Magnetic seeding sedimentation (MSS) of coal slimes

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Abstract. Magnetic seeding sedimentation (MSS), i.e. adding magnetic seeds and pre-magnetization for sedimentation, is a technique especially for sedimentation of fine slimes, improving the sedimentation performance by introducing the magnetic interactions between particles in a suspension and enlarging the apparent size of the fine particles. The fine coal slimes with a size of 66.68%-38μm were investigated by the MSS. Sedimentation tests were conducted, and some measurements, such as laser size analysis, magnetic susceptibility by vibrating sample magnetometer (VSM), were also applied in order to probe the mechanism of the MSS. Based on the tests, measurements and calculations it was demonstrated that the sedimentation of coal slimes increased with the additions of the magnetic seeds, and in the presence of the polyacrylamide，and also there appeared a relatively large apparent size of slimes after additions of magnetic seeds and/or polyacrylamide. So, the reason for the influence of MSS lies in fact that the presence of the polyacrylamide intensified the adsorption of magnetic seeds on the coal particles and the coverage of the magnetic seeds on the coal surface from 0.2% wt. to1.3% wt., resulting in increased magnetic susceptibility of coal particles from $9.13\times10^{-9}m^3/kg$ to $22.17\times10^{-9}m^3/kg$ and thus a low magnetic field strength of pre-magnetization needed for the magnetic agglomeration to happen among the coal particles (the threshold of magnetic field strength for agglomeration) from 602mT to 24mT prior to proper sedimentation.

1. Introduction

Fine minerals with fine-grained particle size are not suitable for effective sedimentation, and further study on the sedimentation of fines has important practical significance. Take coal slimes as an example, slimes produced during the coal washing process, forms a stable suspension easily with difficult sedimentation due to its good hydrophobic surface, fine particle size, less momentum, high clay content, high negative potential, and etc. In order to improve the sedimentation of coal slimes, quite a few of settling techniques have been investigated. Most of them are based on the addition of various organic and inorganic chemical agents, such as the application of new organic flocculants [1-2], the use of mixed organic flocculants [3], the combined application of surfactants and flocculants [4-6], combination of inorganic coagulants and organic flocculants [7], the introduction of magnetic field and electric field [8-10], and etc.

Magnetic seeding flocculation is a technology of separation which is mainly used in magnetic minerals [11-12]. The author [13] patented a new method, so-called 'magnetic seeding flotation' (MSF), can be used for fines flotation of coal slims, enlarging the apparent size of fine particles by magnetic seeding agglomeration (MSA). This method is characterized in that the directional adsorption of magnetic seeds and agents on the target mineral surface, enlarging the apparent size of fine particles.

Based on the method of MSA, this paper is intended to investigate the magnetic seeding sedimentation (MSS) of coal slimes, and to explore the mechanism of magnetic seeding agglomeration (MSA) of mineral slimes as well.

2. Materials and methods

2.1. Materials

(1) Coal slimes: taken from a colliery in Shanxi province, China, containing 44.21% of fixed carbon and 28.41% of ash. Its particle size was 66.80% -38μm, and its specific surface area 1.33m2/g, so it's far below the optimum particle size for flotation. The X-ray diffraction analysis showed that the ash was mainly composed of kaolinite and quartz.

This slimes was mainly used for the investigation of the MSS and size analysis of the magnetic seeding agglomeration (MSA) in this study.

(2) Pure coal: purified from the above coal slimes by the following sub-processes: screening two times respectively with the apertures 0.5mm and 0.074mm to obtain the fraction between the two sizes, then two gravity separations by a shaking table to achieve the purity of containing 2 wt.% ash, and then being ground in a ceramic ball mill for ten minutes after filtering and drying. This sample was mainly used for magnetism analysis.

(3) Magnetic seeds: synthesized in laboratory by the method of air-oxidation of ferrous salts in an open system [14]. The synthesis was conducted in a 200 ml beaker with pure water inside. The water was maintained at 85 ℃ while stirring at a speed of 300 r/min, and then $FeSO_4 \cdot 7H_2O$ and ammonium hydroxide were added in sequence. The synthesis was finished after 30 min stirring, and the formed suspension was kept in store for use, and the average particle size of the magnetic seeds was 2.05μm.

(4) Polyacrylamide（PAM）: anionic type with a molecular weight of 3 million.

2.2. Methods

(1) Sedimentation test

A suspension with the concentration of the slimes 20% wt., with additions of the magnetic seeds, the PAM or the PAM plus magnetic seeds, was conditioned for 3 minutes in a pre-magnetizing blender with the volume 100 ml and the maximum magnetic field intensity 50mT [15], and then was poured into a 100 ml graduated glass cylinder for sedimentation test.

(2) Laser diffraction for agglomerate size analysis

A suspension with the concentration of the slimes 5%wt., without or with additions of the magnetic seeds and/or the PAM, was conditioned for 3 minutes in the above pre-magnetizing blender and then was introduced into a beaker for laser diffraction analysis by the equipment Mastersizer2000.

(3) Vibrating sample magnetometer (VSM) analysis

Hysteresis loops of the pure coal, the pure coal coated by the magnetic seeds, and the pure coal coated by the magnetic seeds at the presence of the PAM, were obtained by vibrating sample magnetometer HH-15.The pure coal coated by magnetic seeds was prepared by mixing the pure coal and the magnetic seeds in the above pre-magnetizing blender for 4 minutes, then the slurry passed through a magnetic separation tube with a magnetic field intensity of 150mT to remove free magnetic seeds, and the passed tailing was then filtered and dried for the VSM [16].

3. Magnetic seeding sedimentation (MSS) tests and size analysis

3.1. Magnetic seeding sedimentation (MSS) tests

The influences of some variables on the magnetic seeding sedimentation were tested, and the results are shown in following figures. It can be seen in Figure 1 that in the presence of the magnetic seeds the polyacrylamide has a stronger sedimentation than the PAM alone, i.e. the MSS is conducive to the sedimentation of the coal slimes.

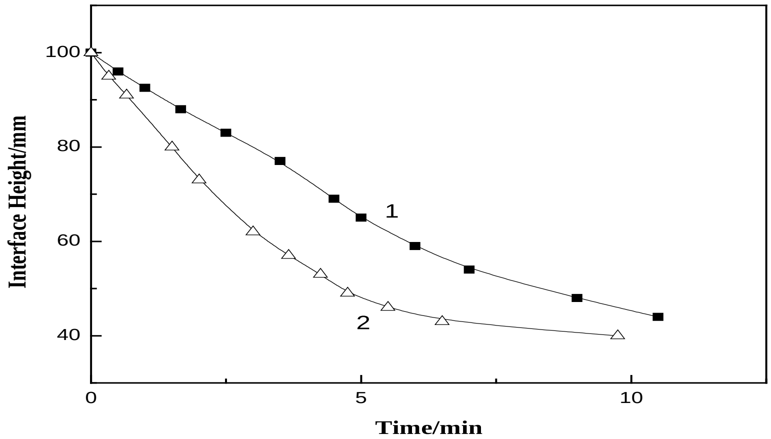

Figure 1. Sedimentation curves of coal slimes
1-60mg/L polyacrylamide, 2-60mg/L polyacrylamide+70mg/L magnetic seeds

Considering that the magnetic field intensity of pre-magnetization is an important parameter in the process of MSS, the influence of the magnetic field intensity on the MSS, under the condition of 60mg/L Polyacrylamide plus 35mg/L magnetic seeds， as shown in Figure 2.

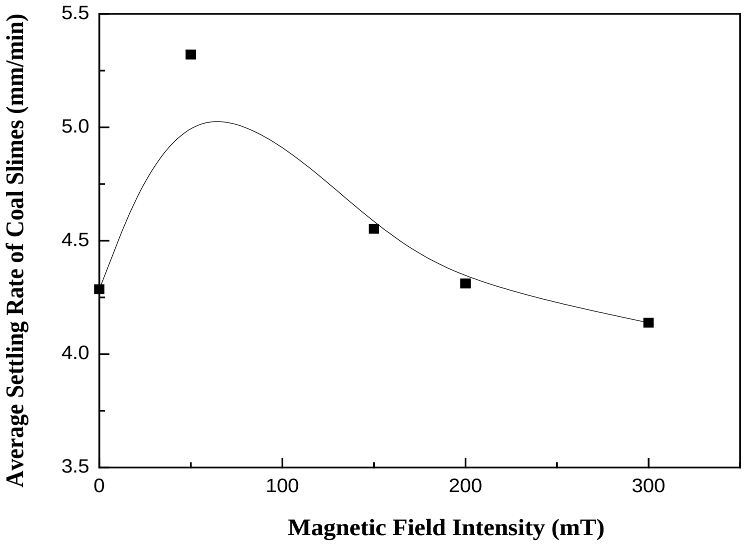

Figure 2. Influence of magnetic field intensity on the average settling rate of coal slimes
with 60mg/L polyacrylamide and 35mg/L magnetic seeds

Figure 2 indicates that the settling rate of coal slimes is enhanced in the presence of the magnetic field. The settling rate increases with the increase of magnetic field intensity with the maximum rate of 5.31 mm/min by using the magnetic field intensity of 50 mT which can be attributed to the MSA of the slimes, magnetic seeds and the polyacrylamide, enlarging the apparent particle size for MSS. However, it also can be inferred that beyond 50 mT, the settling rate decreases which may be attributed to the self-agglomeration of magnetic seeds prematurely during the process of pre-magnetization, reducing the effect of MSA, and then reducing the settling rate of coal slimes.

3.2. Size analysis in the MSS

In consideration of the magnetic seeds and the coal particles are both in the range of micro sizes, the laser diffraction method was applied to analyze the sizes of coal slimes in the MSS in order to investigate if the magnetic seeding agglomeration (MSA) happens. For the convenience to observe the size changes, all size distribution curves, under conditions of blank, magnetic seeds, polyacrylamide, and magnetic seeds plus polyacrylamide, are listed in Figure 3.

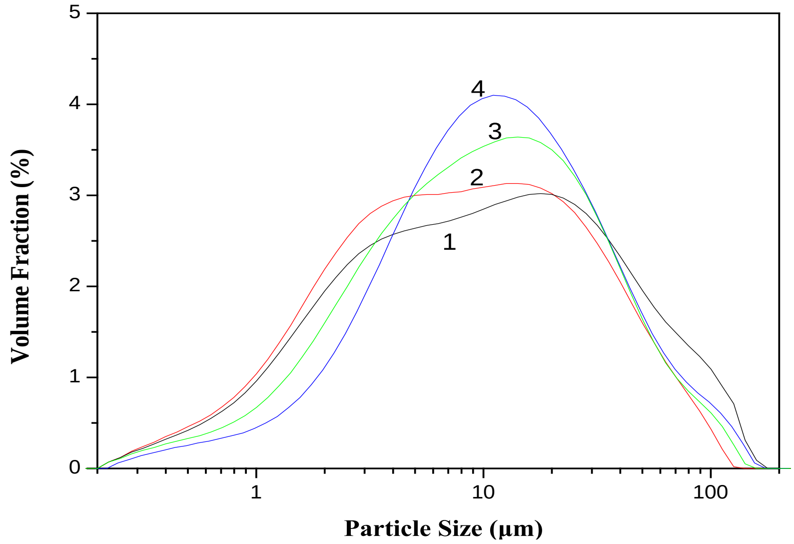

Figure 3. Size distribution of coal slimes

1-blank, 2-50 mg/L magnetic seeds, 3-10 mg/L PAM, 4-50 mg/L magnetic seeds and 10 mg/L PAM

As shown in Figure 3, the average particle size of coal slimes increased to 21.74μm after adding 50mg/L magnetic seeds and 10 mg/L PAM whilst in the blank and the presence of the magnetic seeds or the PAM their average particle sizes were 16.40μm, 18.25μm and 20.24μm, respectively. It is inferred from the size changes that the coal slimes were agglomerated after the additions of the magnetic seeds and/or the PAM. The PAM is a well-known flocculant [17], and by contrast it is a surprise that the magnetic seeds agglomerate well with the coal slimes, and particularly the combination of the magnetic seeds plus polyacrylamide is a powerful agglomerant.

4. The mechanism of magnetic seeding sedimentation (MSS)

4.1. General explanation of the MSS-Expanded DLVO with additional magnetic interaction

Whether the particles in a suspension are dispersed or agglomerated is determined by the interactions between particles, and the variation of total potential energy of the suspension system is a decisive factor on its stability. According to the DLVO theory, the total energy of colloidal particles V_T is summed by electric potential V_R and Van der Waals interaction V_A:

$$V_T = V_R + V_A \quad (1)$$

Svoboda expanded the DLVO theory to a system with fine weakly magnetic particles, and built a theoretic model inclusive of magnetic interactions [18]:

$$V_T = V_R + V_A + V_M \quad (2)$$

where V_M is the magnetic interactions between particles.

While in the presence of applied magnetic field, an equation to calculate the magnetic energy was proposed:

$$V_M = -\frac{32\pi^2 a^6 \chi^2 B_0^2}{9\mu_0 r^3} \quad (3)$$

where a is the radius of particles, χ the volumetric magnetic susceptibility of the particles, B_0 the magnetic induction, μ_o the permeability of vacuum and r the distance between two particles.

Hence, the suspension of the slimes tends to be instable as a result of the pre-magnetization and magnetic seeds covering the surface of particles. In the MSA of the coal slimes, the combined positive effect of the magnetic seeds and polyacrylamide is noteworthy of further study. So, the mechanism of MSA in the MSS was probed through the vibrating sample magnetometer analysis (VSM) and related calculations below.

4.2. Determinations of magnetism by the VSM, coverage of magnetic seeds on coal surface and the critical magnetic field intensity BA for agglomeration

According to equation (3), the magnetic interaction VM is highly related to the volumetric magnetic susceptibilityχ. The hysteresis loops of the pure coal, the pure coal coated by the magnetic seeds, and the pure coal coated by the magnetic seeds at the presence of the PAM, were obtained by the VSM, as shown in Figure 4.

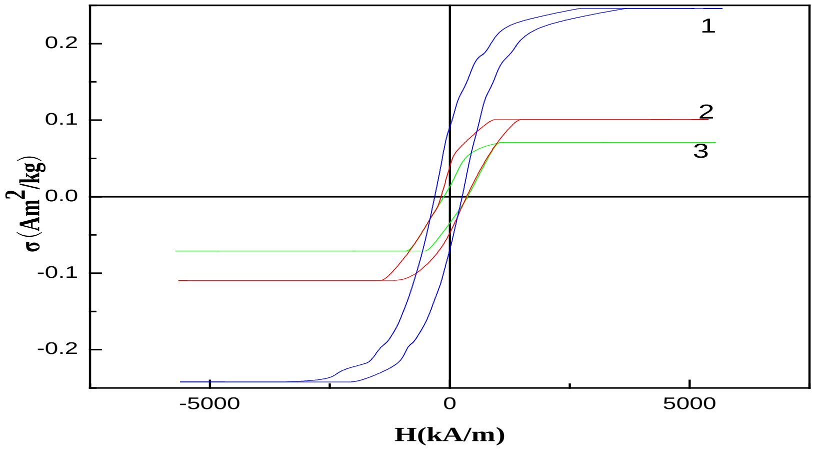

Figure 4. Hysteresis loops of coal

1-Coal-35 mg/L magnetic seeds and 12 mg/L PAM, 2-Coal-35 mg/L magnetic seeds, 3-Coal

As illustrated in Figure 4, surprisingly the pure coal presents a weak magnetism of saturation magnetic induction 0.065 Am^2/kg probably due to contamination of trace of pyrite inside. After the additions of the magnetic seeds and the PAM, its saturation magnetic induction reached 0.244Am^2/kg whilst only addition of the magnetic seeds, its saturation magnetic induction raised to 0.089Am^2/kg. This may be attributed to the combined effect of the magnetic seeds and the PAM. Without doubt, the increase of the magnetism of the coal means a largely increased value of magnetic interactions between particles VM based on the equation (3).

Furthermore, the author [19] translated the difference of their magnetisms into the adsorption or coverage of the magnetic seeds on the surface of coal by an indirect model, and the results can be briefed as follows: in the same dosage of the magnetic seeds 35 mg/L, the coverage of the magnetic seeds on the coal surface is increased from 0.2% wt. to 1.3% wt.， namely, the PAM strengthens the adsorption of the magnetic seeds on the surface of coal.

According to equation (3), the magnetic energy is related to the applied magnetic field B_0 (i.e. .the pre-magnetization field intensity here) as well. Watson [20] put forward a formula to calculate the critical magnetic field intensity B_A for flocculation of minerals to happen as follows:

$$B_A = -\left(\frac{2KT\mu_0}{\pi^2 x^2 a^3}\right)^{\frac{1}{2}} \tag{4}$$

where *K* is Boltzmann constant, its value 1.3806505× 10^{-23} J/K; T degree Kelvin, μ_o the vaccum permeability, its value 4π×10-^{7}N/A^{2}; χ is specific magnetic susceptibility of the mineral, and a the radius of mineral particles. The result of calculation is listed in Table 1.

Table 1. Critical magnetic field intensity of coal to flocculation

Sample	χ ($10^{-9}m^3/kg$)	B_A (mT)
Coal	0.89	601.95
Coal with magnetic seeds	9.13	58.67
Coal with magnetic seeds+ PAM	22.17	24.16

As shown in Table 1, the threshold of magnetic field strength for coal to agglomeration decreased greatly by adding the magnetic seeds, especially by simultaneously adding the magnetic seeds and the PAM.

In addition, based on his calculations the author [19] also explained that when the magnetic seeds are placed in a 50mT pre-magnetization field, their specific magnetization is 13.4Am^2/kg, resulting in a magnetic field intensity on their surface 112.26mT.

5. Conclusions

(1) The MSS (the addition of magnetic seeds under a low applied magnetic field) was beneficial to the sedimentation of coal slimes, and also greatly strengthened with the aid of polyacrylamide.
(2) The mechanism of the MSS lies mainly in the magnetic actions between particles in the suspension. The MSS promoted the agglomeration of slimes, resulting in properly-sized agglomerates right for sedimentation. The average apparent sizes of coal slimes in four agglomeration conditions, such as the blank, magnetic seeds, polyacrylamide and polyacrylamide plus magnetic seeds, were 16.41μm, 18.25μm, 20.24μm and 21.74μm, respectively. The increase of granularity of coal slimes under the MSS facilitated the sedimentation process.
(3) The effect of the polyacrylamide plus magnetic seeds on the agglomeration stood out among them. The PAM strengthened the adsorption of magnetic seeds on the surface of coal particles from mass fraction 0.2% to 1.3%, consequently raising the specific susceptibility from 9.13×$10^{-9}m^3$/kg to 22.17×$10^{-9}m^3$/kg. So, the MSA under the condition of polyacrylamide plus magnetic seeds reduced the critical magnetic field intensity for the agglomeration of coal slimes from 602 mT to 24 mT.

Acknowledgements

The authors would like to acknowledge the financial support from the National Natural Science Foundation of China (No.51274256).

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