PERFORMANCE OPTIMIZATION OF THE IMHOFLOT G-CELL FOR FINE COAL CLEANING

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Abstract

G-Cell is a new design modification of the Imhoflot pneumatic flotation technology, which utilizes a self-inducing aerator inside a downcomer, where bubble-particle attachment takes place. The flotation slurry containing the particle-bubble aggregates are introduced tangentially to a cylindro-conical separation vessel through multiple inlets. The high tangential velocity along with the limited capacity of the froth-separating vessel results in an increased kinetics of separation. In addition, the resulting centrifugal field in the separation vessel tends to provide a congenial environment to reject the high-density solid particles, for example, coal pyrite particles in the feed, to the tailings stream.

The present study has investigated the suitability of the G-Cell technology for cleaning fine coal using a 0.8 meter diameter prototype unit at a coal preparation plant operating in the US. A slip-stream obtained from the overflow of raw coal cyclones operating in the plant, containing nominally minus 150 micron size particles and having high ash content and moderately high sulfur content, has been used as the feed for the G-Cell. The metallurgical data produced from the G- Cell tests are found to be very close to the ideal performance curves produced from release analysis. A statistically designed experimental program has been conducted to investigate the parametric effects on various key process responses, such as combustible recovery, product ash and sulfur rejection. The empirical models developed in this

study have been utilized to identify a suitable experimental region for achieving a desired combination of response targets.

Introduction and background

Imhoflot G (gyratory)-Cell, in short, G-Cell, is an improved design of a pneumatic flotation technology, which initially originated from the work of Professor Bahr at the Technical University of Clausthal, Germany (Battersby et al., 2003). The unique feature of the G-Cell technology is the tangential entry of the down-comer discharge to a cylindro-conical separating vessel and the resulting centrifugal field. G-Cell utilizes a self-aspirating aerator based on the principle of multi-jet venturi operating at a pressure of nearly 2.0 bar. Bubble-particle contact and attachment take place in a down-comer, whereas froth-separation takes place in the separating vessel equipped with a froth washing system. Unlike other pneumatic flotation technologies, which utilize a residence time of a few minutes in the separating vessel for an adequate froth separation, G-Cell achieves froth separation in several seconds due to high tangential velocity and limited capacity of the separating vessel. This phenomenon may result in a multi-fold increase in the throughput capacity of G-Cell in comparison to other flotation technologies. In addition, the centrifugal environment in the separating vessel may allow effective rejection of coal pyrite particles, which may be attached to the air-bubbles due to weak hydrophobicity.

A few technical publications (Imhof et al., 2002; Battersby et al., 2003; Lubbe, 2003) are found in literature related to G-Cell operations. Imohf et al. (2002) were the first to report the invention of the G-Cell technology. Battersby et al. (2003) reported G-Cell's application as a part of modular plant to recover fine coal from coal slurry impoundments. For a combination circuit of G-Cell flotation and Steel Belt Filter dewatering, it was reported that pre-tax profit could be realized from a modular plant having a throughput capacity of 40 metric ton per hour with a minimum sales price of around 75 cents per GJ (of coal heating value). Lubbe (2003) in South Africa conducted G-Cell tests in an operating coal preparation plant, where he investigated the effect of feed inlet orifice size as well as weir settings, which allow a partial recirculation of tailings. However, the marginal enhancement in product quality from 18% to 14% and the best separation efficiency (=combustible recovery-ash recovery) of a meager 20% are indicative of the preliminary nature of this G-Cell study.

The present study aimed at conducting a more scientific study to investigate the best potential of G-Cell in comparison to the optimum flotation cleanability provided by a standard release analysis. A factorial experimental design was conducted to study the factor main effects and interaction effects on several key process responses including combustible recovery, product ash and sulfur rejection performance achievable by the G-Cell technology. Using a statistical response methodology, it has been shown how to identify an appropriate experimental region, or in other words, a set of experimental conditions to produce a desired set of process response.

Experimental

A plant site was selected to obtain an unlimited supply of flotation feed slurry for the 0.8 meter diameter G-Cell tested during this investigation. As shown in the experimental layout, a slip stream was obtained from the overflow of the classifying cyclones operating inside the plant. At present, being a high ash stream of nominally minus 150 micron particle size, this stream is rejected directly to the plant-thickener without any attempt to recover the clean coal present in this plant stream. The slip stream from the cyclone overflow discharges directly to the feed sump having a capacity of nearly 800 liters. In majority of the G-Cell tests, which were conducted without any tailings recirculation, a batch of 800 liters of flotation feed was collected in the feed sump and conditioned with a desired dosage of fuel oil (#2) for nearly five minutes before beginning the flotation tests. A variety of frother types were tested during the experiment; subject to its solubility in water, a frother was either added directly to the feed line or the feed sump at the desired concentrations. The tests conducted with a partial tailings re-circulation were carried out with a continuous supply of plant feed slurry and partly recirculated tailings to the feed sump. The amount of fresh feed material had to be adjusted by controlling a valve to maintain a constant level in the feed sump. For example, to conduct a test with a 25% tailings recirculation and G-Cell feed flow rate of 100 L/Min, 75 L/Min of fresh feed and 25 L/Min of tailings material were continuously supplied to the feed sump.

Initially, several series of exploratory tests were conducted to select a proper size of feed inlet orifice, select a suitable type of frother, gather an estimate of the plant variability and also to establish the range of values for the key process parameters to be varied in the optimization test program. The process parameters and their respective range of values selected based on these exploratory tests are listed in Table 1. As shown, four process parameters, including feed flow rate, wash water rate, frother concentration and collector dosages, were varied in the range of 80 to 100 L/min, 5 to 8 L/Min, 10 to 20 ppm and 0.4 to 0.8 kg/tonne, respectively, during the optimization test program. Feed pressure varied from 1.7 Bar to 2.4 Bar by changing the feed flow rate in the aforementioned range. The height of the tailings discharge port (which controls the froth height in the G-Cell) was maintained constant at nearly 12 cm below the lip of the internal product launder since it was not practicable to vary it over a reasonably wide range. The other process parameters that were maintained constant included the Pine oil type of frother and the orifice size of 10 mm for the four feed inlets. In total, 29 tests were conducted during the optimization test program in accordance with a test matrix generated utilizing Central Composite Design. A set of three samples: feed, product and tailings, were collected for each G-Cell test for subsequent analysis of different types of assays, including ash and sulfur. A composite feed sample was collected during the entire optimization test program, which lasted for nearly 16 hours, for conducting release analysis.

Results and discussions

Metallurgical performance

The maximum cleaning potential of a given coal is measured by the characteristic recovery-grade curve generated from release or tree analysis. As exhibited by Figures 2 (a) and (b), the proximity of the G-Cell data to the recovery-grade curve generated from release analysis, is indicative of the superior ash and sulfur cleaning achievable by the G-Cell technology. The G-Cell data shown in Figure 2, were obtained from the experiments conducted as a part of the optimization test program utilizing a Central Composite Design (CCD) test matrix. A few test data had to be eliminated from the analysis due to the extreme variability in the plant conditions. The feed quality variation that was considered normal for the plant condition and thus acceptable for analysis ranged from 40% to 50% ash. The sulfur content of the G-Cell feed was typically around 1.4% to 1.5%. The product ash, combustible recovery and sulfur rejection achieved by the G-Cell varied in the range of 6.25% to 17.4%, 23.3% to 69.5% and 41.7% to 89%, respectively. The corresponding ash rejection values ranged from 88.4% to 97.6%. The best separation efficiency of nearly 53% was obtained at a test condition that achieved a mass yield of 45.0%, a combustible recovery of 69.5% and a product ash content of 10.9%. The corresponding ash and sulfur rejection values were 88.4% and 41.7%, respectively. It may be noted that the proportion of organic and inorganic sulfur present in the G-Cell feed was nearly 50:50, which may explain the aforementioned relatively low sulfur rejection value.

A careful examination of the ideal performance curve produced by the release analysis may reveal the possibility of increasing the combustible recovery values up to nearly 80% at a reasonable product ash content of nearly 10%. However, the best combustible recovery values obtained from the G-Cell tests without any tailings recirculation was below 70% at a reasonable product ash content in spite of testing significantly higher collector and frother dosages. To further improve combustible recovery values, additional tests were conducted by recirculating a portion of the tailings. Although, combustible recovery values were increased up to 78.7% and 86.1%, for 25% and 40% tailings recirculation tests, respectively, the corresponding product ash content were above 20%, which is considered excessively high.

Parametric study

Empirical models were developed for important process responses, including combustible recovery, product ash and sulfur rejection achieved from the G-Cell as a function of the aforementioned four key process parameters. Step-wise regression analysis was conducted to include significant main-factors and factor-interactions in the model equations. A few of the extreme response data, considered as outliers, had to be eliminated while conducting the regression analysis to develop suitable quadratic models with reasonably high R^2 values of around 0.85. The model equations are described as follows:

$$\sqrt{Combustible\ \mathrm{Recovery}} = 7.24 - 0.046A + 0.628B + 0.293C + 0.602D + 0.670AB - 0.379BC - 0.745BD - 0.601CD \quad [1]$$

$$\frac{1}{\mathrm{Pr}\,oduct\ Ash} = 0.113 - 0.032A - 0.003B + 0.003D + 0.028BD - 0.019AD \quad [2]$$

$$Sulfur\ \mathrm{Re}\,jection = 67.0 - 0.140A - 2.385B - 8.798C - 1.127D + 11.5A^2 - 8.57AC + 13.1BD \quad [3]$$

where, A, B, C and D represent feed flow rate, frother concentration, collector dosage and wash water rate, respectively in coded terms, which are described by the following expressions:

$$A = \frac{Feed\ Rate\,(L/Min) - 90}{10}$$
$$B = \frac{Frother\,(ppm) - 15}{5}$$
$$C = \frac{Collector\,(kg/tonne) - 0.6}{0.2}$$
$$D = \frac{Wash\,Water(L/Min) - 6.5}{1.5}$$

The main factor effects and interaction effects, which were found to be statistically significant at α value of 0.05 have been included in the above equations to describe the three process responses. By coding the factors in the aforementioned manner, a normalized range, i.e., -1 to +1 is established for each factor so that it is easier to examine the relative effects of operating parameters on the process responses. For example, it would be safe to conclude from Equation 1 that the most influencing main factors for combustible recovery include frother concentration (B) and wash water rate (D) whereas, the most important factor interactions include BD, AB and CD. Feed rate (A), Collector dosage (C), and factor interaction (BC), although statistically significant, have relatively lesser effect on combustible recovery response.

Although, the above three equations help determine the relative importance of factor main effects and interaction effects on the process responses, the nature of the effect can not be assessed by examining only these equations. For example, the positive sign of the term D in Equation 1 may appear to indicate that the combustible recovery increases with an increase in wash water rate; however because the CD interaction has a negative sign, it is difficult to ascertain the exact nature of the relationship without a graphical analysis. Therefore, graphical illustrations of Figures 3-5 have been utilized to further analyze the parametric effects on the aforementioned three key process responses.

<u>Combustible recovery:</u> Figures 3 (a)-(d) help study the effect of various key process parameters on combustible recovery response in detail. As shown in Figure 3 (a), combustible recovery obtained from the G-Cell increases from 62% to 83% with an increase in feed rate from 80 L/Min to 100 L/Min at the highest level of frother concentration, i.e., 20 ppm. On the other hand, combustible recovery decreases from 43% to 27% for the aforementioned change in feed

rate at the lowest level of frother concentration, i.e., 10 ppm. With the aforementioned increase in feed rate, the feed pressure at the venturi is increased from nearly 1.7 Bar to 2.4 Bar. Higher feed pressure promotes better shearing action in the downcomer and thus helps produce more fine bubbles in the presence of sufficient amount of frother solution. As a result, more clean coal particles get a chance to be attached to the air bubbles and be carried over to the product launder, thereby increasing the combustible recovery. However, in the absence of sufficient amount of frother, the air bubbles are relatively larger and lesser is the total available bubble surface area for the clean coal particles. This phenomenon is believed to be causing the decrease in combustible recovery with an increase in feed rate at the lowest frother concentration.

A considerable increase in combustible recovery from 25% to nearly 70% is indicated in Figure 3 (b) due to an increase in frother concentration from 10 ppm to 20 ppm at the lowest collector dosage of 0.4 kg/tonne. An increase of a relatively smaller magnitude is indicated at the highest collector dosage of 0.8 kg/tonne. Since frothers are known to have collecting properties, a portion of the frother is believed to be used up by the coal particles as collectors due to an apparently insufficient collector dosage. Understandably, this phenomenon may affect bubble generation process the most at the lowest frother concentration resulting in the lowest combustible recovery at this condition. As the frother concentration is increased, the proportion of frother used in the bubble generation processes increases producing finer and more air bubbles. As a result, combustible recovery increases significantly to nearly 70%, which is also nearly the same recovery value achieved with high dosage of collector at the highest frother concentration. It appears that the high collector dosage of 0.8 kg/tonne provides sufficient amount of collector required for enhancing the hydrophobicity of the coal surfaces so that 100% of the frother solution is used in the bubble generation and froth stabilization process.

Figures 3 (c) and (d) illustrate the interaction effects of frother-wash water and collector-wash water. It appears that the mobility of the froth is significantly improved by increasing the wash water level from a low of 5 L/Min to a high of 8 L/Min resulting in a near 33% increase in combustible recovery at a frother concentration of 10 ppm. On the other hand, wash water rate appears to have little effect on combustible recovery at the highest frother concentration of 20 ppm indicating a significant frother-wash water interaction. It is quite reasonable to expect an increase in combustible recovery with an increasing collector dosage, as shown in Figure 3 (d), especially at low wash water rate. However, this increase in combustible recovery, which results from the increasing recovery of weakly hydrophobic coal particles due to increasing collector dosages, is reversed at high wash water rate. High wash water rate is believed to force the detachment of weakly attached particles from the froth zone of the G-Cell to its pulp zone and thus, reduces combustible recovery at high collector dosage.

<u>Product ash content:</u> As indicated by Equation 2, the main factors A, B and D as well as the factor interactions AD and BD were found to be statistically significant for the product ash response. The nature of these factor main effects and interaction effects are illustrated in Figures 4 (a) and (b). The increased froth mobility due to an increase in wash water rate not only increases combustible recovery, as explained in the previous paragraph, but also allows more water to report to the flotation concentrate launder. Higher amount of feed water in the concentrate launder results in higher product ash content. An increase in frother concentration from 10 ppm to 20 ppm leads to the production of more and finer air bubbles. It is well understood that when the bubble surface area availability is limited, the more hydrophobic (which are usually with lesser ash content) coal particles are captured by the air bubbles and recovered to the product launder. As more and more bubble surface area becomes available with an increase in frother concentration, coal particles of relatively higher ash contents are captured and carried over to the product launder, thus increasing the product ash content. In addition, more air bubble carry-over to the concentrate launder also means more entrainment of feed water to the product. These two phenomena may be the causes of an increase in product ash content as a function of increasing frother concentration at the lowest water rate of 5 L/Min. However, this increasing trend of product ash content appears to be reversed at high wash water rate of 8 L/Min. It is believed that high wash water rate force the weakly hydrophobic (typically with high ash content) coal particles to selectively detach so that product ash content reduces inspite of increased combustible recovery. In addition, high wash water rate also tends to minimize the entrainment of feed water to the product launder. Thus, the product ash content is reduced with an increasing frother concentration at high wash water rate.

As illustrated in Figure 4 (b), product ash content increases as a function of feed rate irrespective of the wash water addition rate. However, the increase is more significant at higher wash water rate. At the lowest feed rate, high wash water rate is effective in reducing the product ash content to as low as 6.0%. However, with the increase in feed flow rate to 100

L/Min, the pulp/froth interface in the G-Cell rises since the tailings discharge is maintained at a constant level of 12 cm from the top of the internal product launder. This phenomenon reduces the amount of froth drainage and thus, increases the amount of water recovered to the product launder. Increased amount of feed water to the product launder results in increased product ash content. In addition, it also appears that higher volumetric flow of wash water also further raises the pulp/froth interface inside the G-Cell causing higher product ash content.

<u>Sulfur rejection:</u> As indicated in Equation (3), all four factor main effects as well as AC and BD interaction effects were found to be statistically significant for sulfur rejection response. In addition, it is also clear that sulfur rejection has a quadratic relationship with feed flow rate. The exact nature of these parameter relationships are illustrated in Figures 5 (a) and (b). It may be noted that with an increase in the feed flow rate, the tangential feed inlet velocity inside the separation vessel of the G-Cell also increases resulting in a centrifugal field of higher magnitude. Therefore, the coal pyrite particles, which are believed to be weakly hydrophobic, tend to be detached from the air bubbles and rejected to the tailings stream under the action of increased centrifugal force at a feed flow rate of 90 L/Min or higher. The effect of centrifugal force on the rejection of coal pyrite particles appear to be minimal at lower feed rates. However, at high collector dosage, the hydrophobicity of the pyrite particle is sufficiently enhanced, a fact which has been measured by other investigators (Olson and Aplan, 1984), to prevent their detachment even under the action of high centrifugal field. On the other hand, as described earlier, the pulp/froth interface rises in the G-Cell with an increasing feed flow rate. This reduces bubble coalescence and increases the recovery of coal pyrites along with majority of the combustibles in coal in the presence of sufficient amount of frother. This phenomenon is believed be the cause of a significant decrease in sulfur rejection with an increase in feed rate at the highest level of collector dosage.

As illustrated in Figure 5 (b), the sulfur rejection response increases significantly from 55% to more than 75% with an increase in frother concentration from 10 ppm to 20 ppm at the highest level of wash water. It is believed that the high wash water rate of 8 L/min is sufficient to force the weakly attached coal pyrite particles to drop back to the pulp but allow the more hydrophobic combustibles to remain attached to the air bubbles. Therefore, sulfur rejection increases although combustible rejection (100-recovery) decreases due to more availability of bubble surface area with an increase in frother concentration. This finding agrees well with the previous explanation for the increase in combustible recovery as a function of increasing frother concentration. However, lower wash water rate does not appear to be sufficiently strong to detach any weakly attached particles from the air bubbles. Therefore, recovery of coal pyrites and also organic sulfur increases as a function of increasing frother concentration and thus causes the total sulfur rejection to decrease as shown in Figure 5 (b).

Process optimization

A statistical response surface methodology (Box, Hunter and Hunter, 1978) was pursued to identify an optimum experimental region to achieve a desired set of target responses. The empirical models developed for the three key process responses were utilized to generate response surface contours using a commercially available statistical software package. Response surface contour plots generated over the entire range of parameter values for all four operating parameters investigated provide insight into the feasibility of achieving a specific target response value. Then by overlaying contour plots for each response, an appropriate experimental region is identified to simultaneously achieve each target response values. Based on the model predictions about the optimum achievable performances, a target set of response variables such as, a minimum combustible recovery of 70%, maximum product ash content of 13% and a minimum sulfur rejection of 50%, may be selected. Using the aforementioned software package, an appropriate experimental region may be located that is shown as the shaded (dark) area in the overlay plot of Figure 6. As indicated, the suitable experimental region to achieve the selected set of response targets is described by a feed rate in the range of 97 L/Min to 100 L/Min, frother concentration in the range of 17.5 ppm to nearly 18.5 ppm, a collector dosage of 0.8 kg/tonne and wash water rate of 5.0 L/Min. It may be noted that the identified experimental region is not necessarily the only experimental region that can produce the desired response targets. Similar other experimental regions may be found out by investigating the entire range of other process parameters, which are maintained at a constant level for the above analysis.

Conclusions

1. An improved design of a pneumatic flotation technology, known as Imhoflot G-Cell, has been successfully tested and optimized for fine coal cleaning application at a coal preparation plant in the US. The best G-Cell performance obtained from cleaning a nominally minus 150 micron size coal stream having an average ash content of nearly 45% may be described by a combustible recovery of nearly 70% at an ash content of nearly 11%.
2. The recovery-grade data generated from the G-Cell compared satisfactorily with the ideal performance curve generated from a standard release analysis. However, combustible recovery value above 70% was not achievable from a single stage G-Cell operation without resorting to partial tailings-recirculation, in which case the product ash contents were unreasonably high. This implies that a two-stage (rougher-scavenger) operation may be required to achieve high mass yield and combustible recovery from G-Cell operation.
3. Excellent sulfur rejection values, as high as 60%, were achievable from the G-Cell at fairly high combustible recovery values. The centrifugal field created in the froth-separation vessel of the G-Cell by the tangential entry of the downcomer discharge is believed to force-detach the weakly hydrophobic coal pyrite particles from the air bubbles and thus helps achieve excellent rejection of sulfur.
4. A detailed parametric study indicated the major role the parameter interaction effects play in influencing the key process responses such as, combustible recovery, product ash content and sulfur rejection. The frother-feed rate, collector-frother, frother-wash water and collector-wash water interactions were found to be significant in affecting combustible recovery response. Frother-wash water, and feed rate-wash water were found to be significant for product ash response, whereas feed rate-collector and frother-wash water interactions were found to be significant for sulfur rejection response. Among all four operating parameters studied, frother concentration in the range of 10 ppm to 20 ppm was found to have the maximum influence on all three key responses.

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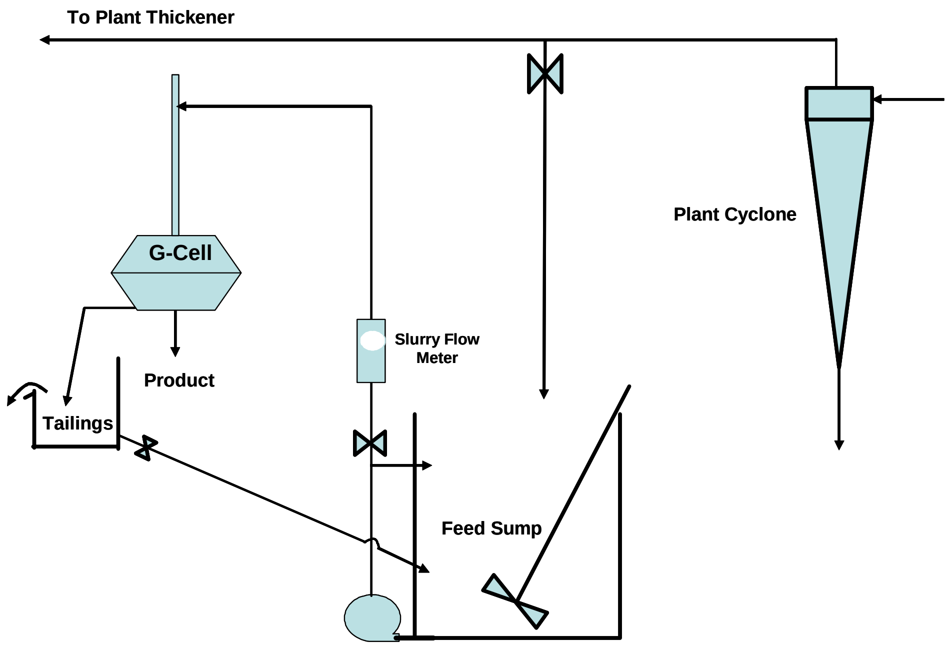

Figure 1: A schematic diagram of the experimental setup utilized for the G-Cell study conducted at a coal preparation plant site in the US

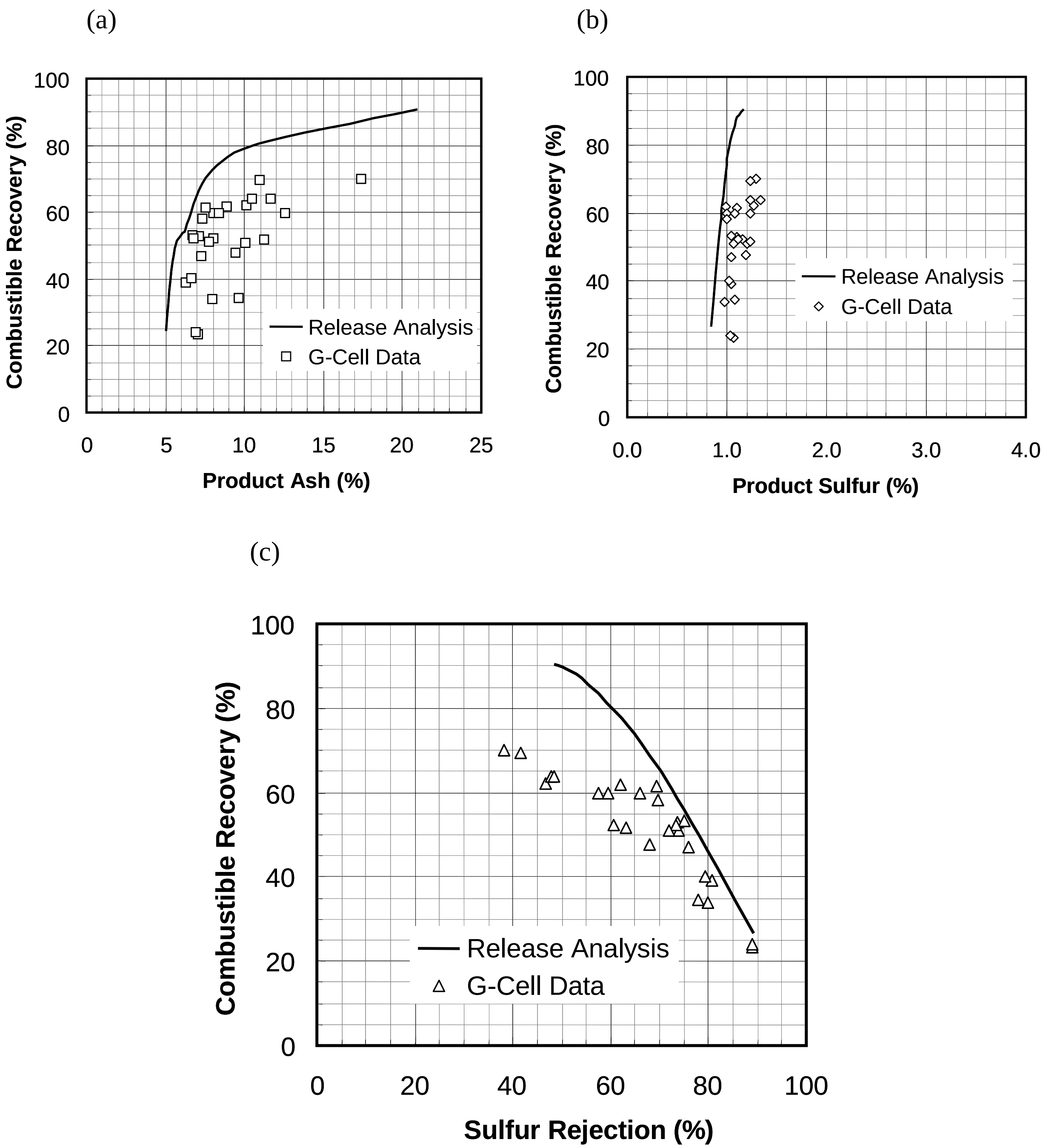

Figure 2: Metallurgical performance data obtained from G-Cell experiments in comparison the ideal flotation performance obtained from Release analysis

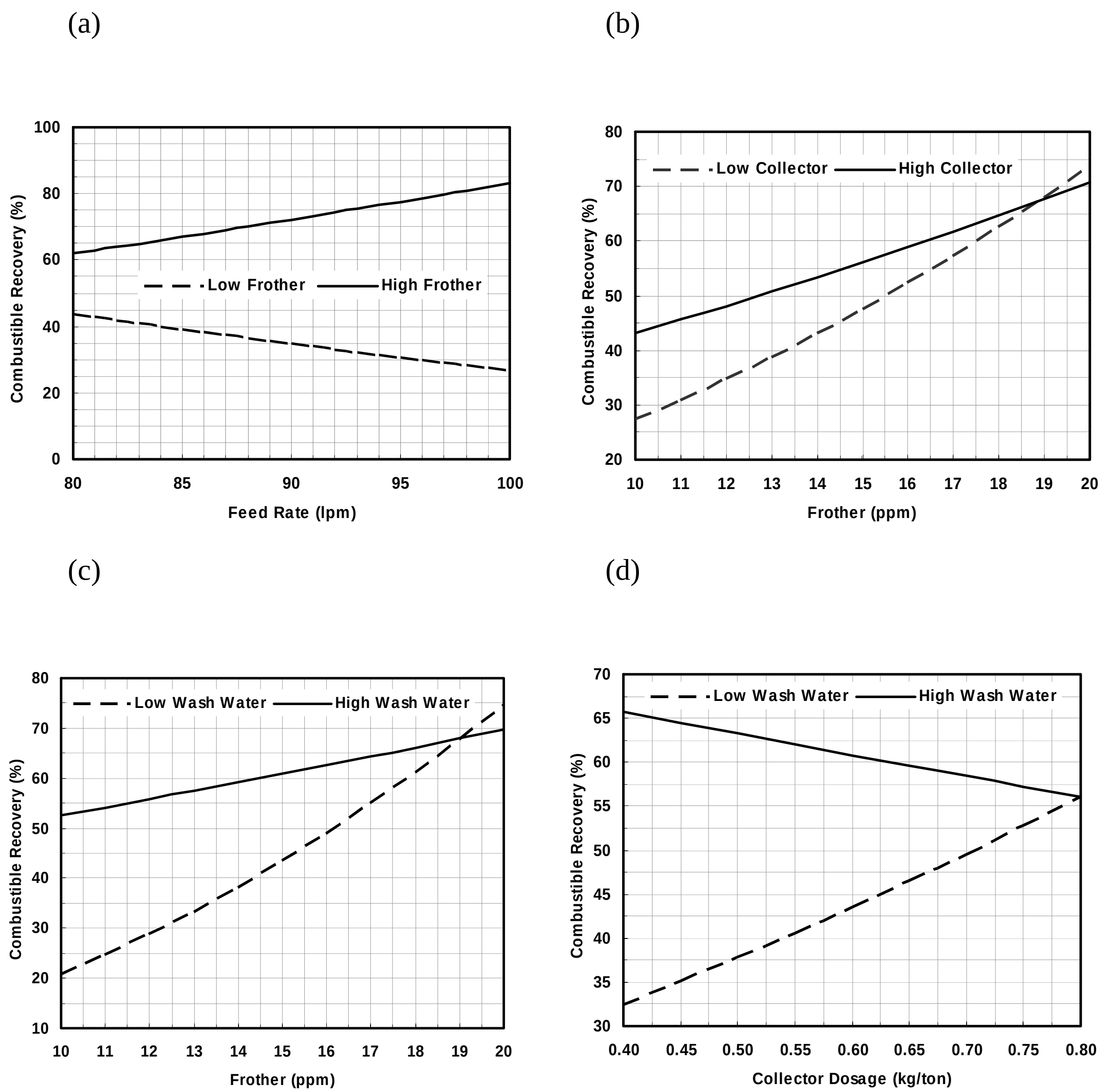

Figure 3: The parametric effects on combustible recovery response

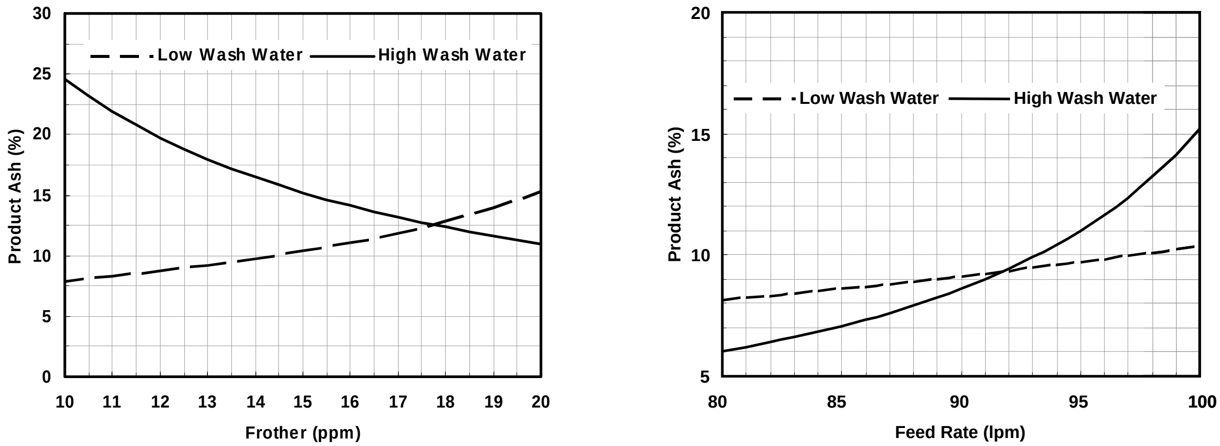

Figure 4 The parametric effects on product ash response

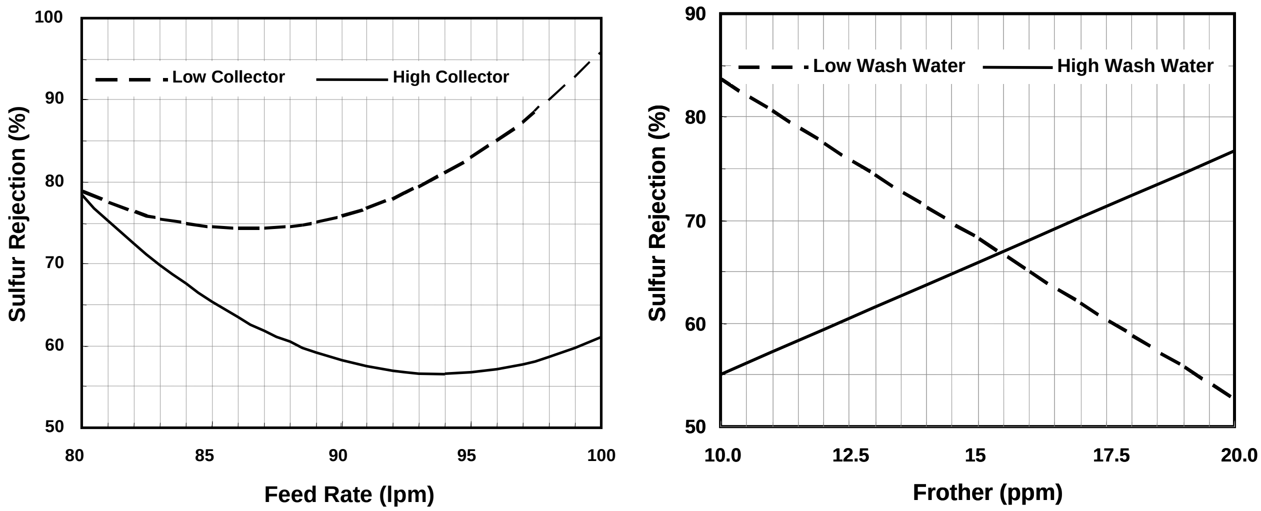

Figure 5: The parametric effects on sulfur rejection response

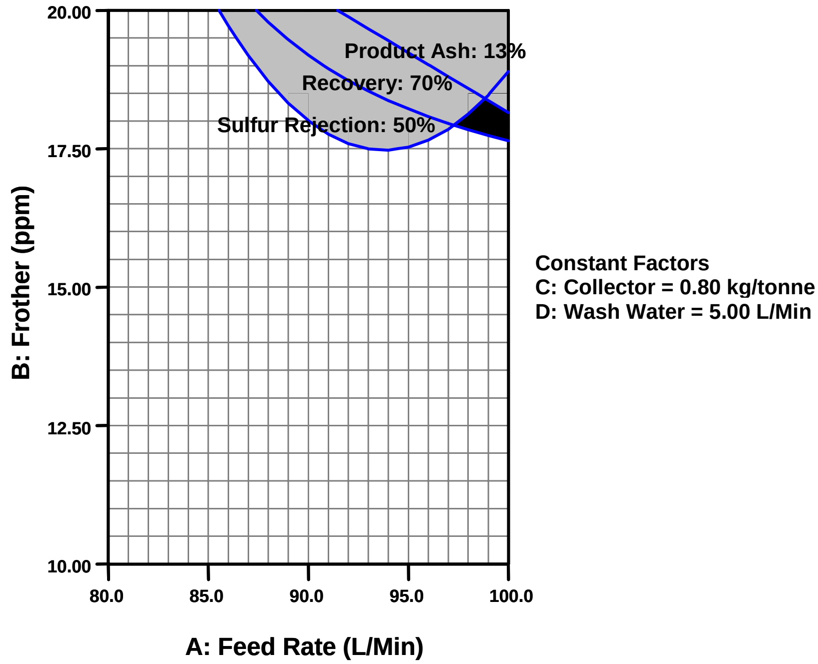

Figure 6: Optimized experimental conditions to achieve a desired separation performance, which is described as a combustible recovery of 70% or greater, sulfur rejection of 50% or greater and a product ash content of 13% or lower