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 Oder, R. R.(1984) 'The Application of High Field and High Gradient Methods to the Magnetic Separation of Mineral Matter from Micronized Coal', Separation Science and Technology, 19: 11, 761 — 781
To link to this Article: DOI: 10.1080/01496398408068593
URL: http://dx.doi.org/10.1080/01496398408068593

SEPARATION SCIENCE AND TECHNOLOGY, *19*(11 & 12), pp. 761-781, 1984-85

The Application of High Field and High Gradient Methods to the Magnetic Separation of Mineral Matter from Micronized Coal

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Abstract

In exploratory laboratory measurements, high field high gradient magnetic separation (HGMS) has removed as much as 74% of the mineral matter and 99% of the pyritic sulfur from micronized coals with mineral contents up to 16.39 wt%. Magnetic cleaning methods are limited by the fact that not all mineral matter in coal is magnetic. HGMS methods are further restricted when mineral matter levels generally exceed about 2 to 3% because of excessive capture-matrix loading which leads to poor clean coal weight yields. The use of selective flocculation of coal mineral matter and processing at high flow velocities (made possible with the use of high field superconductive magnet technology) offer hope for overcoming these process limitations and for extending use of HGMS technology to preparation of low ash and low sulfur coal-slurry fuels. Measurements of mineral matter and sulfur removals achieved in high field HGMS processing of water slurries of dispersed micronized coals are presented. Field strengths up to 15 Tesla, flow velocities up to 3 cm/s, and slurry solids up to 38.4% were investigated. The use of models of the magnetic capture mechanism for scaling laboratory data to commercial applications is discussed.

INTRODUCTION

Interest is growing in the development of coal/water slurries for use as a new alternative to expensive petroleum-based residual fuels (*1*). Micronized coals may be required in this application for practical reasons associated with handling and combustion of coal slurries.

It is expected that the use of low ash and low sulfur coal will add significantly to the value of the coal–water fuel. The supply of quality coals

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suited to this application, however, is severely limited. Because of this, it is desirable to develop methods for preparing the appropriate clean coal from widely available and inexpensive sources. The refining technology must have the capability of practical separations of micron-sized minerals liberated in the size reduction operation.

There are no commercial operations in place which clean micronized coal. Methods used for removal of mineral matter in laboratory investigations range from chemical dissolution with reducing acids (HCl and HF) (*2*) to mechanical separations based on phase disengagement (*3*) and selective agglomeration (*4*). None of these methods, however, has yet been developed on a commercial scale.

High gradient magnetic separation, HGMS, is a mechanical separations technology which has received considerable attention for possible application to removal of pyritic sulfur from fine coal (5). It is used now for commercial beneficiation of kaolin clay in a water-based process where feebly magnetic and micron-sized nonleachable mineral discolorants are separated from kaolin particles with the use of a sophisticated magnetic filtration process (*6*). Broad similarities coupling the two applications suggest (*7*) a high potential for development of the HGMS technology for use in the coal-cleaning application.

HGMS technology developed for coal cleaning, however, is expected to be qualitatively and quantitatively different from that used in the kaolin application. First, the mineral impurities to be removed are more concentrated in coal. This means that the batch-operated magnetic-capture process developed for kaolin beneficiation (*7*) may not be applicable to refining high ash coals, even when quasi-continuous versions of the technology are used (*8*). Second, only a portion of the mineral matter in coal is expected to be even feebly magnetic. The extent to which magnetic methods can remove all mineral matter from coal is yet to be fully understood; it will surely be coal specific. Last, much larger throughputs will be required for the coal application. The practicability of scaling up the kaolin technology for use in coal processing is a topic of considerable commercial interest (*9*).

The process parameter to be exploited in translating HGMS technology to coal refining is the magnetic field strength. The magnetic field strength employed in commercial practice is limited to 2 T (1 T = one tesla = 10,000 gauss) by practical considerations associated with the use of iron-based electromagnet technology. There is good reason to believe that the use of very high magnetic field strength in HGMS processing, such as can be achieved with the use of innovative superconducting magnet technology, offers several opportunities to overcome practical limitations of the batch-operated process. If high field strength facilitates process improvements as

TABLE 1
Experimental parameters for High Field HGMS Measurements

Magnets	Bitter and superconductive solenoids
Magnetic field strength	Up to 15 T
Coal	Upper Freeport seam
Mean particle diameter (μm)	7.2, Upper Freeport
Canister dimensions:	
Length (cm)	10.95
Volume (cm^3)	105 and 125
Flow velocity (cm/s)	0.42 to 3.07
Matrix packing (%)[a]	6
Slurry solids (wt%)	14.8 to 38.4
Slurry viscosity (cP)	3.2 to 31

[a]Medium grade #430 felted stainless steel wool pads.

anticipated, and if the development of suitable superconducting magnets proves feasible, the application of magnetic beneficiation to coal cleaning has real potential.

This paper reports results of preliminary measurements of the removal of mineral matter and pyritic sulfur from micronized-coal/water slurries made with the use of laboratory scale high field HGMS technology. This work was undertaken to explore the technical and economic feasibility of developing superconductive magnets for HGMS cleaning of coal. This work was supported by the Department of Energy Small Business Innovation Research Program (*10*).

EXPERIMENTAL

The experiments in magnetic separation were carried out using the facilities of the Francis Bitter National Magnet Laboratory at the Massachusetts Institute of Technology. Both a 15-T Bitter solenoid and a 2-in. room temperature access, 15 T superconductive magnet built by IGC of Guilderland, New York, were used. The range of experimental parameters covered in the measurement program which are reported here are given in Table 1.

The coal used was deep mined Upper Freeport seam sampled from the middlings circuit of the Homer City Preparation Plant, Homer City, Indiana County, Pennsylvania. Characteristics of the coal are given in Table 2.

The coal was wet size-reduced with the use of a batch-operated bench-scale Perl Mill employing $\frac{3}{16}$ in. diameter steel balls. The coal/water slurry

TABLE 2
Analysis of As-Received Coal, Upper Freeport

Analysis, dry basis	
Ash (%)	16.32
Btu/lb	12,947
Pyritic sulfur (%)	1.22
Sulfate sulfur (%)	0.01
Organic sulfur (%)	0.65

was dispersed to minimum viscosity with the use of a proprietary reagent package added during size reduction.

The coal/water slurries exhibit non-Newtonian behavior. The effects of time and spindle rpm on viscosity measured for a 34.6% solids nondispersed Upper Freeport slurry are shown in Fig. 1. A Brookfield viscometer was used for all viscosity measurements.

Viscosities measured for dispersed Upper Freeport coal/water slurries with solids up to 40% are shown in Fig. 2. The measurement configuration of spindle, rpm, and time of measurement are shown, in that order, within the brackets on the vertical axis label of the figure (e.g., [1, 60, 1]). Use of the

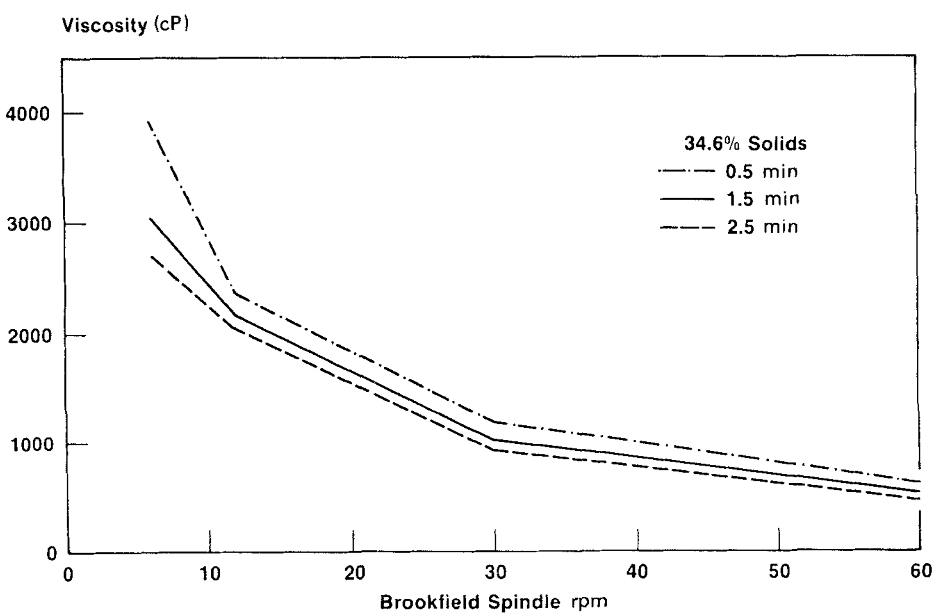

FIG. 1. Non-Newtonian behavior of viscosity for nondispersed micronized Upper Freeport coal, 7 μm diameter.

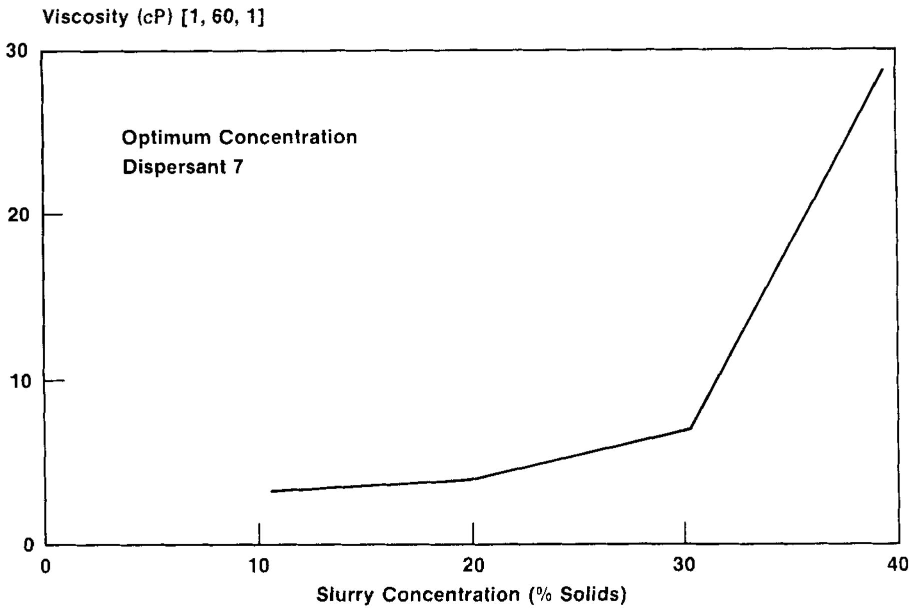

FIG. 2. Viscosity of dispersed micronized Upper Freeport coal versus solids content, 7 μm mean particle diameter.

dispersing reagents reduces both measured viscosity and associated time and rpm effects. The data of Fig. 2 can be represented to within 8% accuracy by the empirical relationship

$$\text{viscosity} = n = 1.1 + 0.13S + 72/(42 - S) \tag{1}$$

Flow through the HGMS separator was controlled by a hand-operated manifold schematically outlined in Fig. 3. The manifold was connected to a canister embedded in a high field magnet. The canister contains a fixed-bed magnetic filter made of medium grade ferritic stainless steel wool. Slurry was pumped from the canister bottom with the use of a parastaltic pump. The throughput was regulated between 100 and 3000 cm^3/min by control of the drive motor dc voltage.

The experimental canisters were made from 2 in. o.d. nonmagnetic stainless steel. The maximum o.d. and the canister length ($4\frac{5}{16}$ in.) were fixed by magnet considerations. The stainless steel wool was retained inside the canisters (of either $1\frac{5}{8}$ or $1\frac{3}{4}$ in. i.d.) by screens secured by snap rings. When the magnet was on, the canister was rigidly held in place by strong, symmetric magnetic forces on the steel wool.

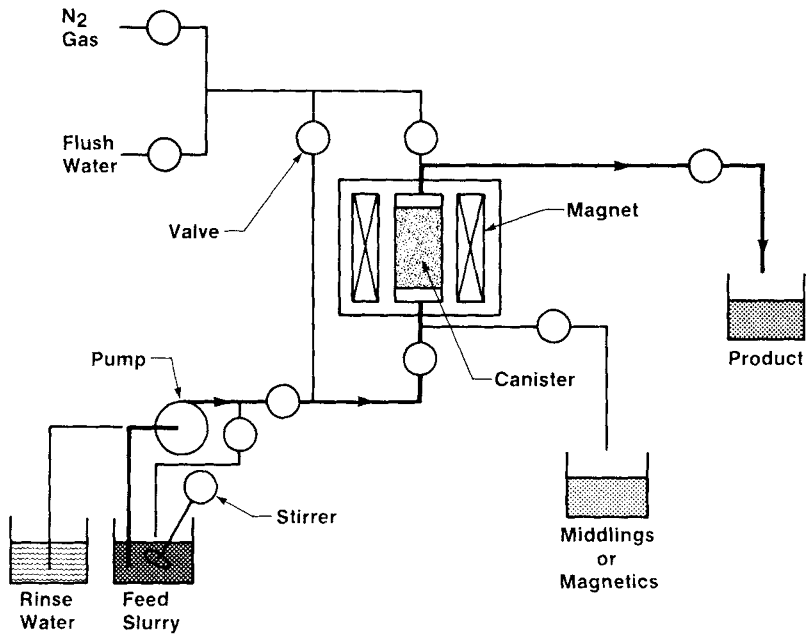

FIG. 3. Experimental arrangement.

The experimental procedure consisted of pumping a 6-canister-equivalent slurry volume through the apparatus at predetermined experimental conditions of flow rate, magnetic field strength, slurry solids, etc. Experimental samples of approximately 25 to 29 cm^3 were collected from the initial spillover and at time intervals equivalent to processing of 2, 4, and 6 canisters. The entire throughput could be recombined to form a composite sample.

After transfer of 6 canisters the system was rinsed with distilled water under the same processing conditions, including flow direction. For the rinse operation, the canister was left in place inside the energized magnet. The rinse material was collected for separate analysis.

Following the rinse operation, the magnet was deenergized and, in the case of the superconductive magnet, the canister was lifted out of the magnet chamber for flushing in zero field. Flushing and drying was carried out with the use of high velocity house-pressure water and high-pressure gaseous nitrogen. All flush material was collected as a magnetic fraction for separate analysis. Weights and solids contents were determined for slurry feed, composite, middling, and magnetic fractions. Viscosity control measurements were made on all feed material.

TABLE 3
Ash Levels of Dispersed 25% Solids Upper Freeport Coal/Water Slurries Processed by HGMS at 0.4 cm/s

Magnetic field (T)	Sample treatment	Ash (%), dry
NA	As received	16.32
2	Initial spillover	6.54
2	5-Canister sample	13.55
2	5-Canister magnetic composite	31.06
15	Initial spillover	4.05
15	5-Canister sample	13.17
15	5-Canister magnetic composite	34.86

RESULTS

An overview of separation results obtained in HGMS processing of micronized Upper Freeport coal is given in Table 3.

The initial spillover sample shows the best result obtainable with the experimental configuration used since the material has been processed with a clean, unloaded filter. The data shown in Table 3 indicate that the ash has been reduced from 16.3 to 6.5% in processing at 2 T or further reduced to 4.1% in processing at 15 T. Significant ash reductions can be achieved by magnetic processing of this coal, and increasing the magnetic field above 2 T facilitates ash removal.

The data show that the clean coal emerging from the filter after 5 canister-volumes of slurry have been processed is only moderately reduced in ash. It appears that the filter is loaded near its capacity to retain magnetics by the time this amount of 25% solids Upper Freeport coal has been processed. Accordingly, the ash levels observed for the composite magnetic fractions represent material captured by fully-to-overloaded matrices.

Measurements of the effects of magnetic field, flow velocity, and solids level on ash removal for initial spillover samples are summarized in Table 4. The experiments represented were designed around the use of three levels each of magnetic field strength, flow velocity, and slurry solids. Values for the three main variables used—H, V, and n = slurry viscosity—were chosen so as to give a series of different experiments, some of which were characterized by common values of H/nV even though individual values for H, n, and V for the runs were different.

This experimental design was used in order to demonstrate directly tradeoffs possible in the magnetic process and to establish a basis for scale-up of experimental data. The possibility of tradeoff of relevant magnetic separation parameters—including magnetic field strength, slurry solids, flow velocity, matrix properties, and particle characteristics—in order to improve process efficiency and throughput has been recognized for some time in the kaolin industry (*11*).

TABLE 4
Ash Levels in Initial Spillover Samples of Upper Freeport Coal for Various Levels of Magnetic Field, Flow Velocity, and Slurry Solids

Run #	Magnetic field (T)	Flow velocity (cm/s)	Slurry solids (%)	Slurry viscosity (cP)	Ash (%)
Head	NA	NA	38.4	31	16.4
17	2.15	1.15	38.4	31	10.5
18	5.57	1.15	38.4	31	7.13
19	15.01	1.15	38.4	31	5.93
Head	NA	NA	29.4	7.9	16.2
20	2.15	1.15	29.4	7.9	8.47
21	5.27	1.15	29.4	7.9	6.45
22	15.01	1.15	29.4	7.9	5.01
Head	NA	NA	14.8	3.8	16.0
23	2.19	0.42	14.8	3.8	7.15
24	5.58	0.42	14.8	3.8	5.42
25	15.01	0.42	14.8	3.8	4.35
Head	NA	NA	14.8	3.8	16.0
26	2.20	1.14	14.8	3.8	8.03
27	5.58	1.14	14.8	3.8	6.33
28	15.01	1.14	14.8	3.8	4.81
Head	NA	NA	14.8	3.8	16.0
29	2.20	3.07	14.8	3.8	11.4
30	5.57	3.07	14.8	3.8	8.87
31	15.01	3.07	14.8	3.8	7.24
Head	0	0.42	39.4	53.2	16.2
43	0	0.42	39.4	53.2	15.2
Head	0	0.42	31.0	15.5	16.6
44	0	0.42	31.0	15.5	15.0
Head	0	0.43	15.3	4.3	16.6
45	0	0.43	15.3	4.3	14.8

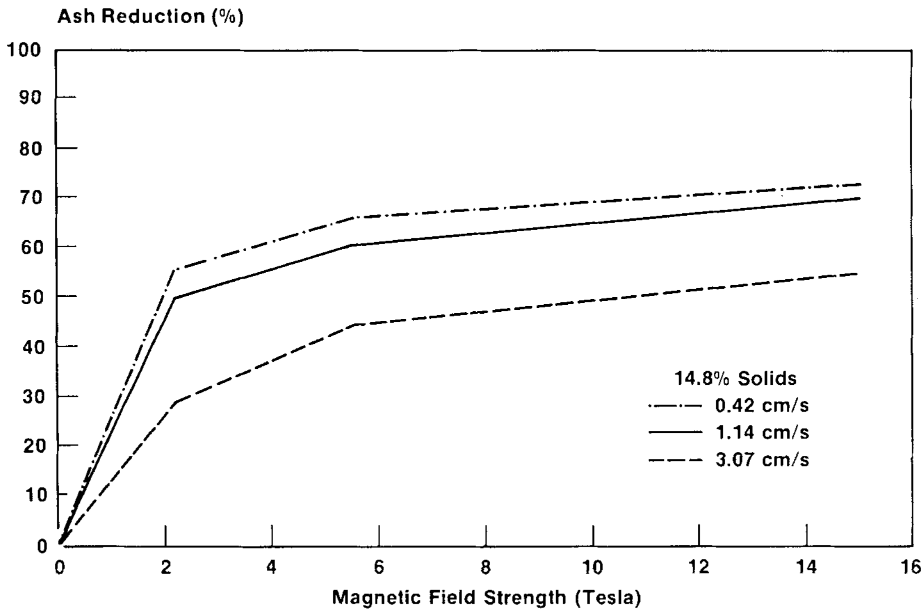

FIG. 4. Magnetic field and flow velocity dependence of HGMS deashing of Upper Freeport coal. 16.39% ash.

Field Effects

The effects of magnetic field and flow velocity on ideal filter performance for the Upper Freeport coal are illustrated in Fig. 4. The elements of the figure indicate that equivalent levels of ash removal can be achieved at different flow velocities by making appropriate changes in the magnetic field strength. For example, 55% ash removal is observed at 2 T and 0.42 cm/s flow velocity. The same level of ash removal can be achieved at 1.14 cm/s flow velocity if the magnetic field is increased to 4 T. Again, achieving the 55% level of ash removal would require a magnetic field strength of about 15 T when processing at 3 cm/s for this filter. The data indicate a significant potential for increasing process flow velocity when employing magnets capable of producing fields well in excess of 2 T.

The slurry solids level, which affects slurry viscosity, has an effect on separator performance. The potential for tradeoff between slurry solids and magnetic field strength is shown in Fig. 5 where ash reductions observed for initial spillover samples of differing solids levels are plotted versus magnetic field strength. As before, these measurements show that the use of high

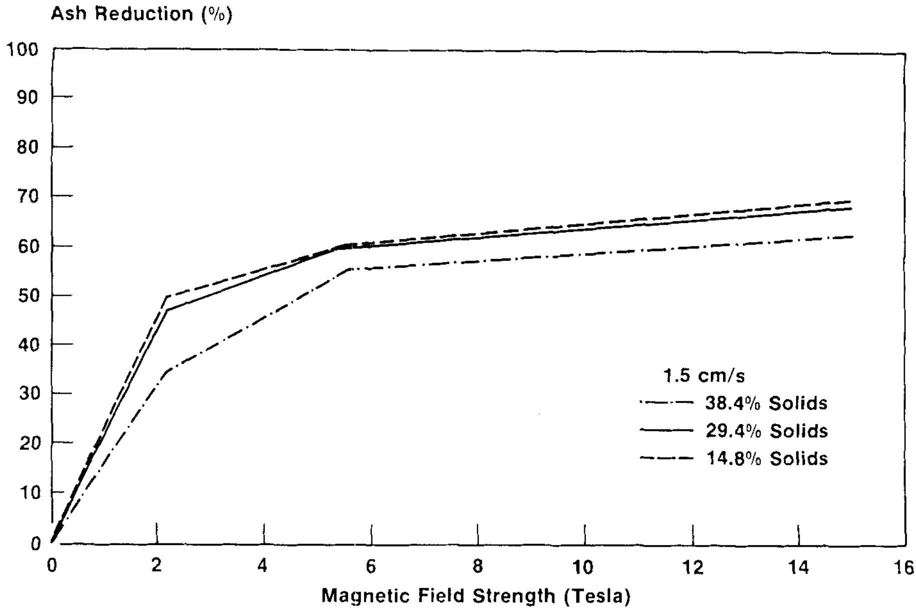

FIG. 5. Magnetic field and slurry solids dependence of HGMS deashing of Upper Freeport coal. 16.39% ash.

magnetic field strength can facilitate processing of high solids slurries. The use of high flow velocity and high solids slurries offers potential for significant increases in separator throughput.

Matrix Loading

Some effects of matrix loading are illustrated in Fig. 6 where product ash is shown as a function of slurry volume processed at several slurry solids levels. No significant difference is observed in the loadings for 14.8 and 29.4% solids at 15 T and 1.15 cm/s. Increasing solids to 38.4% for the Upper Freeport coal with this canister configuration, however, has a pronounced detrimental effect on performance.

More resolution of loading curves such as Fig. 6 is needed, especially for small amounts of material processed. By way of comparison, magnetic processing times of the order of 20 min with retention times of 2 min are not unusual in HGMS batch processing of kaolin clay under conditions similar to those used here for coal. The concentration of the titaniferous mineral removed from Middle Georgia kaolin by the magnetic process is about 2% of the dry solids to the separator. With coal at 16% ash one would expect full matrix loading for magnetic deashing, then, after processing slurry volumes (at 30% solids), equivalent to $\frac{2}{16}(\frac{20}{2}) = 1.25$ canisters. Full magnetic filter loading can be expected when two or more canisters of material have been processed for the 16% ash Upper Freeport coal.

Weight Yield

The elements of Table 5 correlate ash level and weight recovery data for six-canister composite samples taken for the Upper Freeport coal under widely varying conditions of field strength, flow velocity, and slurry solids. The data of Table 5 have been obtained for fully-to-overloaded filter matrices.

The effects of velocity and solids on recovery can be seen in the elements of Table 5. Runs 23, 27 and 31 are all characterized by the same solids, 14.8%, and have the same viscosity, 3.8 cP. These runs also all have substantially the same value of H/V and are characterized by similar values of product ash. For these runs it can be seen that increasing V in proportion to H has the effect of increasing recovery from 79% at 0.42 cm/s to 91% at 3.07 cm/s.

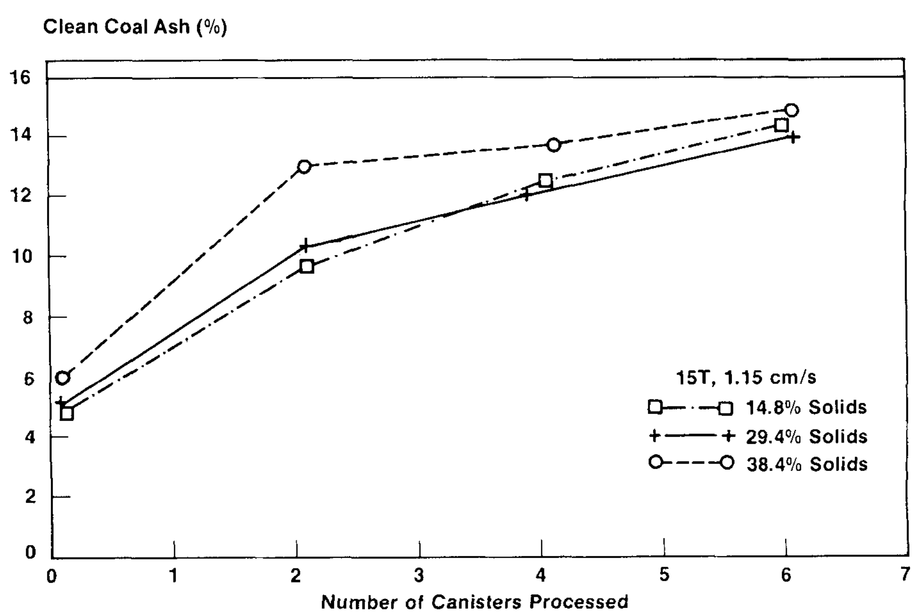

FIG. 6. Matrix loading. 16.39% ash Upper Freeport coal.

TABLE 5
Properties of 6-Canister Composite Samples for Upper Freeport Coal

Run	H (T)	V (cm/s)	n (cP)	H/V (T·s/cm)	Feed ash	Product ash	Weight recovered (%)
17	2.15	1.15	31.0	1.89	16.4		89.8
18	5.57	1.15	31.0	4.89	16.4	14.9	90.1
19	15.01	1.15	31.0	13.04	16.4	14.1	90.2
20	2.15	1.15	7.9	1.87	16.2		88.4
21	5.27	1.15	7.9	4.58	16.2		87.0
22	15.01	1.15	7.9	13.05	16.2		89.1
23	2.19	0.42	3.8	5.21	16.0	12.6	79.4
24	5.58	0.42	3.8	13.29	16.0		76.1
25	15.01	0.42	3.8	35.74	16.0	11.4	74.9
26	2.20	1.14	3.8	1.93	16.0	14.6	90.1
27	5.58	1.14	3.8	4.89	16.0	13.0	87.4
28	15.01	1.14	3.8	13.17	16.0		84.7
29	2.20	3.07	3.8	0.72	16.0	14.9	87.8
30	5.57	3.07	3.8	1.81	16.0		92.3
31	15.01	3.07	3.8	4.89	16.0	12.3	90.7
43	0.00	0.42	53.2	0.00	16.2	15.6	96.5
44	0.00	0.42	15.5	0.00	16.6	15.3	97.8
45	0.00	0.43	4.3	0.00	16.6	14.8	95.5

The use of high flow velocity, made possible with the use of high magnetic field strength, can improve weight recovery in HGMS batch processing of high ash coals.

Runs 18 and 26 are characterized by the same velocity. Run 26 was carried out at 2.2 T and used 14.8% solids slurry. Run 18 was carried out at 38.4% solids and 5.57 T. HGMS resulted in substantially the same product grade and recovery for these two widely different runs. Increasing the field strength from 2.2 to 5.57 T allows processing much higher solids at the same level of performance.

Runs 43, 44, and 45 correspond to mechanical entrapment under low flow velocity conditions at zero magnetic field. The results show some entrapment, indicating that the medium-grade steel wool used was relatively open to the fine coal. The measurements indicate that viscosity is important and that there is the possibility for some differential sedimentation at low flow velocities.

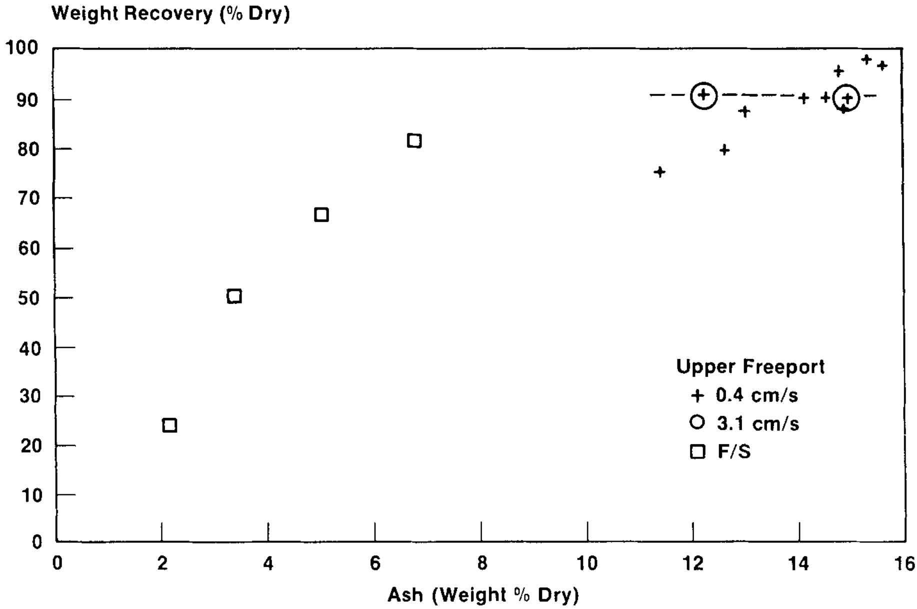

FIG. 7. Weight recovery versus ash level for HGMS deashing of Upper Freeport coal, 6-canister composite.

For comparison, float/sink results for $\frac{1}{8}$ in. × 16 mesh Upper Freeport coal taken from the middlings circuit at the Homer City preparation plant are given in Table 6. These comparison data indicate that low ash and sulfur material can be prepared from the Upper Freeport coal by ideal gravimetric separations but that recoveries will be low for ash values much below 5%. The float-sink data are compared with preliminary HGMS results in Fig. 7.

TABLE 6
Cumulative Float Data for 3.15 by 1 mm Middlings Product of the Homer City Coal Preparation Plant (*12*)

Gravity		Cumulative float				
Sink	Float	Wt%	Ash	Sulfur	Btu/lb	#S/MBtu
	1.270	24.3	2.24	0.79	15,316	0.52
1.270	1.300	49.9	3.40	0.90	15,105	0.59
1.300	1.350	67.7	4.85	0.99	14,853	0.66
1.350	1.500	81.2	6.77	1.12	14,516	0.77
1.500		100.0	16.89	2.26	12,733	1.78

The points in Fig. 7 marked by + symbols relate weight yield and ash levels prepared by HGMS for the case of overloaded filters in the present work. The comparison data are represented by boxes in the figure. The two data points enclosed by circles correspond to material prepared magnetically under conditions of the highest flow velocity (Runs 29 and 31 of Table 5).

The recoveries achieved by the magnetic method in these preliminary measurements are not as good as those obtainable with ideal gravimetric separations as indicated by the float/sink data. This may reflect several possible limitations of the magnetic method. First, not all mineral matter in coal is magnetic. Second, there is the possibility of incomplete dispersion of the magnetic mineral matter. Third, there is the possibility of inadvertent mechanical entrapment in the filter bed. Last, low weight yield may be an inherent part of batch processing of material which has high concentrations of magnetic reject material. While none of these objections can be ruled out at this time, it appears likely that more extensive measurements under better conditions will be required in assessing the recovery characteristics of the magnetic method. Indeed, the trend in recovery observed for the high velocity HGMS runs indicates the possibility of achieving significant yield improvements with the use of high flow velocities in the magnetic method.

Sulfur

Selected coal samples were analyzed for total sulfur in addition to ash. The total sulfur measurements, in turn, were used to calculate pyritic sulfur levels in the samples assuming no sulfate or elemental sulfur present. The results are summarized in Table 7.

Measurements of total sulfur in the initial spillover samples show trends similar to those observed for ash except that excellent desulfurization is already achieved at low field strength. Calculations of the pyritic sulfur content indicate removals in excess in 99% for the low-field/low-flow velocity case. Basically, the measurements indicate that HGMS of micronized Upper Freeport coal achieves excellent removal of pyritic sulfur.

Total sulfur recovery measurements for 6-canister composite samples obtained under the same test conditions as for ash are shown in Table 8. These values are plotted in Fig. 8 versus measured values of total sulfur. Comparison data from the float/sink analysis are shown as before.

Just as for the case of ash, increasing flow velocity and magnetic field strength in proportion has the effect of increasing recovery without loss of product quality. The sulfur separations are different from those for ash,

TABLE 7
Sulfur Values for Initial Spillover Samples of Upper Freeport Coal

14.8% Solids

Measured Total Sulfur

	Flow velocity (cm/s)		
H (T)	0.42	1.14	3.07
2.19	0.72	0.77	1.02
5.58	0.76	0.74	0.85
150.01	NM	0.74	0.83

Calculated Pyritic Sulfur[a]

	0.42	1.14	3.07
2.19	0.008	0.064	0.34
5.58	0.17	0.02	0.15
150.01	NM	0.008	0.12

1.14 cm/s

Measured Total Sulfur

	Slurry solids (%)		
	1.48	29.4	38.4
2.19	0.77	0.82	0.99
5.58	0.74	0.77	0.81
15.01	0.74	0.77	0.77

Calculated Pyritic Sulfur[a]

	1.48	29.4	38.4
2.19	0.064	0.12	0.03
5.58	0.02	0.05	0.094
150.01	0.008	0.038	0.044

[a]Pyritic sulfur = total sulfur − 0.78(1 − ash/100).

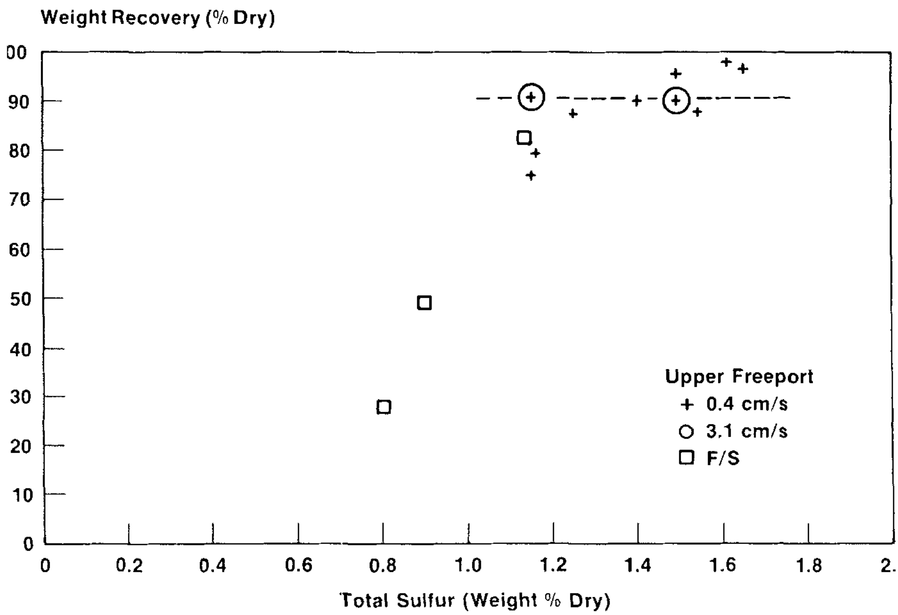

FIG. 8. Weight recovery versus total sulfur for HGMS desulfurization of Upper Freeport coal, 6-canister composite.

however, in that excellent sulfur removals are achieved even in 6-canister composite samples. Indeed, the high velocity projections indicate an outstanding potential for application of HGMS to removal of pyrites from fine coal fractions taken from the Upper Freeport coal.

Modeling

Results of the experiments are interpreted through the measured filter transmittance. The transmittance, defined by the ratio of the concentration of the magnetic portion of the feed at the output, C_0, to that at the input of the filter, C_i, is expressed in terms of the length of the filter, L, and of the filter absorption length, a, through the relation

$$C_0/C_i = e^{-L/a} \tag{2}$$

Various models have been given to interpret magnetic filter performance. For the interpretations to be derived here, a widely accepted model based on capture from flow (trajectory model) will be used (*13*).

The trajectory model stresses capture from flow and ignores shear forces in effect on the surface of the steel wool strands which tend to dislodge entrapped magnetics after they have collided with the capture surface. In essence, the model assumes that the probability of removal is related only to the probability of collision with a steel wool strand. The approach ignores the possibility of not sticking once having collided.

For the trajectory model the filter absorption length, a, is given by

$$a = A_m/(2RcY) \tag{3}$$

where A_m = cross-section area of a matrix element, cm^2
Y = matrix packing density = 6%
c = capture radius = $C(xD_p^2 MB_0 A_m/18\pi n V_0)^{1/3}$ cm (4)
C = numerical constant of the order of 1
π = 3.146

TABLE 8
Properties of 6-Canister Composite Samples for Upper Freeport Coal

Run	H (T)	V (cm/s)	n (cP)	H/V (T·s/cm)	Feed ash	Product: Ash	Product: Total sulfur	Product: Pyritic sulfur	Weight recovered (%)
17	2.15	1.15	31.0	1.89	16.4				89.8
18	5.57	1.15	31.0	4.89	16.4	14.9			90.1
19	15.01	1.15	31.0	13.04	16.4	14.1	1.49	0.82	90.2
20	2.15	1.15	7.9	1.87	16.2				88.4
21	5.27	1.15	7.9	4.58	16.2				87.0
22	15.01	1.15	7.9	13.05	16.2				89.1
23	2.19	0.42	3.8	5.21	16.0	12.6	1.16	0.48	79.4
24	5.58	0.42	3.8	13.29	16.0				76.1
25	15.01	0.42	3.8	35.74	16.0	11.4	1.15	0.46	74.9
26	2.20	1.14	3.8	1.93	16.0	14.6	1.40	0.73	90.1
27	5.58	1.14	3.8	4.89	16.0	13.0	1.25	0.57	87.4
28	15.01	1.14	3.8	13.17	16.0				84.7
29	2.20	3.07	3.8	0.72	16.0	14.9	1.54	0.88	87.8
30	5.57	3.07	3.8	1.81	16.0				92.3
31	15.01	3.07	3.8	4.89	16.0	12.3	1.15	0.47	90.7
43	0.00	0.42	53.2	0.00	16.2	15.6	1.65	0.99	96.5
44	0.00	0.42	15.5	0.00	16.6	15.3	1.61	0.95	97.8
45	0.00	0.43	4.3	0.00	16.6	14.8	1.49	0.83	95.5

[a]Pyritic sulfur = total sulfur − 0.78(1 − ash/100).

The elements of Eq. (4) are defined as follows:

x = magnetic susceptibility = 6×10^{-6} cgs
D_p = diameter of magnetic particulate = 0.0007 cm
M = magnetization of steel wool = 1590 G
B_0 = applied magnetic field = 8 T
D_s = diameter of steel wool strand = 0.0250 cm
A_m = 4.9×10^{-4} cm^2
n = slurry viscosity = 7.9 cP at 30% solids
V_0 = flow velocity = 1.15 cm/s

Using the above values and assuming $C = 1$, one calculates

$$RC = 0.0028 \text{ cm}$$

and

$$a = 8.8 \text{ cm}$$

Using this model, the calculated absorption length is estimated to be of the order of the canister length itself.

Transmittance measurements for all the experimental runs are plotted in Fig. 9 versus the separation parameter, X, derived from the trajectory model,

$$X = [H/n(V/(1 - Y/100))]^{1/3} \tag{5}$$

In the figure,

A_0 = product ash
A_{nm} = ash value of nonmagnetic mineral matter
A_i = feed coal ash

The values of A_0 and A_i used in the plot are measured. A value of 4.05% has been taken for A_{nm}. This value is obtained from projections of ash rejection at high values of the separation parameter, X. Since the measurements of ash rejection were made under short canister conditions, it is feasible that the value of A_{nm} could be even less for this coal.

The smooth curve of Fig. 9 is a least-squares exponential fit to the data points. This fit is given by the expression

$$C_0/C_i = 1.012e^{-1.67X} \tag{6}$$

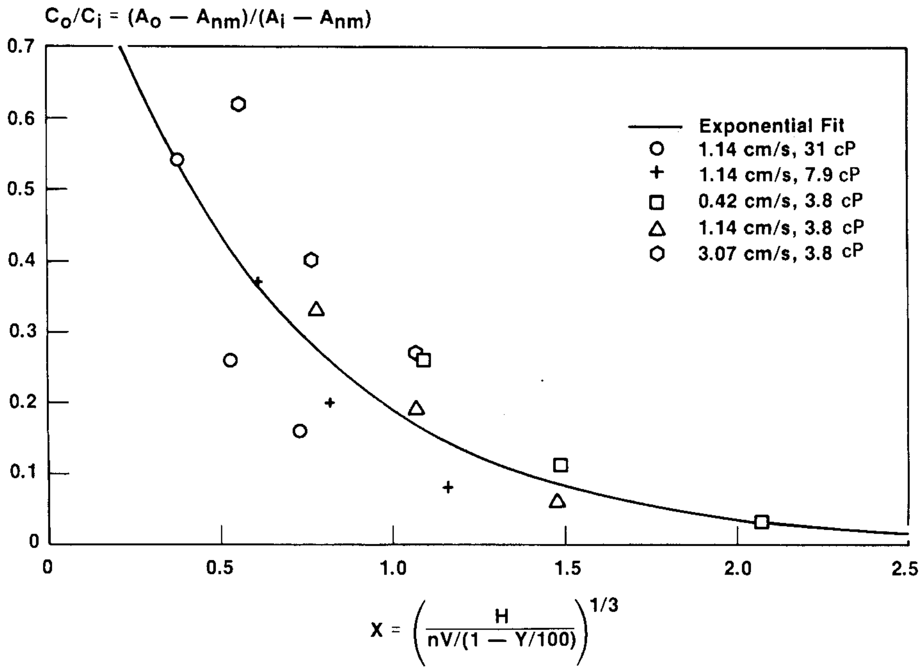

FIG. 9. Magnetic filter transmittance versus trajectory model separation parameter for HGMS deashing of Upper Freeport coal.

r^2, the coefficient of determination for the fit, is found to be

$$r^2 = 0.79 \tag{7}$$

The observed variation of the transmittance with magnetic field strength is smoother than indicated by the scatter of Fig. 9. When individual runs characterized by like values of velocity and of slurry solids but differing values of the magnetic field strength are analyzed together, even better exponential fits are generated with little scatter. This can be seen in the figure where the three data points for a set of runs differing only by the magnetic field strength are all denoted by common symbols which are described in the legend.

This may be a result of limitations in the trajectory model. Other approaches such as that tested earlier for kaolin processing (*11*) and ones which can be derived from models of shear effects in particle retention on the capture surface (*14*) all give about equally good mathematical fits. Each has radically different interpretations, however. Further, the appearance of large scatter for the data points actually may be a result of the use of a short filter length in these experiments. Because the filter and absorption lengths are nearly equal, Eq. (2) is an oversimplification and the interpretation of the transmittance may be more complex than indicated here (*15*).

One can proceed to develop technical and cost information on magnetic separator size using a scaling approach based on Eq. (2). That information will be developed elsewhere.

DISCUSSION

High magnetic fields can be used to advantage in HGMS processing of micronized Upper Freeport coal. Throughput can be increased significantly, and measurements indicate that increasing flow velocity, possible with the use of high magnetic field strength, can improve weight recovery. Pyrites are removed effectively with the use of high field technology. Ash removals up to 74% were observed for the Upper Freeport coal.

If the HGMS technology is to be developed commercially, practical operation of the batch-operated process will be required. There are significant questions related to the use of this approach, however, which will have to be answered before further development can be justified. Acceptable weight recoveries will have to be demonstrated in producing low ash and low sulfur coals. Further, the method will have to be tested successfully on a wider range of coals of commercial significance. The extent to which nonmagnetic mineral matter will impose a restriction on the utility of the method is yet to be determined. Further, the economics of cleaning micronized coal by high field magnetic methods needs to be investigated.

Acknowledgment

Supported by The Small Business Innovation Research Program of the U.S. Department of Energy under Contract No. DE-AC01-83ER80037.

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