

# **HYDROPHOBIC FLOCCULATION APPLIED TO FINE MINERAL AND COAL PROCESSING**

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## **ABSTRACT**

This paper highlights hydrophobic flocculation applied to fine minerals and coal processing. Initially, hydrophobic flocculation and its separation technology are briefly described. Then, several examples on the application of this technology to the beneficiation of fine minerals and coals are presented. Finally, the three main parameters affecting hydrophobic flocculation, namely particle hydrophobicity, non-polar oil addition and suspension stirring, are discussed. It is demonstrated that the separation technology based on hydrophobic flocculation is a potential mean to efficiently recover valuable minerals in the fine size range and to effectively remove finely disseminated impurities from coals.

## **RESUMEN**

Este artículo presenta la aplicación de la floculación hidrofóbica en la recuperación de minerales valores en lamas y en menas con minerales finamente diseminados, así como en el procesamiento de finos de minerales de carbón. Inicialmente, se describe brevemente la floculación hidrofóbica y las bases de ésta tecnología de concentración de minerales. Posteriormente, se presentan algunos ejemplos de su aplicación en el beneficio de minerales y carbón. Finalmente, se analizan los tres parámetros principales que afectan la floculación hidrofóbica, i.e. la hidrofobicidad de las partículas, la adición de aceite no polar y la energía cinética en acondicionamiento. Los resultados demuestran que la floculación hidrofóbica es un método viable y la mejor tecnología para la recuperación de valores que se encuentran a un tamaño muy fino y para eliminar impurezas finamente diseminada en minerales de carbón.

## **I. INTRODUCTION**

The beneficiation of ultra-fine minerals and coals has recently attracted increasing attentions because of the following: (1) Many mineral resources that mineral industry is facing exist in finely disseminated form, which require very fine grinding to liberate valuable minerals before any beneficiation commences. (2) The majority of valuable mineral losses in current concentration plants is due to slimes, which are generated in grinding circuits or from raw ores because of deep oxidization in nature. (3) The needs for ultra-pure minerals and coals are rapidly increasing, which requires to deeply remove impurities that are finely inter-grown with valuable matters. (4) The environmental concerns require rejecting harmful matters from concentrates before they are further treated, which are usually disseminated finely. For example, sulfur matters in coal must be removed before burned. Unfortunately, the standard separation methods fail to process ultra-fine particles. It is therefore significant to develop effective and economic techniques for fine mineral and coal processing.

During last four decades, numerous investigations have been performed on fine mineral and coal processing, presenting various physical separation techniques. These techniques can be classified into two categories, i.e. increasing particle size through aggregation, and extending the lower size limit of standard separation methods. The former includes the techniques of polymer flocculation (Frommer and Colombo, 1966; Attia, 1982), hydrophobic flocculation (Koh and Warren, 1977; Song and Trass, 1997) and magnetic flocculation (van Kleef, et al, 1984), etc. The latter includes micro-bubble flotation (Zabel, 1992), high-gradient magnetic separation (Iannicelli, 1979), and super-conducting separation (Wasmuth and Unkelbach, 1991), etc. Hydrophobic flocculation is a term for that hydrophobic particles aggregate in aqueous suspension due to hydrophobic interaction between particles and kinetic energy of sufficient magnitude. It is characterized by its high selectivity, namely that it could happens to one matter in a mixture system, leaving other matters in dispersion. Thus, it is welcome by separation technology. Hydrophobic flocculation applied in mineral processing can be traced back to 1950s when emulsion flotation was presented to process manganese ores in fine size range (McCarrol, 1954). In emulsion flotation, proper surfactants and fuel oil are added to induce the aggregation of valuable mineral fines, while a strong mechanical stirring is applied to mineral slurry. Later, carrier flotation was developed to remove fine anatase from kaolin, in which fine anatase selectively aggregates with coarse calcite due to the addition of sodium oleate, followed by the flotation of calcite (Green and Duke, 1962). In 1960s, oil agglomeration or spherical agglomeration was developed at the National Research Council of Canada for fine coal cleaning (Mealus, 1968; Capes and Germain, 1982), in which coal fines aggregate into pellets through the bridging action of non-polar oil, followed by screening to separate the pellets from fine mineral suspension. In 1970s, shear flocculation flotation was presented by Warren and his co-workers (Warren, 1975; Koh and Warren, 1979) to efficiently recover fine scheelite ( $-5 \mu\text{m}$  in size), which aggregated due to sodium oleate present and an intensive slurry conditioning. Since then, separation methods based on hydrophobic flocculation

has been greatly improved due to the achievements on the theories of hydrophobic interaction and hydrophobic flocculation. Up to date, it has found a wide range of applications such as: removal of organic matters in drinking water treatment, processing of waste water and solid, separation of microorganisms and cells in medical science, and fine mineral and coal processing, etc.

Hydrophobic flocculation has been being an research interest in our laboratory, including the fundamental and application aspects (Song and Trass, 1997; Song and Lopez-Valdivieso, 1998; Song, et al, 1999; Song and Lu, 1990, 1994, 1996; Lopez-Valdivieso and Song, 1998). Various ores that contain valuable minerals in fine dissemination or slimes (gold, iron oxide, ilmenite, rutile, and metallic sulfides) and coals (bituminous, and anthracite) were tested for the beneficiation of fine particles with hydrophobic flocculation separation technology. The experimental results suggest that it has potential as a mean for the beneficiation of fine minerals and coals. In the present paper, hydrophobic flocculation and its application in fine mineral and coal processing are reviewed and discussed. Some experimental results are presented to show how hydrophobic flocculation separation technology improves the recovery of fine mineral and coals, and to illustrate how the main factors, namely particle hydrophobicity, suspension stirring and non-polar oil addition, influence hydrophobic flocculation.

## II. HYDROPHOBIC FLOCCULATION TECHNOLOGY

Hydrophobic flocculation technology is a term for all the separation methods on the basis of hydrophobic flocculation of fine particles in aqueous suspension. It can be divided into two steps, namely the formation of hydrophobic flocs and the separation of the flocs from other matters in dispersion. The former is just hydrophobic flocculation, and the latter could be one of standard separation methods that is appropriate for the properties of flocs to be recovered.

The key of this technology is hydrophobic flocculation step, in which only particular mineral particles form hydrophobic flocs while other minerals remain in dispersion. This step consists of dispersion, selective hydrophobization, hydrophobic flocculation, which are depicted as follows: (1) *Dispersion* is needed to stabilize fine mineral particles to prevent them from hetero-coagulation that would be detrimental to separation efficiency. Dispersants are usually used along with slurry pH adjustment for this purpose. Common dispersants used are sodium silicate, sodium hexametaphosphate, tannic acid, lignosulfonates, and sodium fluorosilicate. Dispersants can be added in either grinding mills during size reduction or mixing tanks. (2) *Selective Hydrophobization* is achieved by adding special collectors to selectively render particular mineral particles hydrophobic upon their adsorption, which is not unfamiliar to flotation scientists and engineers. Also, particle hydrophobicity can be enhanced by non-polar oil due to its spreading on hydrophobic surfaces. For the mineral particles being hydrophobic in nature, this stage could be omitted. (3) *Hydrophobic Flocculation* is usually performed in a

mechanical mixing tank, through which kinetic energy is provided mechanically to hydrophobic particles to collide each other and surmount energy barrier between them due to electric double layer repulsion and water films. In this stage, hydrophobic flocs form as a result of hydrophobic interaction between particles and kinetic energy input. The size and density of hydrophobic flocs depend on particle hydrophobicity and non-polar oil addition. In general, hydrophobic flocs are much more compact than the aggregates formed due to electrolytic coagulation and polymer flocculation.

Figure 1 schematically represents hydrophobic flocculation of fine particles in an aqueous suspension, in which the block arrows represent the three stages of hydrophobic flocculation mentioned above. Hydrophobic flocs vary in size, structure and properties with the involvement of special matters and force fields in the stage of hydrophobic flocculation, which is described as follows: (1) *Shear Flocculation* happens to hydrophobic particles when sufficient kinetic energy is provided mechanically. Such a flocculation could not be very powerful except for the particles with high hydrophobicity (for example, non-polar matters). It seems to not be suitable for the purpose of fine mineral processing because of small flocs and the requirement for high power consumption. Although shear flocculation flotation was early presented for fine mineral beneficiation, it is still only marginally economic as a potential mean. (2) With a small amount of non-polar oil, *Hydrophobic Flocculation* is greatly enhanced. This enhancement not only increases aggregation degree, but also incurs flocs more compact. Also, this enhancement does not bring the decrease of selectivity, and is readily realized in practice. From the point of view of economic benefits, hydrophobic flocculation enhanced by non-polar oil is the best choice because of low costs of operation and installation. Accordingly, we defined standard hydrophobic flocculation to the phenomenon that hydrophobic particles aggregate due to sufficient kinetic energy input and non-polar oil addition. Shear flocculation is regarded as a special case of hydrophobic flocculation. (3) Hydrophobic flocs appear in the form of pellets if their pores are filled up by non-polar oil. Such a phenomenon is called *oil agglomeration*, which requires a large amount of non-polar oil addition. Oil agglomerates are usually very big in size and behave real solid particles. (4) Micro-bubbles of air could be involved into hydrophobic flocs, forming *air flocs* of hydrophobic particles (Wheelock, et al, 1994). As air bubble surfaces are strongly hydrophobic, hydrophobic flocculation could be greatly enhanced due to the involvement of air bubbles. Obviously, such kind of floc could be recovered only with froth flotation. (5) Fine particles could adhere on coarse particle surfaces due to hydrophobic flocculation, forming *Carrier Flocs*. It has been found that collision rate is over 1000 folds larger between coarse particle and fine particle than between fine particles themselves (Samekin, 1968). Thus, coarse hydrophobic particles can strongly increase hydrophobic flocculation of fine particles. Carriers or coarse particles could be either the same matter as fine particles or different matters. (6) Ferromagnetic particles, no matter fine or coarse particles, could enter into hydrophobic flocs if they are pretreated to be strongly hydrophobic, increasing the magnetic susceptibility of the flocs. The degree of the increase depends on the magnetic property of ferromagnetic matter and the content in flocs. (7) For

paramagnetic particles, the hydrophobic flocculation can be enhanced by conditioning suspension in an external magnetic field. This phenomenon is called *Simultaneous Hydrophobic and Magnetic Flocculation* (Song and Lu, 1996). In this case, between particles exists not only hydrophobic attraction, but also magnetic attraction, leading to a powerful floc strength. (8) The foregoing factors of enhancing hydrophobic flocculation can be appeared simultaneously. For instance, air bubbles could be introduced into a system of hydrophobic flocculation in the presence of non-polar oil; and simultaneous hydrophobic and magnetic flocculation can be further enhanced by adding ferromagnetic particles.

Separation method of hydrophobic flocs from dispersed particles should be chosen according to the properties of the flocs, including size, density, and magnetic property, etc., which is summarized as follows: (1) *Froth Flotation* is a common way for recovering hydrophobic flocs because of their hydrophobic surfaces, unless those being too large to be floated. Experimental results (Song and Lu, 1990) showed that hydrophobic flocs behave similar manner in froth flotation as real solid particles with the same size range. Thus, flotation cells and columns can apply to hydrophobic flocs without any modification. (2) *Magnetic Separation* is a good choice for hydrophobic flocs with a high magnetic susceptibility. These flocs are composed either by fine paramagnetic minerals such as hematite, siderite and rhodochrosite, or with ferromagnetic particles involved (magnetic seed flocs). (3) *Screening* is only used for big and compact flocs such as oil agglomerates. The flocs are supposed to sustain very strong floc-rupture forces and keep their shapes on screens. (4) *Sedimentation*, in principle, could be applied to all kinds of hydrophobic flocs, but air flocs. However, it makes much lower separation efficiency than the foregoing three methods. It is recommended to be used for the case that density difference between valuable minerals and gangues is huge.

### III. APPLICATION IN FINE MINERAL AND COAL PROCESSING

#### 1. Beneficiation of Donganshan Hematite Ore

Donganshan hematite deposit locates in Anshan, Liaoning province, China, and is a typical iron ore with rich silica (55% SiO<sub>2</sub>) and poor iron (30% Fe). Also, part of hematite is finely disseminated with silica. The concentration plant runs in froth flotation, producing a concentrate assaying 60% Fe with recovery of 60%. The majority of the iron loss is found in the form of fine particles and locked particles. Hydrophobic flocculation technology was tested on this hematite ore. The ore sample was finely ground to 81% minus 10 μm in size. After slurry dispersing with water glass as dispersant, hematite fines were subjected to hydrophobic flocculation induced by sodium oleate and a small amount of kerosene. Then, the slurry was treated with one-step desliming, leaving the overflows as final tailings (this pretreatment was used because the head ore was too poor on iron content). The sediments past a high-intensity magnetic separator,

obtaining a magnetic product as concentrate and a non-magnetic product as middling. Hematite flocs were recovered in the magnetic product. This process is called hydrophobic flocculation magnetic separation (HFMS). Table 1 gives the beneficiation results of Donganshan hematite ore processed by the HFMS process, in which the test conditions were attached. An iron concentrate assaying 65.7% Fe was produced with recovery of 76.6%. If concentrate grade decreased to 62.7% Fe, the recovery could reach 87%. Obviously, hydrophobic flocculation technology is a very effective method for the beneficiation of the finely disseminated hematite ores. It is noted that from the point of view of economic benefits, for Donganshan hematite ore, hydrophobic flocculation technology should be used to treat flotation middling or tailings instead of head ore. See reference (Song, 1993) for the details.

## 2. Separation of Rhodochrosite and Quartz Artificial Mixture

Hydrophobic flocculation technology was tested on the separation of fine rhodochrosite (volumetric mean diameter  $d_{50}=1.7 \mu\text{m}$ ) from fine quartz ( $d_{50}=5.5 \mu\text{m}$ ) in an artificial mixture. After dispersed with sodium hexametaphosphate as dispersant, the suspension of the mixture was strongly conditioned for a given period in an external magnetic field while sodium oleate and kerosene emulsion were added, in which rhodochrosite fines were simultaneously subjected to hydrophobic and magnetic flocculation. After that, one-step desliming was used to separate the flocs from dispersed particles. Through this procedure, a concentrate containing 83% rhodochrosite was obtained with the recovery of 86%, as shown in Table 2. Considering that it is hard to separate rhodochrosite from quartz and the rhodochrosite sample was that small in size, the simultaneous hydrophobic and magnetic flocculation-desliming process achieved a satisfactory separation result.

## 3. Preparation of Ultra-clean Coal from Bayi Bituminous

Hydrophobic flocculation flotation (or floc flotation) was tested on Bayi bituminous from Shandong province of China for producing an ultra-clean coal with less than 1% ash remaining that is used for the preparation of an ultra-clean coal water slurry as a substitute for diesel oil used in internal combustion engines. The coal sample was the flotation concentrate of the Bayi coal cleaning plant, having 11.86% ash remaining. It was first finely ground to the volumetric mean diameter ( $d_{50}$ ) of  $4.2 \mu\text{m}$  with a ball mill while 1.0 kg/ton tannic acid was added as dispersant. Then, the slurry was strongly conditioned at the stirring speed of 1800 rpm for 40 minutes with 20 kg/ton kerosene. After that, the slurry was transferred to a flotation cell for recovering the hydrophobic flocs. Through one-step rougher and two-step cleaner flotation, an ultra-clean coal assaying 0.6% ash was produced with 65.5% Btu recovery. See the details of the beneficiation results in Table 3. A clean coal with that low ash remaining is very hard to be produced by other physical cleaning techniques, but chemical processing methods.

#### 4. Upgrading of Tangshan Coke Coal

Tangshan coke coal is one of main resources to produce metallurgical coke in China. The coal washing plant is located in Tangshan, Hebei province of China, in which conventional flotation currently runs to clean coal fines. The flotation concentrate, i.e. clean coal, assays 14.5~17.8% ash remaining with 88~94% Btu recovery. Because of high ash remaining, the clean coal can not be utilized for making metallurgical coke but steam coal, leading to large losses on economic benefits. Hydrophobic flocculation flotation was tried to upgrade the coal fines in our laboratory. The head coal for this experiment was from the jiggling tailings of the plant, which was 100% minus 100 meshes in size and with 23% ash remaining. The slurry was first treated with 2 kg/ton sodium silicate to disperse mineral particles, and then was subjected to an intensive mechanical stirring (stirring speed of 2000 rpm for 20 minutes) while 1.5 kg/ton kerosene was added. After that, one-step rougher flotation was followed to recover the hydrophobic coal flocs, achieving a satisfactory beneficiation result given in Table 4. The beneficiation result obtained by conventional flotation is also shown in the table for comparison. A clean coal assaying 12.5% ash remaining was produced from the Tangshan coal slimes with 97% Btu recovery through floc flotation. This product was qualified to be raw material for metallurgical coke. In comparison to conventional flotation, hydrophobic flocculation flotation decreased the clean coal 3% ash remaining and increased 1.4% Btu recovery.

### **IV. MAIN PARAMETERS AFFECTING HYDROPHOBIC FLOCCULATION**

There are many parameters affecting hydrophobic flocculation, including particle hydrophobicity, non-polar oil addition, suspension stirring, particle surface charge, surfactant adsorption layer, original particle size, temperature, coarse particles, air bubble involvement, external magnetic field, and magnetic seeds, etc. In general, the main parameters are the first three, which are discussed as follows.

#### 1. Particle Hydrophobicity

Of foremost importance in hydrophobic flocculation is particle hydrophobicity. This character can be made clearer by the experimental results on rhodochrosite fines given in Figure 2. The rhodochrosite hydrophobicity, expressed in term of contact angle, was adjusted through immersing them in sodium oleate solution with various concentrations. It is noted that no aggregation happened to the fine particles with zero contact angle even though high shear field was applied to the suspension, indicating that hydrophilic particles are impossible to form flocs. In the presence of sodium oleate that rendered the particles to be hydrophobic (contact angles of 33° to 51°), however, the fine particles strongly aggregated by means of suspension stirring. The more hydrophobic the particles, the more powerful is the hydrophobic flocculation generated. The same principle applies to the hydrophobic flocculation of coal fines, as shown in Figure 3. The coal sample had a much

greater contact angle being fresh than being oxidized at 170 °C. It shows that the fresh coal fines strongly aggregated through a wide range of suspension pH, whereas the oxidized coal fines generated a much weaker flocculation only in a narrow pH range.

Hydrophobic interaction is an unusually strong attraction between hydrophobic particles in aqueous solution, which arises from the rearrangements of hydrogen bond configurations in the overlapping solvation zones as two hydrophobic species come together (Israelachvili, 1992). Direct measurements showed that hydrophobic force is one or two orders of magnitude larger than the DLVO forces in some range of particle separation (Parker, et al, 1993; Pashley, et al, 1985), suggesting that hydrophobic attraction is a dominant factor for interaction between hydrophobic particles in aqueous solution. Because hydrophobic attraction closely depends on particle hydrophobicity (Rabinovich and Derjaguin, 1988), one can expect that hydrophobic flocculation is dominated by the hydrophobicity of particles to be aggregated.

The importance of particle hydrophobicity to hydrophobic flocculation is also observed from the effect of sodium oleate addition on the beneficiation of Donganshan hematite ore with hydrophobic flocculation magnetic separation, given in Figure 4. The results were from one-step magnetic separation without desliming pretreatment. As is well known, hematite hydrophobicity increases as sodium oleate addition in the range of the tests. Thus, we could regard the X axe as particle hydrophobicity. It is noted from this graph that the beneficiation was poor at weak particle hydrophobicity (small sodium oleate addition). As the increase of sodium oleate addition, the concentrate assaying Fe sharply increased until reached a peak, followed by a decline, while recovery also increased. The increase on recovery was very strong in the range of low sodium oleate addition and became mild after a critical point. These increases are certainly resulted from the enhancement of hydrophobic flocculation of hematite fines due to the increase of particle hydrophobicity.

## 2. Non-polar Oil Addition

Non-polar oil such as kerosene, diesel and other fuel oil, was early found to greatly enhance hydrophobic flocculation. The mechanism of this effect is briefly described as follows: (1) *Particle Hydrophobicity Increase*. Non-polar oil droplets in aqueous suspension spread on hydrophobic particle surfaces due to strong hydrophobic attraction between them, producing oil coverage on the particles and thus increasing the particle hydrophobicity. This increase would enhance hydrophobic flocculation of the particles. (2) *Oil Bridge*. Oil involved in hydrophobic flocs is just like a bridge connecting hydrophobic particles. Because of oil bridge, hydrophobic flocs become much stronger to sustain floc-rupture forces from turbulent, leading a much more powerful flocculation (Song, et al, 1999).

Non-polar oil enhancement of hydrophobic flocculation can be observed from the experimental results on rhodochrosite particles rendered hydrophobic by sodium oleate, given in Figure 5. It can be seen from this graph that in the presence of kerosene, as the increase of stirring time, the flocculation degree sharply increased, followed by a plateau. Without kerosene, however, the flocculation degree quickly reached a peak, followed by a decline until reaching an equilibrium value. The flocculation degree was much larger in the presence of kerosene than in the absence of kerosene. This enhancement might be originated from the increase of floc strength due to kerosene addition.

The effect of kerosene addition on the beneficiation of Bayi bituminous with hydrophobic flocculation flotation is illustrated in Figure 6. It shows that the Btu recovery increased dramatically with kerosene addition in the low range. After a critical point of kerosene addition (around 20 kg/ton), any further increase of Btu recovery became minimal. The ash remaining of clean coal decreased as kerosene addition until reached a valley, followed by a rising that might be resulted from the entrainment of mineral fines because flocs became larger. Obviously, kerosene addition brought hydrophobic flocculation flotation much higher separation efficiency for fine coal cleaning.

### 3. Suspension stirring

Suspension stirring of sufficient magnitude is necessary to provide mechanically hydrophobic particles kinetic energy for generating a good hydrophobic flocculation, which is made clearer from the experimental results on galena fines rendered hydrophobic by amyl xanthate adsorption, given in Figure 7. The flocculation degree is represented by the volumetric mean diameters of flocs that were determined by laser diffraction size analyzer. It is noted that as the increase of stirring speed, the floc size dramatically increased until reached a peak around the stirring speed of 900 rpm, followed by a sharp decline. The flocs size was two folds larger at the peak than at the stirring speed of 300 rpm. The decline of floc size in the range of high stirring speed is due to strong floc-rupture forces that is greater than the floc strength. Figure 2 also shows the importance of suspension stirring effect for hydrophobic flocculation. It can be seen that the aggregation efficiency of rhodochrosite fines due to hydrophobic flocculation sharply increased as stirring time, until reached a plateau. The plateau value depended on particle hydrophobicity.

## **V. SUMMARY**

In the present paper numerous methods of fine mineral processing such as emulsion flotation, carrier flotation, oil agglomeration, shear flocculation flotation and magnetic seeding separation, etc., have been integrated into hydrophobic flocculation technology because all of them are based on hydrophobic flocculation of fine particles in aqueous suspension. In general, this technology is consisted of

four sub-processes, namely dispersion, selective hydrophobization, hydrophobic flocculation and separation of flocs from dispersed particles. The centerpiece is hydrophobic flocculation, in which hydrophobic particles aggregate due to kinetic energy of sufficient magnitude and a small amount of non-polar oil. Hydrophobic flocculation could be enhanced by various factors such as air bubbles, carrier particles, external magnetic field, and ferromagnetic particles, etc.

Not only froth flotation, but also other standard separation methods could be applied for the recovery of hydrophobic flocs from dispersed particles, which has been proved by the experimental results presented in this paper. For the hydrophobic flocs with a high magnetic susceptibility, magnetic separation is a better choice. The experimental results suggest that separation technology based on hydrophobic flocculation is an effective mean to recover valuable minerals in fine size range and to deeply remove finely disseminated impurities from coal.

Particle hydrophobicity, non-polar oil addition and kinetic energy input strongly influence hydrophobic flocculation and the separation technology. Great attentions must be paid to these factors when this technology is applied to fine mineral and coal processing. High power consumption due to suspension stirring is a main disadvantage for hydrophobic flocculation technology, which should be overcome by further works.

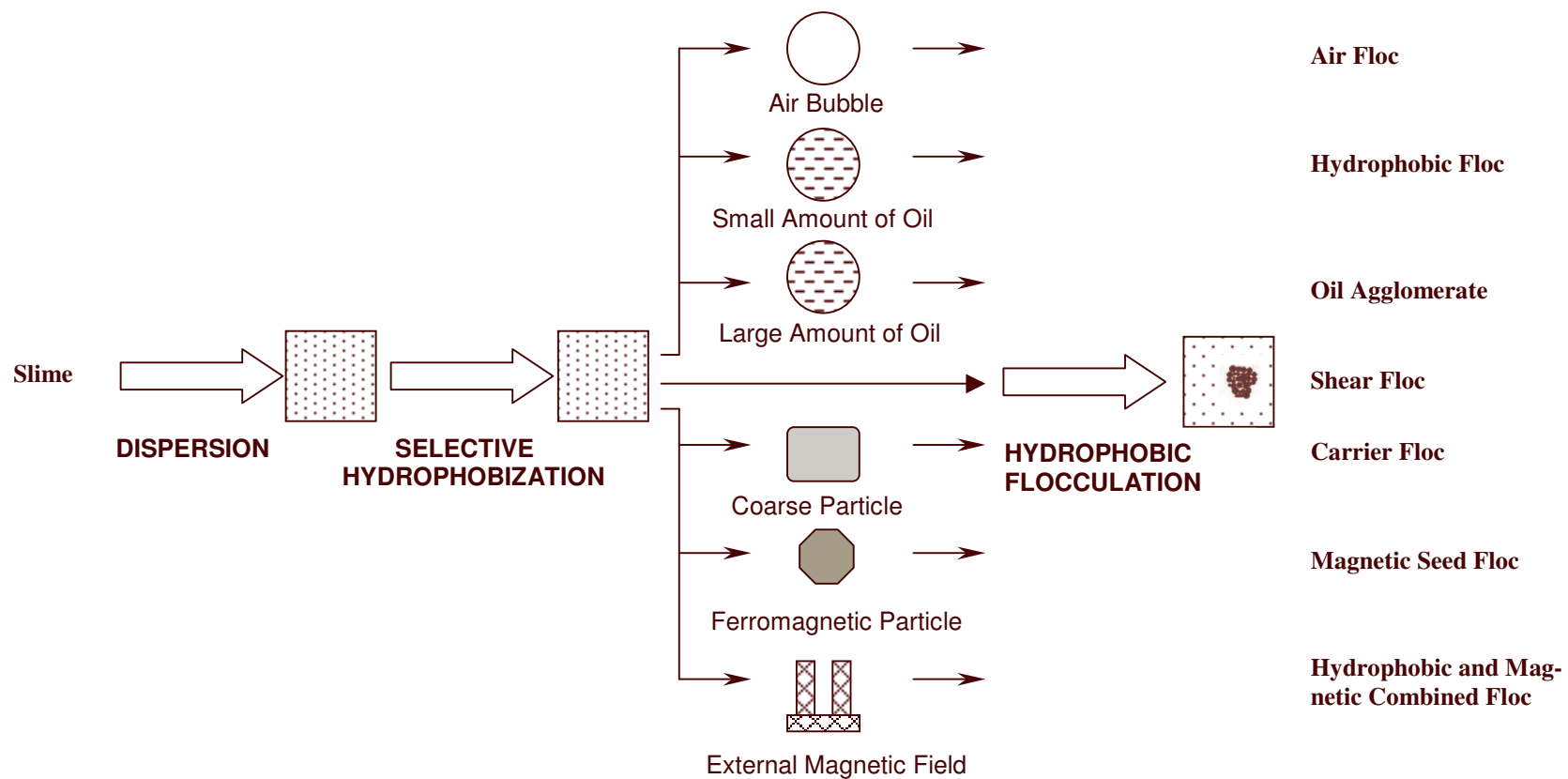
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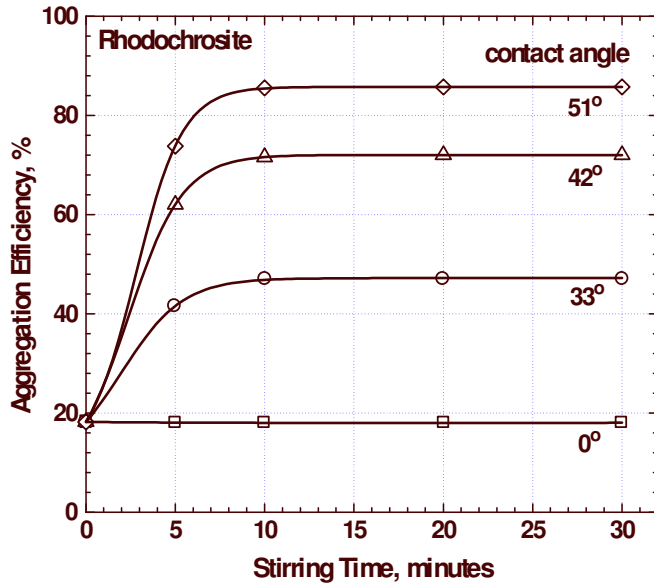
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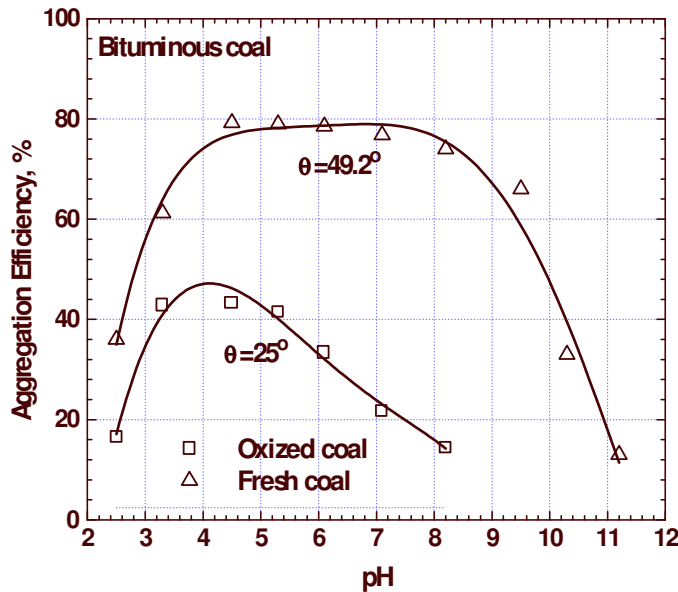
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**FIGURE 1.** Schematic representation of hydrophobic flocculation of fine particles



**FIGURE 2.** Effect of suspension stirring time on the hydrophobic flocculation of rhodochrosite fines (volumetric mean diameter  $d_{50}=1.79 \mu\text{m}$ ) rendered hydrophobic by sodium oleate under different particle hydrophobicity (noted in the graph for each curve) (Song and Lu, 1994). Other test conditions: pH=7.8, suspension stirring speed 1480 rpm.



**FIGURE 3.** Hydrophobic flocculation of bituminous coal fines being fresh (contact angle  $\theta=49.2^\circ$ ) and oxidized at  $170^\circ\text{C}$  ( $\theta=25^\circ$ ) as a functions of suspension pH. Other test conditions: suspension stirring with 1000 rpm for 30 minutes

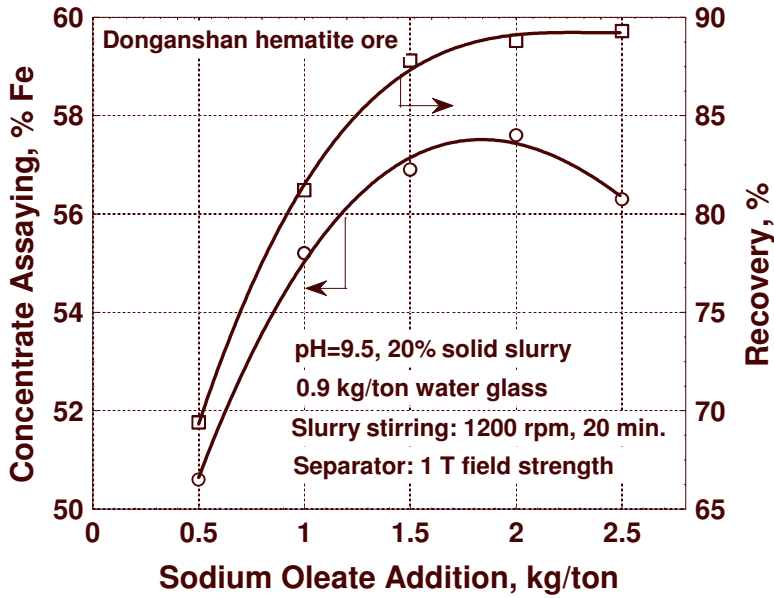


FIGURE 4. Effect of sodium oleate addition on the beneficiation of Donganshan hematite ore (81% minus 10  $\mu\text{m}$  in size) using hydrophobic flocculation magnetic separation

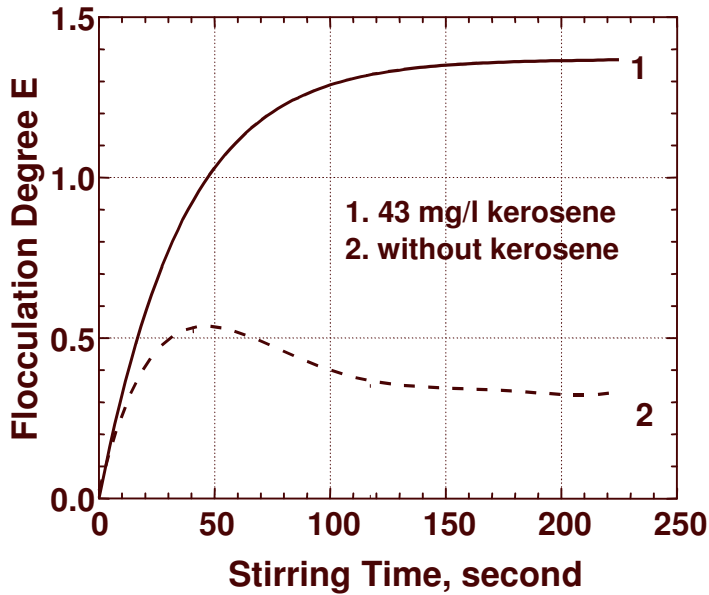


FIGURE 5. Kinetics on hydrophobic flocculation of rhodochrosite (5–10  $\mu\text{m}$ ) fines rendered hydrophobic by sodium oleate in the absence or presence of kerosene. Other test conditions: pH=7.8,  $3 \times 10^{-5}$  mol/l sodium oleate (Song, et al, 1999).

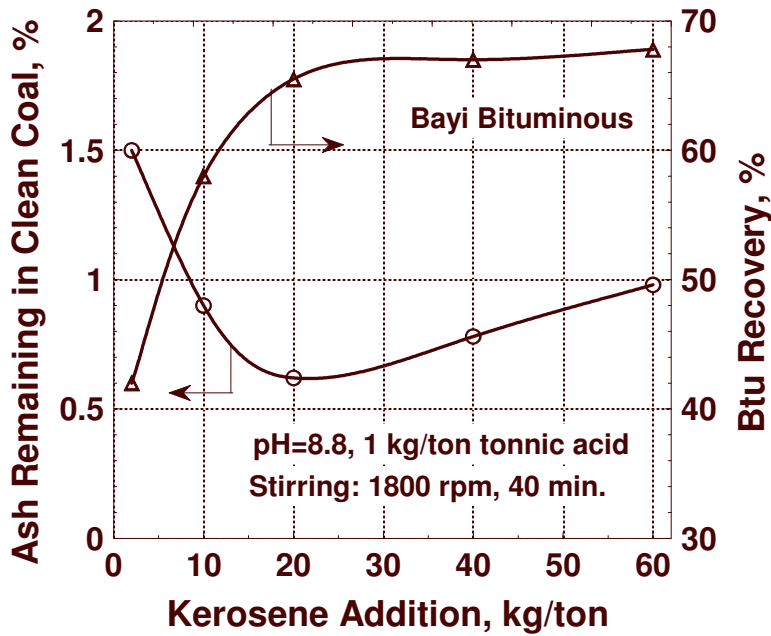


FIGURE 6. Effect of kerosene addition on the ash removal from Bayi bituminous ( $d_{50}=4.18 \mu\text{m}$ ) with hydrophobic flocculation flotation (through rougher and two-step cleaner flotation)(Song and Lopez-Valdivieso, 1998)

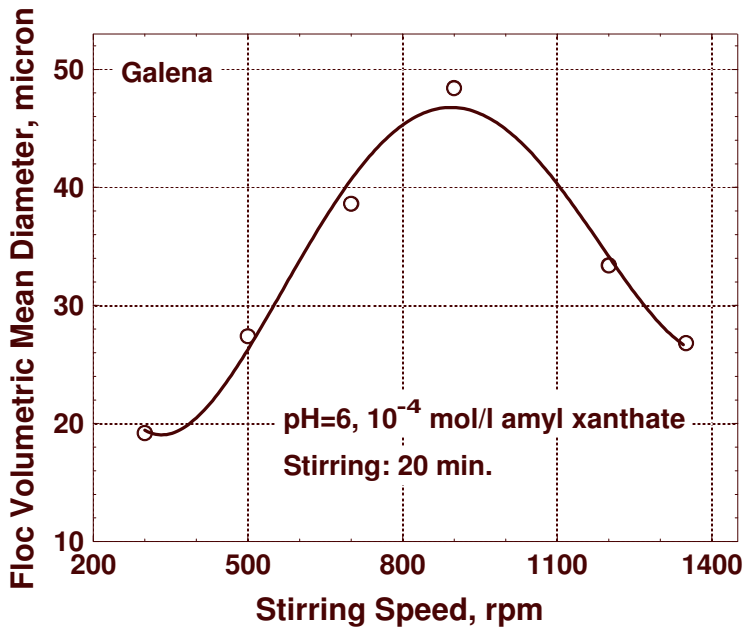


FIGURE 7. Effect of stirring speed for suspension stirring in hydrophobic flocculation step on the floc size of galena fines ( $d_{50}=5.6 \mu\text{m}$ ) induced by amyl xanthate

TABLE 1. The beneficiation results of Donganshan hematite ore processed by hydrophobic floc magnetic separation (HFMS)

Test No.		Head	Concentrate	Middling	Tailings
E-72	% wt	100.00	35.97	15.49	49.04
	Fe assaying, %	30.85	65.71	24.88	6.58
	Fe recovery, %	100.00	76.63	12.90	10.47
E-67	% wt	100.00	42.33	11.74	45.93
	Fe assaying, %	30.41	62.70	9.60	6.00
	Fe recovery, %	100.00	87.27	3.69	9.04

Test Conditions:

No. E-72: pH=9.5; 20% solid slurry; 0.9 kg/ton water glass; 1 kg/ton sodium oleate; 2.5 kg/ton kerosene; 1200 rpm slurry stirring for 20 minutes in hydrophobic flocculation step; 1 T field strength for high-intensity magnetic separator

No. E-67: pH=9.5; 20% solid slurry; 0.7 kg/ton water glass; 1.5 kg/ton sodium oleate; 2.5 kg/ton kerosene; 1200 rpm slurry stirring for 20 minutes in hydrophobic flocculation step; 1 T field strength for high-intensity magnetic separator

TABLE 2. The separation results rhodochrosite and quartz artificial mixture processed by simultaneous hydrophobic and magnetic flocculation-desliming

	% wt	Grade, % MnCO <sub>3</sub>	Recovery, % MnCO <sub>3</sub>
Head	100.00	50.00	100.00
Concentrate	51.78	82.89	85.85
Tailings	48.22	14.67	14.15

Test Conditions: pH=8.8; 2% solid slurry; 6 mg/l sodium hexametaphosphate as dispersant; 10 mg/l sodium oleate; 20 mg/l kerosene; 1000 rpm slurry stirring for 5 minutes in flocculation step; 0.92 T field strength for external magnetic field

TABLE 3. The beneficiation results of Bayi bituminous for the preparation of ultra-clean coal with hydrophobic flocculation flotation

Products	Head Coal	Clean Coal	Middling I	Middling II	Tailings
% wt	100.00	58.02	6.46	10.14	25.38
Ash content, %	11.86	0.62	4.42	15.42	38.04
Btu recovery, %	100.00	65.42	7.01	9.73	17.84
Ash rejection, %		96.97			

Test Conditions: pH=8.8; 20% solid slurry; 1 kg/ton tannic acid as dispersant; 20 kg/ton kerosene; 1800 rpm slurry stirring for 15 minutes in flocculation step

TABLE 4. The beneficiation results of Tangshan coke coal with hydrophobic flocculation flotation, in comparison to conventional flotation

Products	Hydrophobic flocculation flotation			Conventional flotation		
	% wt	% Ash	Btu recovery %	% wt	% Ash	Btu recovery %
Head coal	100.0	22.94	100.0	100.0	23.18	100.0
Clean coal	86.58	12.52	97.03	87.97	15.43	95.60
Tailings	13.42	89.50	2.97	12.03	78.64	4.40

Test Conditions: pH=8.2; 15% solid slurry; 2 kg/ton sodium silicate as dispersant; 1.5 kg/ton kerosene; 2000 rpm slurry stirring for 20 minutes in flocculation step