Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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To cite this Article Song, Shaoxian and Valdivieso, Alejandro Lopez(1998) 'Hydrophobic Flocculation Flotation for Beneficiating Fine Coal and Minerals', Separation Science and Technology, 33: 8, 1195 — 1212

To link to this Article: DOI: 10.1080/01496399808545249

URL: http://dx.doi.org/10.1080/01496399808545249

SEPARATION SCIENCE AND TECHNOLOGY, 33(8), pp. 1195–1212, 1998

Hydrophobic Flocculation Flotation for Beneficiating Fine Coal and Minerals

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ABSTRACT

It is shown that hydrophobic flocculation flotation (HFF) is an effective process to treat finely ground ores and slimes so as to concentrate coal and mineral values at a fine size range. The process is based on first dispersing the fine particles suspension, followed by flocculation of fine mineral values or coal in the form of hydrophobic surfaces either induced by specifically adsorbed surfactants or from nature at the conditioning of the slurry with the shear field of sufficient magnitude. The flocculation is intensified by the addition of a small amount of nonpolar oil. Finely ground coals, ilmenite slimes, and gold finely disseminated in a slag have been treated by this process. Results are presented indicating that cleaned coal with low ash and sulfur remaining and high Btu recovery can be obtained, and the refractory ores of ilmenite slimes and fine gold-bearing slag can be reasonably concentrated, leading to better beneficiation results than other separation techniques. In addition, the main operating parameters affecting the HFF process are discussed.

Key Words. Hydrophobic flocculation; Hydrophobicity; Nonpolar oil; Kinetic energy input; Fine minerals; Fine coal; Flotation

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INTRODUCTION

Mineral and coal industries worldwide need to process finely mineralized ores and recover mineral values from slimes. In these two cases an economically designed process should recover virtually all the mineral values at a fine size range. Desired minerals in the first instance, occur almost entirely in the fine size range, whereas slimes often interfere with the concentration of coarser particles and may simply be removed and discarded while still containing minerals of value.

Because of the losses of mineral values and the need to process particles in the fine size range, there is interest in devising new processes and in improving the existing processes for the recovery of fine particles. Flotation, which is the most common process used to beneficiate ores, is not very effective in processing fine particles in the size range below 10 μm. This is due to the low flotation rate constant for these particles which affects their flotation kinetics. The dependence of the flotation rate constant with particle size is given by (1)

$$k \propto d_p^n$$

where k is the flotation rate constant, d_p is the particle size, and n is a constant, $1.5 < n < 2$. Accordingly, it is expected that by selectively aggregating fine particles, their flotation rate constant and flotation kinetics should improve.

In the 1930s it was reported that there is a direct relationship between the recovery and flocculation of fine particles (2, 3). Fuerstenau et al. (4) indicated that there is a broad spectrum of separation methods based on surface activity and wettability which can be applied to concentrate fine particles: selective flocculation followed by sedimentation, oil agglomeration followed by screening, and carrier flotation. Green and Duke (5) applied the concept of selectively aggregating minerals to remove fine anatase from kaolin in order to improve the quality of kaolin. Carrier flotation was used in which fine anatase selectively aggregates with coarse calcite by using sodium oleate, followed by flotation of calcite. This process was first commercially used in the purification of kaolin at Minerals and Chemicals Phillipp's plant at McIntrye, Georgia, USA (6). It has also been proposed to process fine sulfide minerals, hematite, and cassiterite (7, 8).

Warren (9, 10) reported that flotation of fine scheelite −5 μm in size was improved by conditioning the ore slurry at a high shear rate with sodium oleate. Further studies carried out by Koh et al. (11) showed that fine scheelite flocculates to form flocs 20–30 μm in size. The process in which fine particles form flocs through a high shear rate in conditioning is now known as shear flocculation. It has been reported to work well in processing not only fine scheelite (12) but also fine rhodochrosite, sulfide, and malachite (13–15).

Such a flocculation was later related to hydrophobicity. Warren (16) indicated that shear flocculation is affected mainly by shear rate in conditioning and the degree of hydrophobization of the particles. Lu et al. (17, 18) showed that flocculation of fine particles depends on hydrophobicity. They found that the greater the contact angle, the larger the degree of flocculation. Chia and Somasundaran (19) carried out a detailed study on the carrier flotation of anatase on calcite with sodium oleate. They reported that the surfactant layer and the electrical charge at the solid/water interface of both the fine and coarse particles determine whether the fine particles coat the coarse particles.

In this paper a process, hydrophobic flocculation flotation (HFF), which aims at effectively beneficiating fine coal and minerals is presented. First, the process is briefly described. Second, several examples are given in which the process was applied to beneficiate coals and ores with fine particles, namely coals from China, Canada, and the United States, ilmenite slimes, and gold finely disseminated in a slag from pyrite roasting. Finally, the important parameters of affecting the HFF process are discussed on the basis of the experimental results.

DESCRIPTION OF THE HFF PROCESS

Hydrophobic flocculation flotation (HFF) has been devised to process fine minerals and coals. It is based on the selective flocculation of desired particles which are either naturally hydrophobic or are rendered hydrophobic by the adsorption of specific surfactants with intensive mechanical stirring, strengthened by the addition of a small amount of nonpolar oil. The gangue particles are stabilized by the addition of dispersing reagents which make the gangue surface more hydrophilic. Figure 1 depicts the steps involved in the HFF

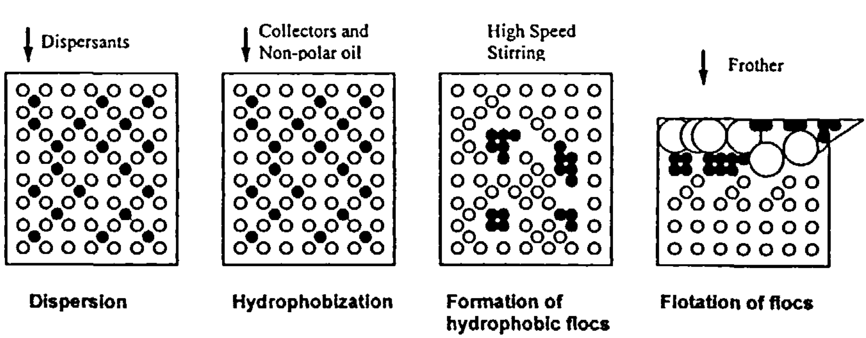

FIG. 1 Schematic representation of the hydrophobic flocculation flotation (HFF) process to treat fine particles.

process: dispersion, selective hydrophobization, hydrophobic flocculation, and flotation of flocs.

Dispersion. This step is needed to stabilize the fine particles to prevent their heterocoagulation which would have a detrimental effect on the separation efficiency. Dispersants must specifically adsorb on the gangue surface to render it more hydrophilic. It is recommended that dispersants be added during grinding when fine particles are produced. Common dispersants used are sodium silicate, sodium hexametaphosphate, sodium fluorosilicate, sodium tripolyphosphate, tannic acid, and lignosulfonates.

Hydrophobization. Following the dispersion stage, specifically adsorbed surfactants are added to the system so as to render specialized minerals hydrophobic, except for naturally hydrophobic particles. The hydrophobicity is enhanced through the addition of nonpolar oil, which spreads on the surface of the hydrophobic particles. Oil consumption is about 0.2 to 1.5% on a dry feed basis. The selection of the surfactant is based on the nature of the polar group of the surfactant as well as on the chemical and electrical characteristics of the surface of the desired minerals. For example, in sulfide minerals the typical surfactants used are those having a sulfhydryl group in their structure, namely mercaptans, xanthates, dithiophosphates, and carbamates.

Hydrophobic Flocculation. This stage consists in conditioning the fine particles at a high shear rate (high stirring speed and long time). Fine hydrophobic particles aggregate in this stage due to hydrophobic interaction and mechanical energy input of sufficient magnitude. The hydrophobic flocculation operation is generally performed in mixing tanks. Although new techniques need to be developed to minimize the energy consumption in this stage. Song and Trass (20) reported a new approach which involves carrying out hydrophobic flocculation while the fine particles are being produced in a centrifugal mill.

Flotation of Flocs. This last stage concentrates the hydrophobic flocs to a froth with the assistance of air bubbles. The froth is then removed from the system and used to produce a concentrate as in the usual flotation process.

The success of the HFF process depends on the selective hydrophobic flocculation of the desired fines, and thus on the interactive effects among the main parameters in the hydrophobic flocculation system: hydrophobicity of particles, high shear mixing, and nonpolar oil, as shown in Fig. 2.

The basis of hydrophobic flocculation is the degree of hydrophobization of the particles to be aggregated, from which the hydrophobic interaction between the surfaces in an aqueous solution originates. The more hydrophobic the particle surfaces, the stronger the hydrophobic attraction between the particles. Direct measurements (21–24) and calculation (25) showed that the hydrophobic attractive force between surfaces with a contact angle of over

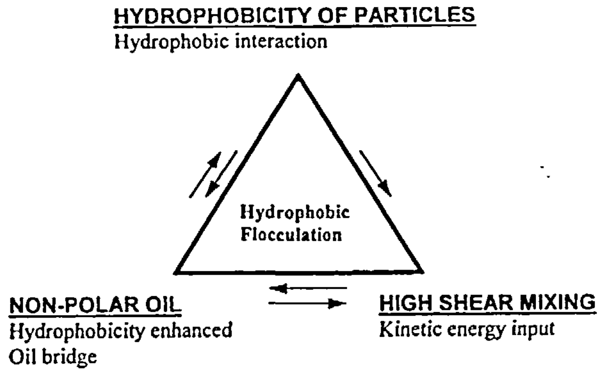

FIG. 2 The three main parameters in the hydrophobic flocculation system.

70° is one or two orders of magnitude larger than an electrical double layer and van der Waals forces in the same range of separation.

The role of nonpolar oil in the system is to intensify the hydrophobic flocculation of fine particles by spreading on the hydrophobic surfaces and thus creating a bridge between these particles. The former gives rise to more hydrophobic surfaces and the latter enhances the ability of flocs to withstand disrupting forces (26, 27).

A high shear mixing suspension supplies kinetic energy to hydrophobic particles to surmount the potential energy barrier between them due to electrical double layer repulsion and the water films. In addition, it is helpful to squeeze flocs to minimize the empty space, i.e., make the flocs more compact.

EXPERIMENTAL

Materials

The work presented here was carried out on numerous coals, ilmenite slimes, and fine gold-bearing slag. The five coal samples were obtained from: 1) the Shenmu coal mine in the Shannxi Province of China (a bituminous coal), 2) the tailings of a gravity concentration process at the Taixi coal mine in the Lingxia Province of China [an anthracite coal and in a fine size range (d_{50} = 19.8 μm)], 3) the Prince coal mine in Nova Scotia, Canada, (a bituminous coal), 4) the Ontario Hydro, Canada (a bituminous coal from Pittsburgh), and 5) the flotation process at the Baiyi coal mine in the Shandong Province of China (a bituminous coal). The ash, pyritic sulfur, organic sulfur, and total sulfur in each of the coal samples are listed in Table 1.

TABLE 1
The Characteristics of the Coal Samples

Sample	% Ash	% Pyritic sulfur	% Organic sulfur	% Total sulfur
Shenmu coal	5.48			0.253
Taixi coal	16.65			
Prince coal	13.94	1.43	1.33	3.32
Pittsburgh coal	7.80	0.09	0.85	1.61
Baiyi coal	11.86			0.788

The ilmenite ore sample was from the slime (−40 μm) classification stage of the Panznihua titanium mine in Sichun Province of China; it assays 9.84% TiO_2. Many attempts have been made to recover ilmenite from the slime, but no one has produced a concentrate of 45% TiO_2 grade with over 30% recovery. The slime is currently taken as tailings in the mine, resulting in a large titanium loss.

The gold ore sample was from the roast-slag of pyrite of the Yongjishan mine in Jiangxi Province of China, in which the gold of −1 μm in size is disseminated in copper oxide and assays 2.9 g/ton Au. Cyanide pulp leaching and other techniques failed to yield a reasonable gold concentrate grade and recovery from this roast-slag.

Equipment

A laboratory ceramic and steel ball mill and an SM160 model Szego mill were used to fine grind in this study. The mixing tanks used for hydrophobic flocculation were 1 L in volume, equipped with four baffles, and had mixing heads which could rotate from 100 to 3000 rpm. Laboratory flotation cells of 1 L capacity were used for rougher flotation, and those of 0.5 L capacity were used for clean flotation. The particle size was determined by using either a Microtrac laser particle size analyzer or by sieving.

Procedure

The research was carried out in laboratory scale of batch tests. The dry feed coal or ore was first finely ground in running water for the liberation of the minerals in a ceramic ball mill for the Shenmu coal and the Baiyi coal with the addition of sodium hexametaphosphate and tannic acid as the dispersant, respectively, in a Szego mill for the Prince coal and the Pittsburgh coal, and in a steel ball mill for the gold-bearing slag. The Taixi anthracite and the ilmenite slimes were not passed through a grinding stage since they were already in the fine size range, so dispersion of the ilmenite slime slurry was performed in the mixing tank with the addition of sodium fluorosilicate. Then the slurries (of 20 and 40% solid concentration for coals and ores, respectively) were moved to mixing tanks. With the addition of octyl alcohol as collector and kerosene for the Shenmu coal, kerosene for the Baiyi coal and the Taixi anthracite, No. 2 fuel oil for the Prince coal and the Pittsburgh coal, benzyl arsonic acid and kerosene for the ilmenite slimes, and butyl xanthate and kerosene for the gold-bearing slag, the slurries were strongly stirred at a given speed and duration to form hydrophobic flocs of the desired materials. After that, the flotation step was carried out in a laboratory flotation cell with 10, 25, and 30% solid slurry for the coals, the ilmenite slimes, and the gold-bearing slag, respectively, to recover the flocs. The rougher flotation time was 4 minutes and the rougher concentrate was cleaned without reagents for 2 minutes.

Reagents

The dispersants (sodium hexametaphosphate, tannic acid, and sodium fluorosilicate), the activator (sodium sulfide), and the collector (octyl alcohol) used in this study were of chemical purity. The collectors (benzyl arsonic acid and butyl xanthate), the nonpolar oils (kerosene and No. 2 fuel oil), and the frother (ethyl ether alcohol) used in this study were commercial products.

RESULTS AND DISCUSSIONS

Beneficiation of Fine Coals and Refractory Ores

Shenmu and Baiyi Bituminous Coal

The HFF process was tested on Shenmu coal and Baiyi coal for the production of an ultra-clean coal of less than 1% ash remaining for the preparation of an ultra-clean coal water slurry as a substitute for diesel oil used in internal combustion engines. By optimizing a number of operating variables, ultra-clean coals of 0.73 and 0.6% ash remaining were produced from Shenmu coal and Baiyi coal, respectively, while 85.94 and 65.42% Btu recovery and 89.10 and 97% ash rejection were achieved respectively, as shown in Tables 2 and 3.

Taixi Anthracite Coal

The HFF process indicates that an ultra-clean coal can be produced from Taixi anthracite coal for preparing high quality activated carbon. The product contained 0.8% ash, and 96.6% ash was removed with the Btu recovery of 81.3% as shown in Table 4. The results listed in Table 4 were achieved at the optimum conditions of the operating parameters.

TABLE 2
The Beneficiation Results of Shenmu Bituminous Coal with the HFF Process[a]

	Feed coal	Cleaned coal	Middling coal	Tailings
Weight recovery, %	100.00	81.83	5.38	12.79
Ash content, %	5.48	0.73	7.86	34.87
Btu recovery, %	100.00	85.94	5.24	8.82
Ash rejection, %		89.10		

[a] Test conditions: d_{50} = 3.14 μm, 0.5 kg/ton sodium hexametaphosphate as dispersant, 6 kg/ton octyl alcohol as collector, and 30 kg/ton kerosene at a stirring speed of 1800 rpm for 30 minutes at the flocculation stage, rougher and one-step clean flotation.

TABLE 3
The Beneficiation Results of Baiyi Bituminous Coal with the HFF Process[a]

	Feed coal	Cleaned coal	Middling I	Middling II	Tailings
Weight recovery, %	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			

[a] Test conditions: d_{50} = 4.18 μm, 1.0 kg/ton tannic acid as dispersant, 20 kg/ton kerosene at a stirring speed of 1800 rpm for 40 minutes at the flocculation stage, rougher and two-step clean flotation.

TABLE 4
The Beneficiation Results of Taixi Anthracite Coal with the HFF Process[a]

	Feed coal	Cleaned coal	Middling coal	Tailings
Weight recovery, %	100.00	68.21	5.63	26.16
Ash content, %	16.65	0.82	14.28	58.72
Btu recovery, %	100.00	81.25	5.79	12.96
Ash rejection, %		96.64		

[a] Test conditions: d_{50} = 19.8 μm, 8 kg/ton kerosene at a stirring speed of 1800 rpm for 15 minutes at the flocculation stage, rougher and one-step clean flotation.

TABLE 5
The Results of Ash and Sulfur Removal from Prince Coal Using the HFF Process (%)[a]

	Feed coal	Cleaned coal	Middling IV	Middling III	Middling II	Middling I	Tailings
Weight recovery	100.00	76.30	4.07	2.85	4.07	5.39	7.32
Ash content	13.31	1.28	16.57	30.70	41.74	53.87	84.57
Btu recovery	100.00	86.90	3.91	2.28	2.74	2.87	1.30
Ash rejection		92.66					
Pyritic sulfur content	1.43	0.63					
Inorganic sulfur content	1.99	0.63					
Total sulfur content	3.32	1.90					
Pyritic sulfur rejection		66.39					
Inorganic sulfur rejection		75.85					
Total sulfur rejection		56.33					

[a] Test conditions: 88.3% minus 45 μm, 10 kg/ton No. 2 fuel oil at a stirring speed of 1800 rpm for 15 minutes at the flocculation stage, rougher and four-step clean flotation.

Prince and Pittsburgh Bituminous Coal

The HFF process was applied to treat Prince coal and Pittsburgh coal for ash and pyritic sulfur removal. Using the optimum values of the operating variables, cleaned coals of 1.9 and 0.8% total sulfur content and 1.3 and 1.2% ash remaining were produced from Prince coal and Pittsburgh coal, respectively, as shown in Tables 5 and 6. For Prince coal, 92.7% ash, 66.4% pyrite, 75.9% inorganic sulfur, and 56.3% total sulfur were removed with a

TABLE 6
The Results of Ash and Sulfur Removal from Pittsburgh Coal Using the HFF Process (%)[a]

	Feed coal	Cleaned coal	Middling III	Middling II	Middling I	Tailings
Weight recovery	100.00	79.03	5.67	4.27	4.97	6.06
Ash content	7.69	1.19	14.01	20.09	30.23	59.24
Btu recovery	100.00	84.59	5.28	3.70	3.76	2.67
Ash rejection		87.77				
Inorganic sulfur content	0.76	0.06				
Total sulfur content	1.61	0.80				
Inorganic sulfur rejection		93.76				
Total sulfur rejection		60.73				

[a] Test conditions: 96.1% minus 45 μm, 15 kg/ton No. 2 fuel oil at a stirring speed of 1800 rpm for 20 minutes at the flocculation stage, rougher and three-step clean flotation.

TABLE 7
The Beneficiation Results of Ilmenite Slimes with the HFF Process[a]

	Feed	Concentrate	Middling IV	Middling III	Middling II	Middling I	Tailings
% Weight	100.00	10.86	4.14	4.34	8.27	14.99	57.39
Grade of TiO_2, %	9.84	45.79	32.37	13.90	7.07	4.64	2.87
Recovery of TiO_2, %	100.00	50.52	13.61	6.13	5.94	7.07	16.73

[a] Test conditions: 95.4% minus 40 μm, 4 kg/ton sodium fluorosilicate as dispersant, 4 kg/ton benzyl arsonic acid as collector, and 6 kg/ton kerosene at a stirring speed of 1600 rpm for 17 minutes at the flocculation stage, rougher and four-step clean flotation using 40 g/ton ethyl ether alcohol as frother.

Btu recovery of 86.9%. For Pittsburgh coal, 87.8% ash, 93.8% inorganic sulfur, and 60.7% total sulfur were rejected with a Btu recovery of 84.6%.

Ilmenite Slimes

The HFF process has advantages over other physical concentration techniques for processing ilmenite slimes from the Panzhihua mine, a refractory ore. The ilmenite slimes were treated at optimum values of each of the operating variables, with the results given in Table 7. A concentrate assaying 45.8% TiO_2 was produced with a TiO_2 recovery of 50.5%.

Gold-Bearing Slag

The HFF process was applied to gold-bearing slag, and the results shown in Table 8 were compared to those of conventional flotation. A 27.5 g/ton Au concentrate was produced by conventional flotation with 33.7% Au recovery,

TABLE 8
The Results from the Concentration of the Gold-Bearing Slag with the HFF Process[a]

	Feed	Concentrate	Middling II	Middling I	Tailings
% Weight	100.00	1.22	7.42	17.21	74.15
Grade of Au, g/ton	2.98	126.27	6.18	1.65	0.94
Recovery of Au, %	100.00	51.69	15.39	9.53	23.39

[a] Test conditions: 82.6% minus 20 μm, 0.6 kg/ton sodium sulfide as the activator of copper oxide, 0.4 kg/ton butyl xanthate as collector, and 1 kg/ton kerosene at a stirring speed of 1600 rpm for 20 minutes at the flocculation stage, rougher and two-step clean flotation using 40 g/ton ethyl ether alcohol as frother.

whereas a 126 g/ton Au concentrate was recovered by the HFF process with 51.7% Au recovery. The HFF process clearly provides better results than conventional flotation. The test conditions listed in Table 8 have been optimized.

Main Parameters Affecting the HFF Process

Dispersant Concentration Effect

The effect of Na_2SiF_6 concentration on the beneficiation results of ilmenite slimes with the HFF process is illustrated in Fig. 3. The maximum values of concentrate grade and recovery clearly exist at 4 kg/ton Na_2SiF_6. Too high an Na_2SiF_6 dosage not only prevents the coagulation of fine gauge minerals, and also that of fine ilmenite.

The need for a dispersant also applies to ash removal from Baiyi bituminous with the HFF process, as shown in Fig. 4. It is noted that with increasing tannic acid, the ash remaining decreases until a plateau is reached at 1 kg/ton tannic acid. Btu recovery decreases slightly in the 0 to 1 kg/ton tannic acid range and declines after that.

Collector Concentration Effect

Figure 5 shows the relationship between benzyl arsonic acid dosage and the beneficiation results of ilmenite slimes with the HFF process. It is noted

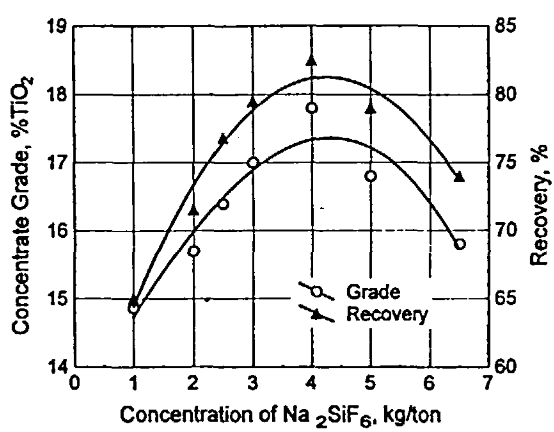

FIG. 3 The effect of Na_2SiF_6 concentration on the beneficiation results of the ilmenite slimes with the HFF process. The other test conditions: 4 kg/ton benzyl arsonic acid as collector and 1600 rpm stirring speed for 15 minutes at the flocculation stage; rougher flotation using 40 g/ton ethyl ether alcohol as frother.

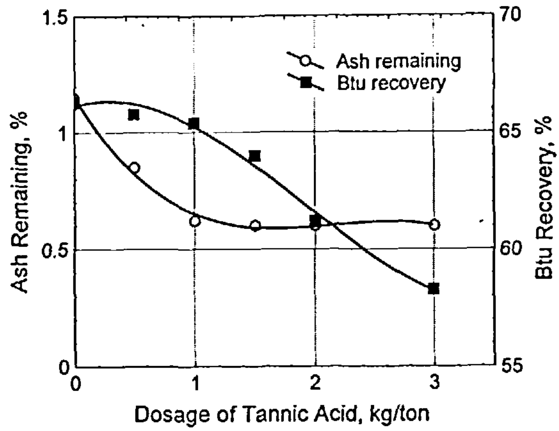

FIG. 4 The effect of tannic dosage on the beneficiation results of the Baiyi bituminous coal with the HFF process. The other test conditions: d_{50} = 4.18 μm, 20 kg/ton kerosene, and 1800 rpm stirring speed for 40 minutes at the flocculation stage; rougher and two-step clean flotation.

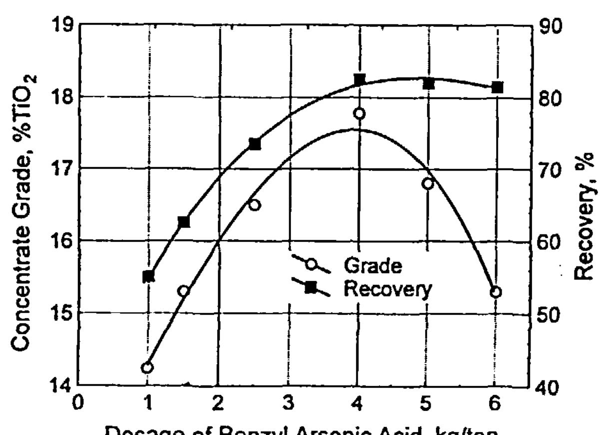

FIG. 5 Relationship between benzyl arsonic acid dosage and the beneficiation results of the ilmenite slimes with the HFF process. The other test conditions: 4.0 kg/ton Na_2SiF_6 as dispersant, 1600 rpm stirring speed for 15 minutes at the flocculation stage; rougher flotation using 40 g/ton ethyl ether alcohol as frother.

that recovery increased sharply with benzyl arsonic acid dosage until a plateau was reached. The concentrate grade appeared to reach a maximum value at 4 kg/ton benzyl arsonic acid, which may be related to the poor selectivity of benzyl arsonic acid at the higher dosage in this system. This result is not surprising to anyone familiar with froth flotation.

Nonpolar Oil Concentration Effect

The effect of a nonpolar oil dosage on the HFF process as applied to the beneficiation of the ilmenite slimes and the bituminous coals is shown in Figs. 6, 7, and 8. It can be seen from these charts that recovery rises dramatically with increasing oil addition. When oil addition reached a critical point (10 kg/ton for Prince bituminous, 15 kg/ton for Pittsburgh bituminous, 20 kg/ton for Baiyi bituminous, 30 kg/ton for Shenmu bituminous, and about 6 kg/ton for ilmenite slimes) any further increase of recovery becomes minimal. However, they show different results on the change of concentrate grade as the oil dosage increases. For instance, the concentrate grade for ilmenite slimes beneficiation increased with the kerosene dosage, and the ash remaining for the Baiyi and Shenmu bituminous beneficiation appeared as a minimum value in the kerosene dosage range.

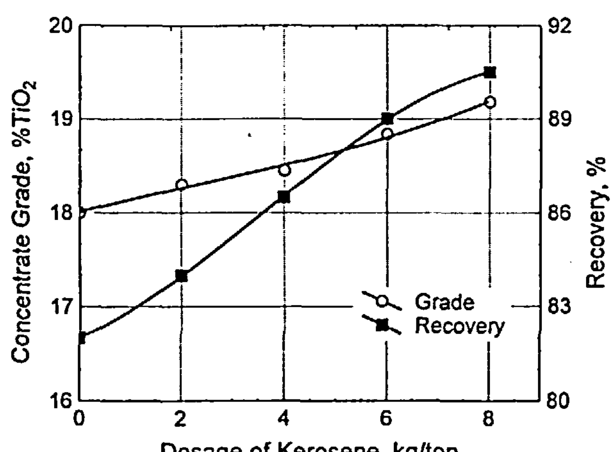

FIG. 6 Effect of kerosene dosage on the beneficiation results of the ilmenite slimes with the HFF process. The other test conditions: 4 kg/ton Na_2SiF_6 as dispersant, 4 kg/ton benzyl arsonic acid as collector, and 1600 rpm stirring speed for 15 minutes at flocculation stage; rougher flotation using 40 g/ton ethyl ether alcohol as frother.

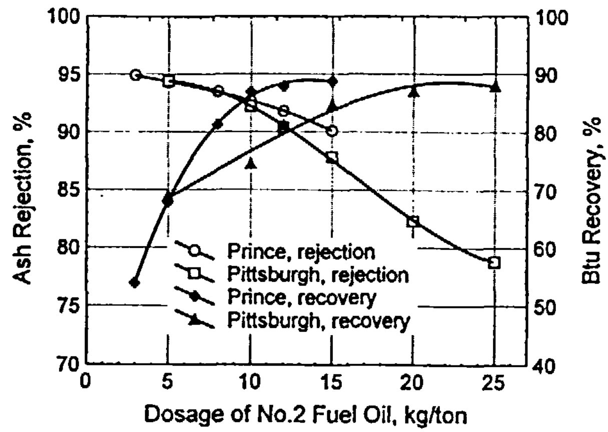

FIG. 7 Effect of No. 2 fuel oil dosage on the ash removal of the Prince and Pittsburgh coals with the HFF process. The other test conditions for the Prince coal: 89% −45 μm, 1800 rpm stirring speed for 20 minutes at the flocculation stage; rougher and four-step clean flotation. The other test conditions for the Pittsburgh coal: 96% −45 μm, 1800 rpm stirring speed for 25 minutes at the flocculation stage, rougher and three-step clean flotation.

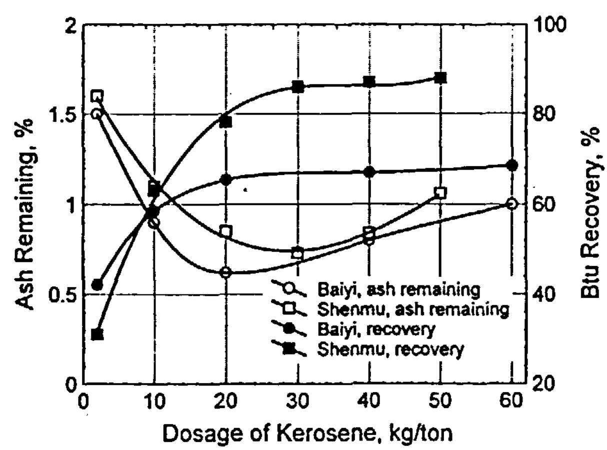

FIG. 8 Effect of kerosene dosage on the ash removal from the Baiyi and Shenmu coals with the HFF process. The other test conditions for the Baiyi coal: d_{50} = 4.18 μm, 1 kg/ton tannic acid as dispersant, 1800 rpm stirring speed for 40 minutes at the flocculation stage; rougher and two-step clean flotation. The other test conditions for the Shenmu coal: d_{50} = 3.14 μm, 0.5 kg/ton sodium hexametaphosphate as dispersant, 6 kg/ton octyl alcohol as collector, and 1800 rpm stirring speed for 60 minutes at the flocculation stage; rougher and one-step clean flotation.

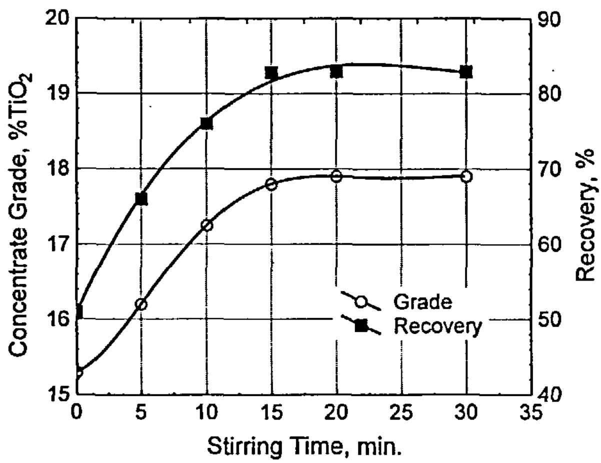

FIG. 9 The beneficiation results of the ilmenite slimes with the HFF process as a function of stirring time at the flocculation stage. The other test conditions: 4 kg/ton Na_2SiF_6 as dispersant, 4 kg/ton benzyl arsonic acid as collector, and 1600 rpm stirring speed at the flocculation stage; rougher flotation using 40 g/ton ethyl ether alcohol as frother.

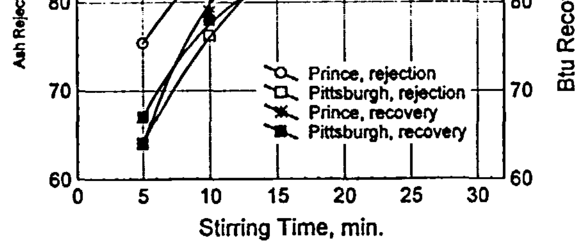

FIG. 10 The ash removal of the Prince and Pittsburgh coals with the HFF process as a function of stirring time at the flocculation stage. The other test conditions for the Prince coal: 89% −45 μm, 10 kg/ton No. 2 fuel oil and 1800 rpm stirring speed at the flocculation stage; rougher and four-step clean flotation. The other test conditions for the Pittsburgh coal: 96% −45 μm, 15 kg/ton No. 2 fuel oil, and 1800 rpm stirring speed at the flocculation stage; rougher and three-step clean flotation.

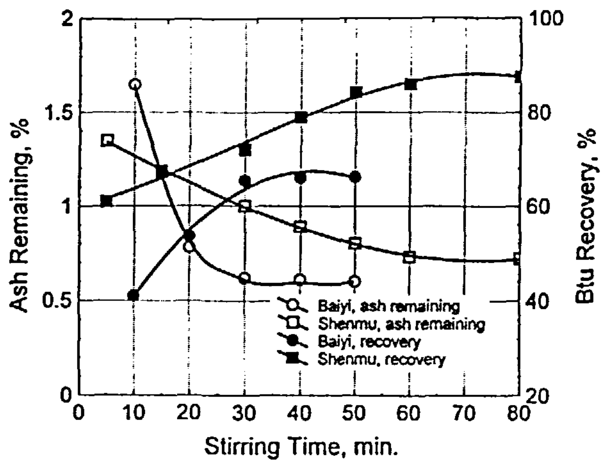

FIG. 11 The ash removal from the Baiyi and Shenmu coals with the HFF process as a function of stirring time at the flocculation stage. The other test conditions for the Baiyi coal: d_{50} = 4.18 μm, 1 kg/ton tannic acid as dispersant, 20 kg/ton kerosene, and 1800 rpm stirring speed at the flocculation stage; rougher and two-step clean flotation. The other test conditions for the Shenmu coal: d_{50} = 3.14 μm, 0.5 kg/ton sodium hexametaphosphate as dispersant, 6 kg/ton octyl alcohol as collector, 30 kg/ton kerosene, and 1800 rpm stirring speed at the flocculation stage; rougher and clean flotation.

Stirring Time Effect

The stirring time at the flocculation stage influences the beneficiation results of ilmenite slimes and bituminous coals as shown in Figs. 9, 10, and 11. The graphs clearly show that a sufficiently long stirring time is necessary. When the stirring time is too short, both the concentrate quality and recovery are lower. With an increase of stirring time, the two curves rise sharply and then level out. Beyond the critical stirring times (15 minutes for ilmenite slimes, 15 minutes for Prince bituminous, 20 minutes for Pittsburgh bituminous, 30 minutes for Baiyi bituminous, and 60 minutes for Shenmu bituminous), both concentrate grade and recovery appear to reach their own equilibrium values.

CONCLUSIONS

Hydrophobic flocculation flotation (HFF) has been shown to be an effective process for the recovery of mineral values or for the removal of undesirable minerals from finely mineralized ores and coal or slimes. The process is based on stabilizing gangue mineral fines with dispersants, followed by hydrophobic flocculation of desired fines through a hydrophobic interaction between the particles which are either rendered hydrophobic by specifically adsorbed surfactants (collectors) or are naturally hydrophobic. Flocculation is induced by conditioning the suspension at a high shear rate, and it is intensified by adding a small amount of nonpolar oil.

The HFF process has been applied to remove fine minerals from coals and to recover fine ilmenite and gold from refractory ores on a laboratory scale. Ultra-clean coals, with low ash and sulfur, have been produced from coal samples which were ground to a fine size range to liberate fine minerals and pyrite. Over 90% ash and 56% sulfur can be rejected from these coals with high Btu recoveries. A ilmenite concentrate assaying 46% TiO_2 has been obtained with 50% recovery from ilmenite slimes of containing 9.8% TiO_2 and 96% -40 μm in size. A gold concentrate assaying 127 g/ton Au has been recovered from a slag containing 2.9 g/ton Au with a gold recovery of 52%. When the slag was treated by conventional flotation, a gold concentrate of 27 g/ton Au was obtained with a gold recovery of 33%.

The main parameters affecting the HFF process are the hydrophobicity of the fine particles to be aggregated, the nonpolar oil addition, the kinetic energy input, and the dispersing suspension. Great attention must be paid to these factors when the HFF process is applied to the treatment of finely mineralized ores and coals.

ACKNOWLEDGMENTS

S.S. gratefully acknowledges the Consejo Nacional de Ciencia y Tecnologia de Mexico (CONACyT) for his fellowship support and the Fondo de Apoyo a la Investigación of Universidad Autónoma de San Luis Potosí for the partial support of this project (#C96-FAI-08-5.68).

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Received by editor March 21, 1997
Revision received August 1997