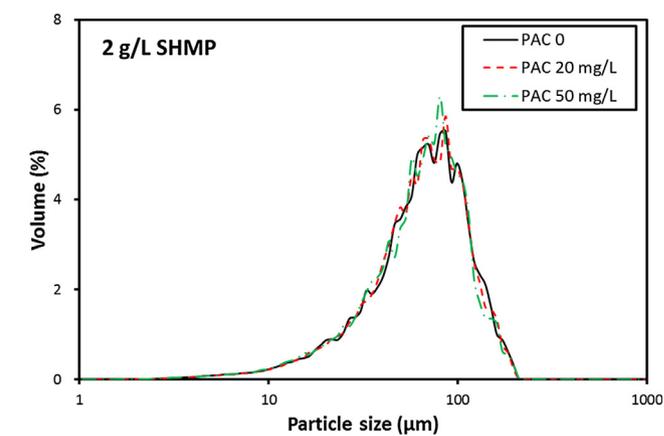


Fig. 7. Particle size distributions of quartz at different PAC concentrations with 2 g/L SHMP.

Table 3

Characterization of particle size distributions of quartz at different PAC concentrations with 2 g/L SHMP.

PAC concentration (mg/L)	Mean particle size (μm)	Volume percentage of particle > 50 μm (%)	Volume percentage of particle > 100 μm (%)
0	60.89	58.51	11.58
20	62.04	60.51	12.52
50	63.34	61.89	13.33

between quartz and coal was small in the tested pH range.

As shown in Fig. 10, as the increase of PAC concentration, the zeta potential of quartz and coal both gradually increased. For quartz particles, when the PAC concentration was close to 20 mg/L, the zeta potential approached to zero, at which the quartz particles could be aggregated due to the neutralization of surface charge. This consists with the results shown in Fig. 5(A) that the lowest quartz entrainment was achieved with 20 mg/L PAC. Thus, it can infer that the mitigation of quartz entrainment in fine coal flotation may be due to the aggregation of quartz particles. With the PAC concentration further increased to higher than 20 mg/L, the zeta potential of quartz became positive and it was strongly positively charged with a zeta potential of +53 mV at PAC concentration of 50 mg/L. For coal particles, the negative surface charge was neutralized at PAC concentration lower than 10 mg/L. The zeta potential reached a stable value around +35 mV at PAC concentration of 30 mg/L and kept in this level regardless of the increase of PAC concentration.

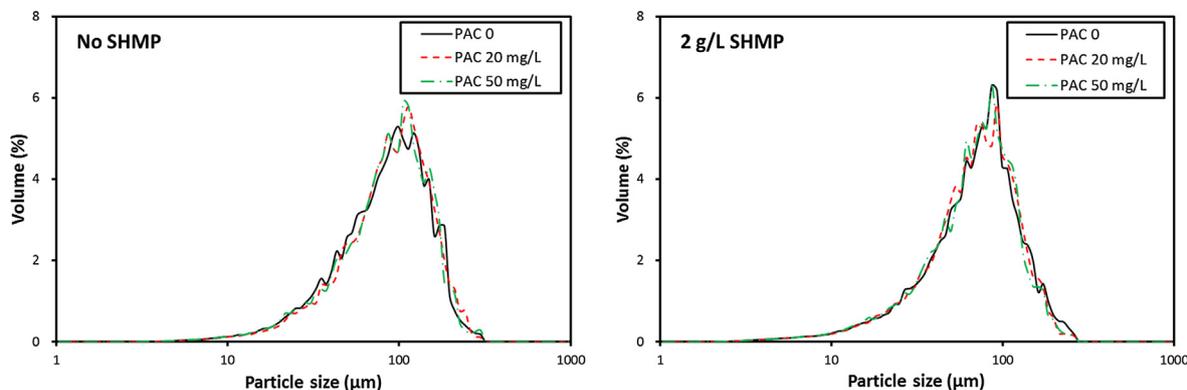


Fig. 8. Particle size distributions of coal at different PAC concentrations without SHMP and with 2 g/L SHMP.

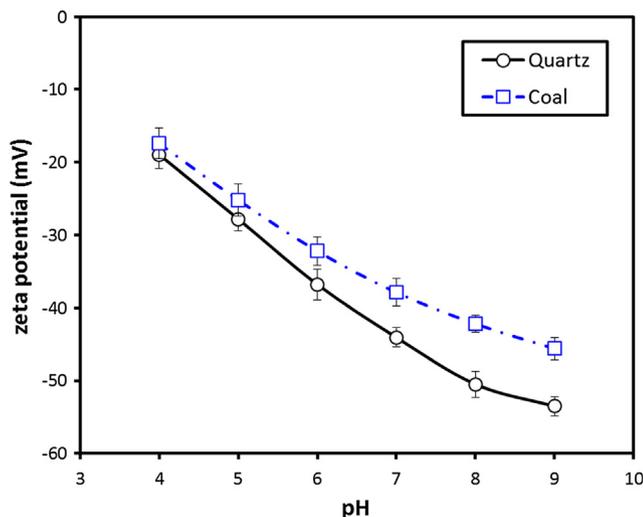


Fig. 9. Zeta potential of quartz and coal particles as a function of pH.

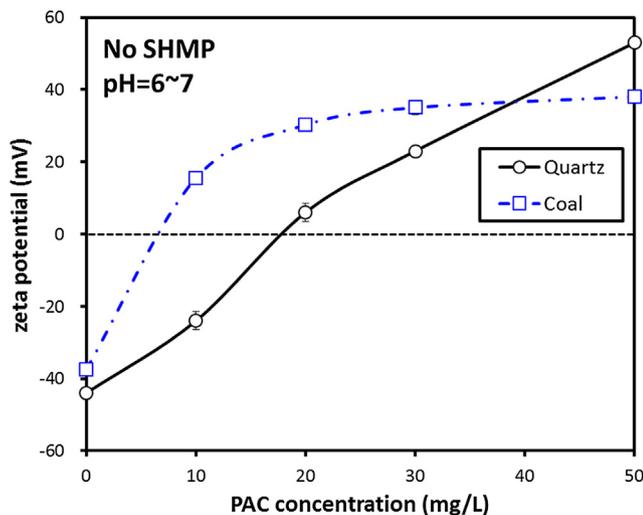


Fig. 10. Zeta potential of quartz and coal particles as a function of PAC concentration at pH 6–7 in the absence of SHMP.

The zeta potential results show that the adsorption of the cations dissociated from PAC on quartz and coal surfaces was not selective, however, a higher PAC concentration was required to realize charge neutralization for quartz than that for coal. This might be due to the fact that the surface area of quartz particles was much higher than that of coal particles since the original top size of the quartz particles (125 µm)

was much finer than that of clean coal particles (250 µm).

The results presented in Fig. 10 also provide explanations why coal recovery decreased when PAC was added, especially for high concentration. This may be owing to the decrease of the hydrophobicity of coal caused by the adsorption of the cations dissociated from PAC, which constitute mainly of aluminum hydroxyl group [33,34]. It is reported that the decrease of the population of hydrophobic coal particles in the froth could result in the slower water transfer rate from the pulp to the froth [35]. Therefore, the decrease of water recovery when PAC of high concentration was used as shown in Fig. 5 also could be a result of the decrease of coal hydrophobicity.

Fig. 11 shows the zeta potential of quartz and coal particles as a function of PAC concentration at pH 6–7 in the presence of 2 g/L SHMP. As seen, the zeta potential of quartz was independent of the PAC concentration and remained steady around -50 mV. This may be due to the adsorption of the negative charged $(\text{PO}_3)_6^-$ from SHMP on quartz surfaces. The hydrated layer around quartz surface was thickened due to the high hydration ability of $(\text{PO}_3)_6^-$. As a result, the adsorption of cations on quartz surface was prevented and the quartz particles could not be aggregated by PAC any more within the tested PAC concentration range. Since the dispersion condition of quartz particles in water did not change, it was expected that the quartz recovery in froth would remain steady. However, the quartz entrainment increased as shown in Fig. 5. This might be due to the decrease of the water recovery. As shown in Fig. 11, the zeta potential of coal still gradually increased with PAC concentration, but not as significant as that in Fig. 10. This indicates that the presence of SHMP did not completely prevent the

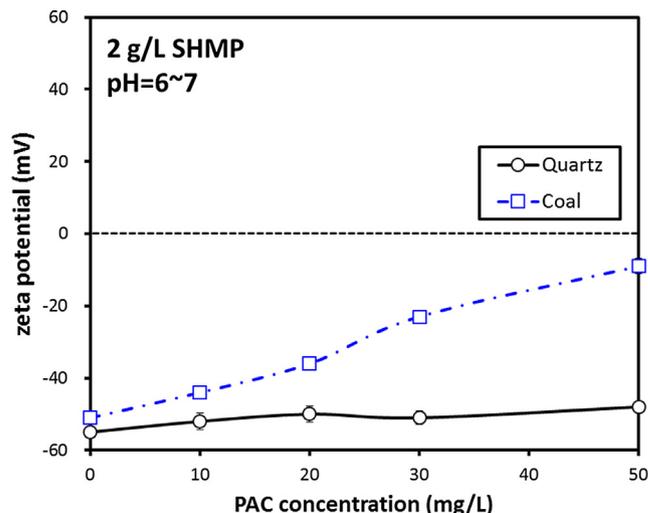


Fig. 11. Zeta potential of quartz and coal particles as a function of PAC concentration at pH 6–7 in the presence of 2 g/L SHMP.

adsorption of PAC on coal surface, therefore, similar to the tests without SHMP, the hydrophobicity of coal also decreased but to a smaller extent. As a result, the coal recovery and water recovery both decreased.

3.4. Interaction between quartz particles calculated by the DLVO theory

To further interpret the aggregation mechanism of quartz particles, the DLVO theory was applied to calculate the interaction energy between quartz particles at different PAC concentrations. The Hamaker approach was used to calculate the van der Waals force, and the Lifshitz theory was applied to predict the Hamaker constant (A_{132}) because it was more valid than the combining rules when the media, such as water in this work, was with high dielectric constant. The electrostatic double layer force (edl) was calculated at the constant surface potential boundary condition since the ion exchange process in this work was assumed to be slow. The models used in the calculation are as follows [36]:

$$E = E_{vdw} + E_{edl} \quad (5)$$

$$E_{vdw} = -\frac{A_{132}R}{12h} \quad (6)$$

$$A_{132} = \frac{3k_B T}{4} + \frac{3h\omega}{16\sqrt{2}} \frac{(n_1^2 - n_3^2)^2}{(n_1^2 + n_3^2)\sqrt{n_2^2 + n_3^2}} \quad (7)$$

$$E_{edl} = 2\epsilon\epsilon_0\pi R\psi^2 \left[\ln \frac{1 + e^{-\kappa h}}{1 - e^{-\kappa h}} + \frac{1}{2} \ln(1 - e^{-2\kappa h}) \right] \quad (8)$$

where A_{132} refers to the Hamaker constant, R refers to the radius of quartz particle (50 μm in this work), h is the distance between two quartz particles, k_B is the Boltzmann constant with value of 1.381×10^{-23} J/K, T is the temperature in K (293.15 K in this work), h is the Planck constant with the value of 6.626×10^{-34} J s, ω is the characteristic relaxation frequency of the UV region with the value of 2.068×10^{16} rad/s, n_1 and n_3 represent the refractive indices of quartz and water, respectively, ϵ is the relative dielectric constant of the 1 mM NaCl solution with the value of 78.5, ϵ_0 is the permittivity of vacuum with the value of 8.854×10^{-12} C²m/J, ψ is the surface potential of quartz, which is substituted by the measured zeta potential value, κ^{-1} is the Debye length with the value of 9.6 nm in 1 mM NaCl solution, determined by Eq. (9) with the unit of nm for κ^{-1} , and mol/L for c_{NaCl} , respectively.

$$\kappa^{-1} = \frac{0.304}{\sqrt{c_{\text{NaCl}}}} \quad (9)$$

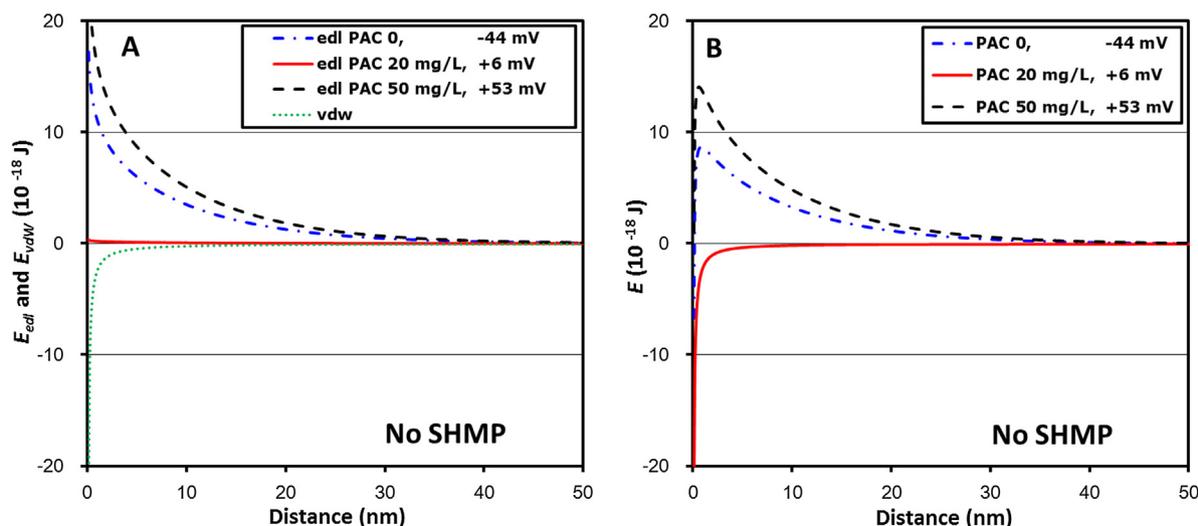


Fig. 12. DLVO interaction energy between quartz particles at different PAC concentrations without SHMP.

Fig. 12(A) illustrates the interaction energy of the individual van der Waals force (vdw) and electrostatic double layer force (edl) at different PAC concentrations, while Fig. 12(B) illustrates the summation interaction energy. Fig. 12 indicates that the van der Waals force was attractive and it was independent of PAC concentration. The electrostatic double layer repulsive force was of high magnitude at PAC concentration of 0 and 50 mg/L due to the high absolute value of zeta potential while it was negligible at PAC concentration of 20 mg/L due to the low zeta potential value. Therefore, the quartz particles were aggregated at PAC concentration of 20 mg/L due to the attractive van der Waals force, which further resulted in the mitigation of quartz entrainment in coal flotation. The interaction energy between quartz particles with SHMP of 2 g/L was shown in Fig. 13. The electrostatic double layer repulsive force remained high at different PAC concentrations because the quartz surfaces were highly negative charged. Under this condition, quartz particles could hardly be aggregated, so the quartz entrainment in coal flotation was not mitigated by PAC.

4. Conclusions

The mitigation of quartz entrainment in fine coal flotation was successfully achieved with the addition of PAC at a suitable concentration (e.g., 20 mg/L). Analysis of results of particle size distribution, zeta potential and interaction energy between particles concludes that the mitigation of quartz entrainment is attributed to the aggregation of quartz particles induced by PAC. Through the zeta potential measurements and the DLVO interaction energy calculation, it demonstrated that PAC of 20 mg/L neutralized the negative charge on quartz surface and impaired the strength of the electrostatic double layer repulsive force between quartz particles. The presence of SHMP prevented the adsorption of PAC on quartz surface, resulting in the ineffectiveness of PAC on the reduction of quartz entrainment in fine coal flotation.

This work provides a new direction on improving the quality of coal flotation concentrates by selectively aggregating the gangue minerals. However, nowadays, the chemistry of recycled water to the flotation system in coal preparation plants in China has become more and more complicated due to the poorer quality of the run-of-mine coal and the increasing use of various chemicals for thickening. The present work has shown that the presence of dispersant SHMP has detrimental influence on the aggregation of quartz particles induced by PAC. Therefore, in the future work, it will be of interest to investigate and analyze the water chemistry in some typical coal preparation plants in China and study the synthetical effects of PAC and other typical residual

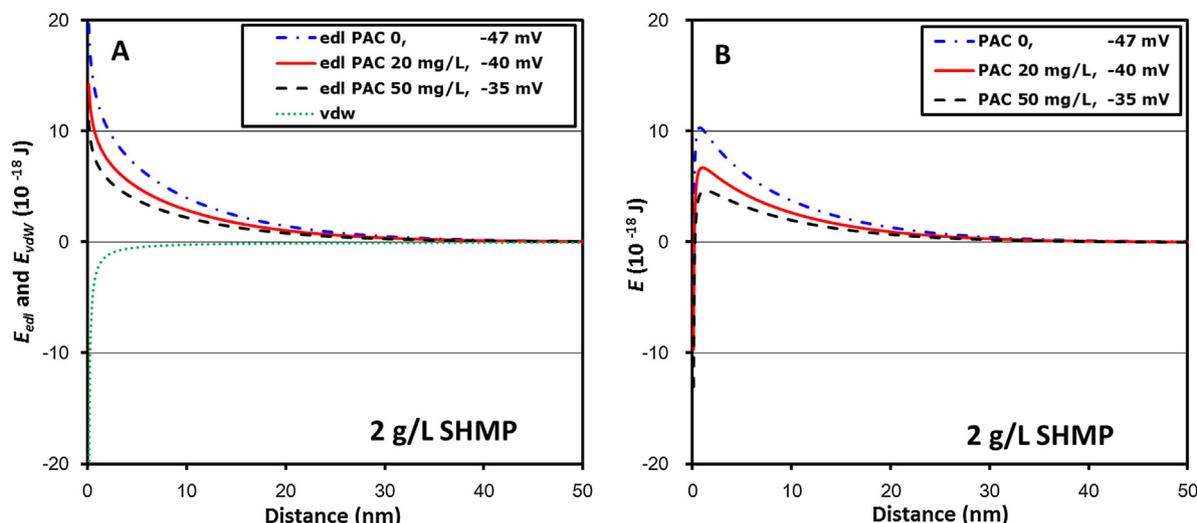


Fig. 13. DLVO interaction energy between quartz particles at different PAC concentrations with 2 g/L SHMP.

chemicals in the recycle water on the mitigation of gangue entrainment.

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