Extending the upper particle size limit for coal flotation

by R.-H. Yoon, G.H. Luttrell, and R. Asmatulu*

Synopsis

Novel flotation reagents were developed to improve the flotation of coarse particles. Laboratory tests conducted on an anthracite coal sample from Kyung-Dong Coal Company, Korea, showed that the reagents can successfully clean 2–3 mm top-size materials. Pilot-scale tests conducted on a 1.41 mm x 0 coal gave substantially better results than those obtained using kerosene as collector. The pilot-scale test results were used to develop a flowsheet, in which the 1.41 mm x 0 fraction is cleaned by flotation and the 4 x 1.41 mm coal is cleaned by single-stage spirals. The performance of this circuit was compared with another flowsheet, in which the 0.5 mm x 0 coal is floated using the conventional flotation reagent, with the 4 x 0.5 mm material being cleaned using two separate spiral circuits. The performance of the two flowsheets was compared by computer simulation. The results showed that the flowsheet consisting of the coarse particle flotation circuit can give substantially higher yields at a given product grade.

Keywords: coal flotation, coarse particle flotation, collector, spirals, computer simulation.

Introduction

Anthracite is the only domestic source of fossil fuel in Korea. Its production peaked at 24 million tonnes in 1988, and declined ever since. The Korean anthracite had been used mainly for domestic heating and cooking applications. With the substantial increase in living standards, coupled with low oil and gas prices, coal is no longer the fuel of choice in the country. The declining demand for Korean anthracite created socio-political problems in the country. Therefore, the Korean government funded several R&D projects to find appropriate methods of cleaning anthracite, so that the clean coal can be used for non-fuel applications. Unfortunately, much of the coal mined in Korea is fine and, therefore, is difficult to clean. Furthermore, many of the mines are relatively small, which makes it difficult to justify large capital expenditures.

Many investigators in Korea carried out beneficiation tests using various solid-solid separation processes[1,2]. They showed that dense-medium cyclones could be used to clean 2 x 0.15 mm coals to 9–13 per cent ash with 30–40 per cent recoveries. The recovery could be increased to 80 per cent by increasing the specific gravity (SG) of separation, but the ash content of the product was also increased to 20 per cent. Spirals were used to produce 16 to 20 ash products with recoveries in the range of 50 to 70 per cent. According to Cho *et al.*[2] flotation is the best method of beneficiating Korean anthracite. They showed that a two-stage flotation of a -2+0.15 mm coal produced 12–15 per cent ash products with 76–93 per cent recoveries. To obtain recoveries of greater than 90 per cent, it was necessary to use 3–4 kg/t of kerosene as collectors. Based on their laboratory test work, Cho *et al.* suggested a flowsheet, in which a run-of-the-mine coal is pulverized in a ball mill and the product is floated after desliming at 0.15 mm.

The objective of the present investigation was to develop a simple flowsheet, which can be used to clean ROM Korean anthracite coal efficiently. The flowsheet development is based on the premise that flotation is the best available method for cleaning the Korean anthracite[2]. In general, however, flotation is effective with particles of less than approximately 0.5 mm[3,4], which can be a serious limitation. The difficulty in floating coarse particles is attributed to the high probability of coarse particles being detached from air bubbles during flotation[5,6]. In the present work, novel flotation reagents have been tested to extend the upper particle size limit. If successful, use of such reagents can substantially increase the efficiency of a gravity-based separator, such as spirals and dense-medium separators, by narrowing the particle size distribution.

* *Minerals and Coal Technologies, Inc., Blacksburg, Virginia, USA.*

Experimental

Sample

A 3 mm x 0 anthracite coal sample was received from Kyung-Dong Coal Company, Korea. The sample was cone-and-quartered to obtain four equal parts. The first quarter was split into several size fractions and subjected to standard washability analysis (float-sink tests). The second part was riffled into 250 g lots and used in batch flotation tests, while the third quarter was used for pilot-scale conventional flotation tests. The fourth quarter was used to determine the head grade and size distribution for the feed sample. The run-of-mine sample, which contained approximately 22 per cent ash and 0.5 per cent sulphur, was 31.5 per cent finer than 0.15 mm, 51.9 per cent finer than 0.5 mm, 66.8 per cent finer than 1 mm, and 82.4 per cent finer than 2 mm.

Reagents

Laboratory and pilot-scale flotation tests were conducted using novel flotation reagents that are designed to increase the kinetics of flotation, particularly those of coarse particles. Due to the proprietary nature of the reagents, the reagents are simply identified as 01DU113, 01DU133, and Reagent AE without identifying their chemical compositions.

Washability analysis

Float-sink tests were conducted on various size fractions (+2 mm, -2+1 mm, -1+0.5 mm, -0.5+0.25 mm, and -0.25 +0.15 mm) of the run-of-mine coal. The tests were performed by sequentially immersing the coal samples into solutions of dense liquids with specific gravities ranging from 1.3 to 2.3 SG in increments of 0.1 SG. Mixtures of perchlorethylene (SG=1.63) and tetrabromoethane (SG=2.96) were used to prepare the dense liquids. The float and sink products were collected, drained, rinsed, dried and weighed. Standard coal analyses (ash, sulphur and heating value) were performed on each product.

Laboratory flotation tests

All of the laboratory tests were conducted in batch mode using a Denver D-12 flotation machine. In each test, a 250g coal sample was used in a 4-litre stainless steel flotation cell. Sufficient make-up water was added in each test to maintain a pulp level approximately 2.5 cm below the froth overflow lip. The coal sample was conditioned in the flotation cell at 1,500 rpm for 2.5 min after adding a known dosage of reagent. After the conditioning, 150 g/t of methylisobuthyl-carbinol (MIBC) was added as frother, and the pulp was agitated for another 30 sec before introducing air to initiate flotation. The froth product was collected until exhaustion to fully recover all of the floatable materials. Each flotation product was filtered, dried, weighed and then subjected to ash analysis. For kinetics tests, 500 g of coal samples were used.

Pilot-scale flotation tests

Pilot-scale flotation tests were conducted using a bank of four Denver Sub-5 flotation cells (28 litres per cell). In these tests, the 3 mm x 0 coals sample was fed to a 14-mesh (1.41 mm) vibrating screen. The screen underflow was sent to a sump where novel flotation reagents (01DU113 or 01DU133) were added in the amount of 800 g/t and agitated. The slurry was pumped to the first cell of the flotation bank and agitated without aeration for approximately 3 minutes, and then floated in the remaining three cells at an aeration rate of 100 litres per minute per cell. The flotation bank was fed at 10 litre per minute of feed rate at 13.7 per cent solids. The flotation tests were conducted for at least 30 minutes before taking representative samples for analyses.

Results and discussion

Washability tests

The washability data conducted on the five different size fractions (+2 mm, -2+1 mm, -1+0.5 mm, -0.5+0.25 mm, and -0.25+0.15 mm) of the Kyung-Dong anthracite showed that the cumulative yield dropped sharply when the specific gravity of separation was below 1.9 SG. Table I shows the yields and ash contents of the products obtained at 1.9 SG. As shown, the clean coal yield increased from a low of 68.3 per cent at +2 mm to an average of approximately 82 per cent at the three finer size fractions. Also, the ash content decreased from 11.2 per cent at +2 mm to 7.9 per cent at the -0.25+0.15 mm fraction. The increase in yield and decrease in ash content are due to improved liberation of the ash-forming minerals with decreasing particle size.

Table I

Results of the washability analysis conducted on the Kyung-Dong anthracite coal sample at 1.90 SG

Particle size (mm)	%Weight		
	Ash	Sulphur	Yield
+2	11.2	0.17	68.3
-2+1	10.1	0.14	78.3
-1+0.5	9.9	0.09	81.8
-0.5+0.25	8.9	0.14	82.9
-0.25+0.15	7.9	0.15	81.6

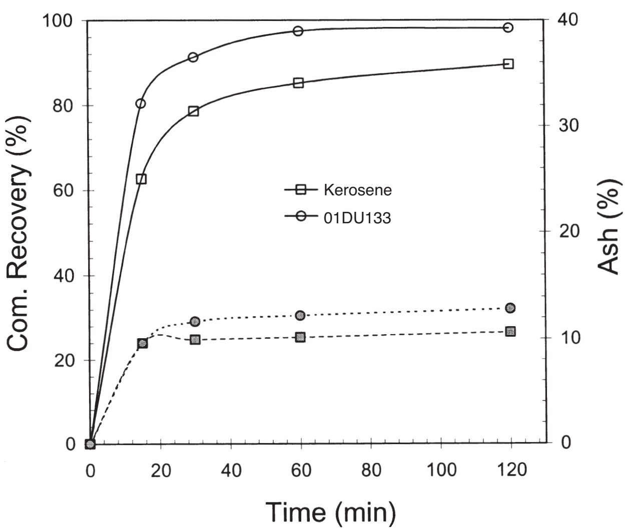

Figure 1—Comparison of the flotation kinetics tests conducted on the 0.6 mm x 0 Kyung-Dong anthracite coal using 800 g/t collector and 150 g/t MIBC

Kinetics tests

Two sets of flotation tests were conducted on the -0.6+0 mm fraction using 800 g/t of kerosene and 01DU133 as collector with 150 g/t MIBC. The froth products were collected as a function of time so that kinetic information could be obtained. The results given in Figure 1 show that the novel flotation reagent gave significantly higher kinetics and, hence, higher ultimate recovery. After 2 minutes of flotation with kerosene, a froth product assaying 10.6 per cent ash was obtained with 89.5 per cent recovery. With 01DU133, the same recovery could be achieved in approximately 25 seconds. At 2 minutes of flotation time, the novel flotation reagent gave 98.1% combustible recovery with 12.8% ash in the froth product.

Figure 2 shows the results of the kinetics tests conducted on the -2+0.6 mm coal sample. With this coarse coal, the kerosene flotation gave only 55.8 per cent recovery at 11.2 per cent ash after 2 min flotation. The low recovery can be attributed to the high probability of detachment for large coal particles. After 2 minutes of flotation using 01DU133, the combustible recovery was increased to 83.6 per cent at 11.2 per cent ash. This large improvement in recovery can be attributed to the decrease in the probability of detachment in the presence of the novel flotation reagent. Note here that the improved recovery was achieved without deterioration in selectivity. From the data given in Figures 2 and 3, one can see that the advantage of using the novel flotation reagent can be best seen with the flotation of coarse particles.

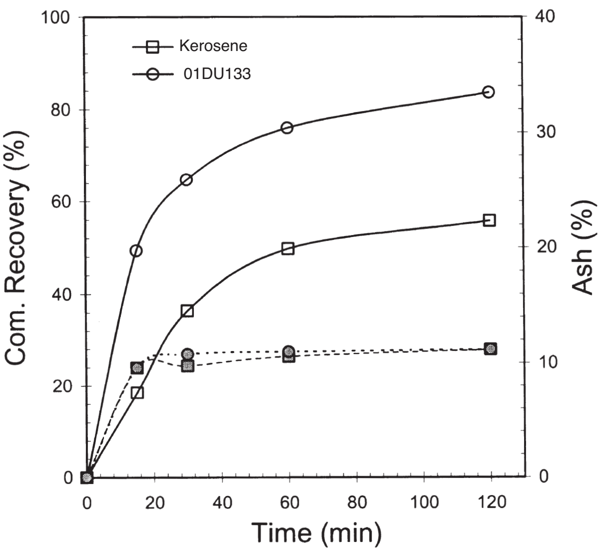

Figure 2—Comparison of the flotation kinetics tests conducted on the 2 x 0.6 Kyung-Dong anthracite coal sample using 800 g/t collector and 150 g/t MIBC

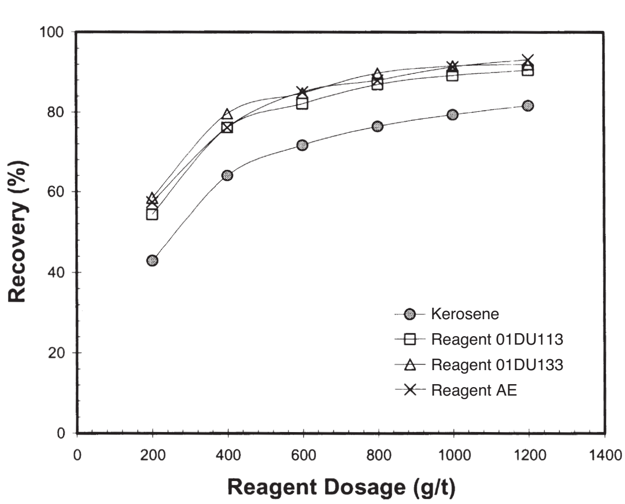

Figure 3—Effect of collector dosage on the combustible recovery of the 3 mm x 0 Kyung-Dong anthracite coal sample

Laboratory flotation tests

Figure 3 shows the results of the flotation tests conducted on the 3 mm x 0 coal sample using four different collectors (i.e., kerosene, 01DU113, 01DU133 and Reagent AE). The tests were conducted by changing the reagent dosages in the range 200 to 1,200 g/t. The recovery increased with increasing reagent dosages for all of the collectors tested. However, the novel flotation agents gave substantially higher recoveries than kerosene at all levels of reagent dosages tested. Figure 4 shows the recovery versus ash plots for the tests conducted on the -3+0 mm coal sample. As shown, all of the data points fall on the same curve, which indicates that the use of the novel flotation reagents did not deteriorate the selectivity. It shows also that the shape of a grade versus recovery curve is dictated by the liberation characteristics of the sample and not by the flotation reagents used.

A series of flotation tests were conducted on the Kyung-Dong anthracite coal sample of different top sizes, i.e., 0.15, 0.25, 0.5, 1 and 2 mm. The maximum combustible recoveries obtained using the four different collectors are plotted as a function of top size, as shown in Figure 5. It is interesting that all of the collectors tested in the present work gave maximum recoveries at the top size of 0.5 mm. At this size, the recoveries obtained using the novel flotation reagents were approximately 6 percentage points higher than those obtained using kerosene only. The differences became larger at higher top sizes. For example, the novel flotation reagents gave nearly 13-percentage points higher recovery at the 2 mm top size. Of the several different novel flotation reagents tested in the present work, 01DU133 and Reagent AE gave about the same results. 01DU113 was slightly inferior, but its performance was as good as Reagent AE and 01DU133 at top sizes below 1.0 mm.

Pilot-scale flotation tests

The data plotted in Figure 5 shows that the optimum top size for the flotation of the anthracite coal is approximately 0.5 mm. The recovery decreased substantially with increasing particle size. Higher reagent dosages would have increased the recovery. However, the higher dosages would also have increased the recovery of ash-forming minerals. It was, therefore, decided to conduct pilot-scale tests with less than 1 kg/t of novel flotation reagents. Table II shows the results of the pilot-scale tests conducted on the -14 mesh (1.41 mm) coal sample using 800 g/t of 01DU113 and 01DU133. The former gave 94.9 per cent combustible recovery at 9.35 per cent ash (6,994 kcal/kg)), while the latter gave 95.3 per cent

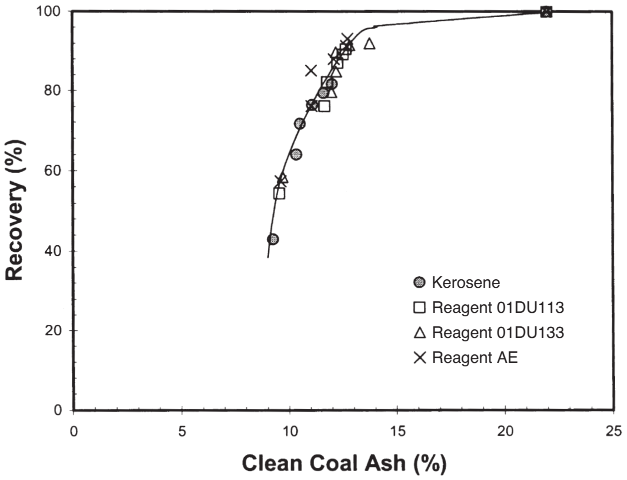

Figure 4—Combustible recovery versus grade plots for the flotation of the 3 mm x 0 Kyung-Dong anthracite coal sample

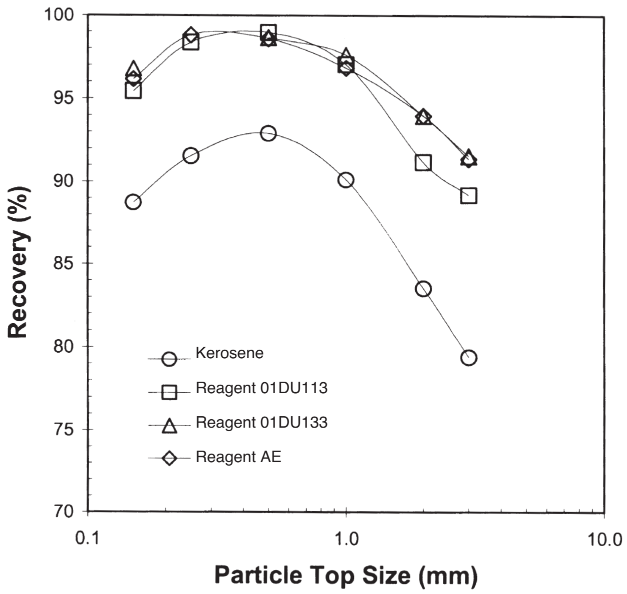

Figure 5—Comparison of the novel flotation reagents and the conventional collector (kerosene). Combustible recoveries are plotted as a function of the feed top size

recovery at 9.61 per cent ash (6,972 kcal/kg). These two data points fall onto the recovery versus top size curves shown in Figure 5, demonstrating that there are no scale-up problems in using the novel flotation reagents. Furthermore, the quality of the product was sufficient for non-fuel use of the anthracite. The requirement for using an anthracite coal as a carbon additive in steel making processes is 6,400 kcal/kg[1].

Flowsheet design

Two different conceptual flowsheets were developed for the beneficiation of the ROM anthracite coal. Figure 6 shows a flowsheet, in which 0.5 mm x 0 coal is floated using the conventional flotation reagent (kerosene), while Figure 7 shows a flowsheet, in which 1.41 mm x 0 coal is floated using one of the novel flotation reagents tested in the present work. An advantage of the former is that the feed to the flotation circuit has an optimum top size of 0.5 mm. On the other hand, the -4+0.5 mm fraction has a relatively wide size distribution, which can only be processed in two separate spiral circuits (i.e., -4+2 mm and -2+0.5 mm).

The advantage of the flowsheet shown in Figure 7 is that by increasing the top size of the flotation feed to 1.4 mm, only one spiral circuit may be sufficient. More importantly, an increase in the top size should allow a larger proportion of the feed to be cleaned by the flotation circuit, which can inherently produce lower-ash products than the spirals. This should in turn allow the spirals to be operated at a higher SG of separation and, thereby, increase the overall plant throughput without lowering the product quality.

Mathematical simulations were carried out to evaluate the performance of the two conceptual flowsheets shown in Figures 6 and 7. For the case of limiting the flotation top size to 0.5 mm, the operating point for the flotation circuit was held constant in all simulation runs at 84.7 per cent yield (96.2 per cent combustible recovery) and 10.49 per cent ash. These values were taken from the results of the flotation test conducted on the 0.5 mm x 0 coal at 0.6 kg/t of 01DU113

Table II

Results of the pilot-scale flotation tests conducted on the -1.41 mm x 0 anthracite coal sample using 800 g/t of novel flotation reagents

	Process stream		
	Clean coal	Refuse	Feed
01DU113			
Ash (%)	9.35	75.82	20.42
Heat (kcal/kg)	6,994	1,298	6,045
Yield (%)	83.35	16.65	100.00
Recovery (%)	94.94	5.06	100.00
01DU133			
Ash (%)	9.61	76.75	20.42
Heat (kcal/kg)	6,972	1,218	6,045
Yield (%)	83.90	16.10	100.00
Recovery (%)	95.30	4.70	100.00

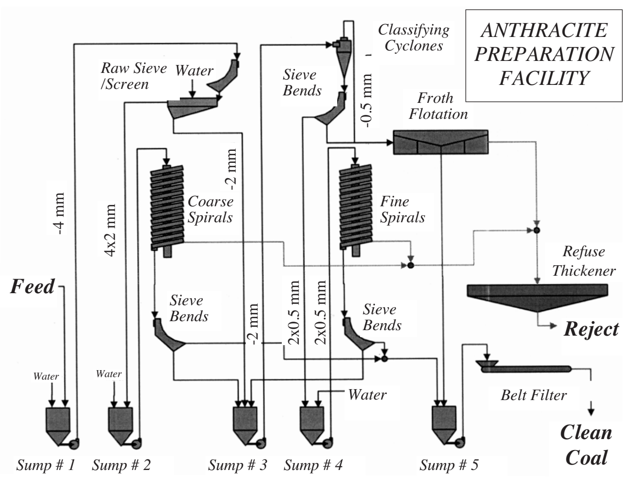

Figure 6—Conceptual flowsheet for the processing of the 4 mm x 0 Kyung-Dong anthracite coal. The flotation circuit is designed to operate with a conventional collector

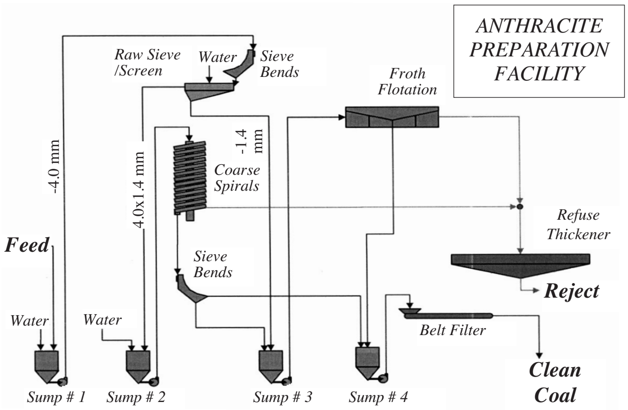

Figure 7—Conceptual flowsheet for the processing of the 3 mm × 0 Kyung-Dong anthracite coal. The flotation circuit is designed to operate with a novel flotation reagent

which gave the highest separation efficiency. Standard partition models were used to simulate the performance of the spiral circuits. The cut points for the coarse and fine spirals were adjusted so as to produce a combined product ash of 11 to 12 per cent. The simulation results suggest that this flowsheet (Figure 6) can give 78.4–89.2 per cent combustible recoveries (68.5 to 78.8 per cent yields).

For the case of extending the flotation top size to 1.4 mm (Figure 7), the simulation runs were run by setting flotation performance at 9.48 per cent ash with 95.1 per cent combustible recovery (83.6 per cent yield), which are the averages of the two pilot-scale flotation test results (Table II). The cut points for the single spiral circuit were adjusted to provide a combined product ash of 11 to 12 per cent. Under these conditions, the simulation runs show that the advanced flowsheet is capable of producing 92.7 to 94.7 per cent combustible recoveries (81.3 to 84.0 per cent yields).

The performance of the two flowsheets is compared in Figure 8. The advanced flowsheet, which is capable of floating 1.41 mm top size particles, gives 5.5 to 14.3 per cent higher combustible recoveries (or 5.2–12.8 per cent higher yields) than the flowsheet where the flotation top size is limited to 0.5 mm. By increasing the upper particle size limit of flotation, the amount of coal cleaned by spirals is reduced substantially. As a result, a larger proportion of coal in the feed can be cleaned to a lower ash level by flotation, which allows the spirals to be operated at a higher set point to give a higher yield.

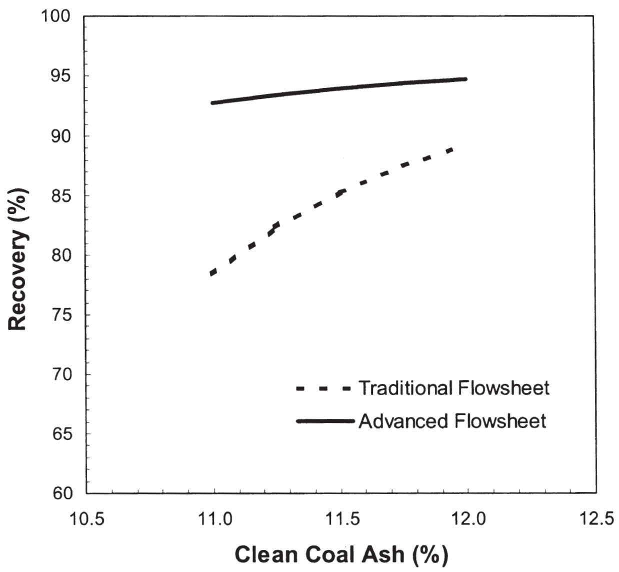

Figure 8—Comparison of the two flowsheets given in Figures 6 and 7

Conclusions

Several new flotation collectors have been tested successfully for extending the upper particle size limit for coal flotation. These reagents are specially formulated to minimize the probability of detachment and, thereby, increase the flotation rates of coarse particles. The results of the present work showed that coal particles as large as 2–3 mm in diameter can be readily floated with combustible recoveries exceeding 90 per cent. By extending the upper particle size limit, spirals can be operated at higher set points, resulting in higher yields. Thus, the results of the present investigation showed that extending the upper particle size limit of flotation using the novel flotation reagents can not only increase the overall plant yields but also simplify the flowsheet.

References

1. JUN, H.T., KIM, M.K., and CHOI, W.Z. A study on the utilization of domestic coal sintering fuel and carbon additives in the steel industry. A Report to the Ministry of Trade and Industry, Korea, February, 1998.
2. CHO, H.C., YU, S.H., KIM, J.W., and WHANG, Y.W. An Investigation on the Use of Kyung-Dong Anthracite for Sintering and Carbon Additives. Final Report to the Ministry of Trade and Industry, Korea, August, 1998.
3. BENSLEY, C.N. and NICOL, S.K. *Coal Preparation*. vol. 1, no. 2, 1985. p. 189.
4. FIRTH, B.A., SWANSON, A.R., and NICOL. S. Flotation circuits for poorly floating coals. *Int. J. of Miner. Proc.* vol. 5, 1979. pp. 321–334.
5. FRENCH, R.M. and WILSON, D.J. Fluid mechanics-foam flotation interactions. *Separ. Sci. Technol.* vol. 15, 1980. p. 1213.
6. YOON, R.H. and MAO, L. Application of extended DLVO theory, IV: Derivation of flotation rate equation from first principles. *J. Colloid Interface Sci.*, Vol. 181, 1996. pp. 613–626. ◆