A guide to maximising ball mill circuit classification system efficiency (CSE), for operators and equipment designers

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ABSTRACT

It is well known in the industry that good classification system performance is vital to efficient ball mill circuit performance. But what is meant by good classification system performance, and how is it achieved? Unfortunately, the perceived complexity of classification systems, and the day-to-day time demands placed on the practicing metallurgist, all too often put the low-hanging fruit of classification system optimisation in the 'I'll do it later' basket. Additionally, lingering confusion about basics such as the relationship between circulating load ratio and ball mill circuit performance makes the optimisation objective seem nebulous to both plant metallurgist and designer.

Some of this confusion can be eliminated by taking a step back from the overwhelming detail of sharpness of separation curves, circulating load ratios, cyclone feed pressures, vortex and apex sizes etc, and focusing on the purpose or function of the classification system – to apply mill power to particles that need further size reduction! The classification system efficiency (CSE) metric captures how well the classification system is performing its function with two quick and easy size distribution analyses.

Once CSE is understood and implemented as the optimisation criteria, well-tested methods for improving CSE can be implemented and quickly measured at plant scale to give confidence that the right change was made.

This paper will describe CSE and how it is measured in practice. Next, a guide for improving CSE through manipulation of design and operating variables in the classification system will be provided. Examples and case studies will illustrate the gains in ball mill circuit efficiency that can be achieved by maximising CSE.

INTRODUCTION

The importance of classification to ball mill circuit efficiency has been studied and emphasized by many comminution experts through the decades (Bradley, Davis, Heiskanen, Hukki, Jankovic, McIvor). The slurry pump/hydrocyclone combination is, perhaps, the most common classification system equipment selection in ball mill circuits, and has been for years. However, confusion persists about what is 'best' for circuit performance when evaluating trade-offs between circulating load ratio, cyclone feed density, and bypass of fines to underflow in the face of pumping constraints. Some of this confusion may be due to the numerous measurements of the individual efficiency which gauge the sorting accuracy of the cyclone, but ignore the residence time, and resultant overgrinding, effect of low circulating load ratios.

WHAT IS CSE?

Classification system efficiency (CSE) is a composite measurement of the net performance of the classification system in a ball milling circuit. Functional Performance, as developed by McIvor, defines Classification System Efficiency, as the net amount of coarse material in the ball mill (McIvor, 1988a). The 'dividing line' between 'coarse' and 'fine' will depend on the grind target of a given circuit, and it is suggested that the target cyclone overflow P80 be chosen. Hence, material in the ball mill finer than the cyclone overflow P80 is already fine enough and any energy being applied to it will result in overgrinding and occupy mill capacity that could have been used for new circuit feed. Material coarser than the circuit P80 requires more grinding and has been properly placed in the ball mill by the classification system. By focusing on the *function* of the classification system (keeping the ball mill loaded with coarse particles) CSE has the advantage of being conceptually easy to understand and apply in practice.

As a review, the Functional Performance Equation, well documented and industrially validated (McIvor 2006, Bartholomew 2014), is shown below:

$$Q = MP \times CSE \times G \times MG_{eff}$$

Where:

Q	= metric tonnes per hour of new fines (<P80) produced by the circuit
MP	= mill power draw (kW, measured at pinion)
CSE	= Classification System Efficiency (%)
G	= ore grindability (grams per revolution)
MGeff	= Mill Grinding Efficiency [(metric tonnes per kWh) / (g/rev)]

The equation components are measured by means of a ball mill circuit survey and a laboratory test of the ore grindability. As can be seen in the equation, the mill power (kW) being used 'effectively' (on coarse particles) is simply the product of the mill power and the CSE, which is the percentage of the mill solids which are coarse. In the equation any changes in the ore grindability (G), or the grinding effectiveness of the ball mill environment (ie, mill % solids, media sizing, etc) are isolated from the performance of the classification system. This helps the plant metallurgist troubleshoot and improve grinding circuit performance by providing a clear, practical understanding of the interacting factors, without the need for complex modeling.

HOW IS CSE MEASURED IN PRACTICE?

CSE can be measured in a very practical way in the plant. This is one of its primary advantages! While a full circuit survey is needed to fully populate the Functional Performance Equation, all that is required to measure CSE is a size distribution for the mill feed and discharge. For the typical reverse configuration ball mill circuit (Figure 1), this is achieved by taking a sample of cyclone underflow and a sample of ball mill discharge, and then running a screen analysis in the lab. For forward fed circuits (e.g. primary ball milling), a size distribution of the combined mill feed (circuit new feed and cyclone underflow) is required. While not as straightforward as taking the CUF as total ball mill feed, forward circuit mill feed can be obtained via a good survey and mass balance.

Once the laboratory has completed the size distribution analysis of the ball mill feed (CUF for the standard reverse circuit) and ball mill discharge, the CSE calculation is straightforward. First, choose the 'size of interest' for your circuit. If the circuit (cyclone overflow) P80 is close to a standard sieve size, simply select that size as the 'size of interest'. Next, at the size of interest, from the analysis of the plant samples, calculate the amount of 'coarse' in the mill by taking the arithmetic average of the % coarse in the mill feed (CUF) and mill discharge (BMD).

Using the data in Table 1, an example CSE calculation for a typical reverse fed ball mill circuit where 75 µs is the circuit (cyclone overflow) target P80 follows:

1. From the ball mill feed size distribution calculate the %+75 µ as: 100 – 19.3 = 80.7% +75 µ.
2. From the ball mill discharge size distribution calculate the %+75 µ as: 100 – 26.5% = 73.5% +75 µ.
3. Calculate the CSE as the average: (80.7 + 73.5) ÷ 2 = 77.1% + 75 µ.

In this example the ball mill circuit classification system efficiency is 77.1 per cent at 75 µs. This means that 77.1 per cent of the particles in the mill are 'coarse' and that 77.1 per cent of the mill power is being used 'effectively'. Conversely, 100-77.1, or 22.9 per cent of the mill contents are 'fine' and are being overground, and 22.9 per cent of the mill power is being wasted on overgrinding.

It should be noted that this methodology, while effective in practice, does assume a more-or-less plug flow of solids through the mill. It should also be noted that arithmetic average technique for calculating CSE, as demonstrated here, is only valid for ball mill circuits with relatively low single pass reduction ratios. If the circulating load is very low for a ball mill circuit, causing a very high reduction ratio through the mill in a single pass, the arithmetic average method should be substituted with a better approximation of the size distribution gradient from feed to discharge (such as a first-order exponential decay model). However, as will be discussed, low circulating load ratios should generally be avoided as they often result in overgrinding

Another calculation option for CSE, which can be better for circuit-to-circuit comparisons, is to use the %+ COF P80 values in the ball mill feed and discharge (instead of using the closest incremental sieve) by interpolation between the experimental size distribution data points. However, as a matter of practicality, most plants have 'sieve of interest' that is close enough to the COF P80 to make the CSE calculations fast and easily relatable to plant operators and management alike.

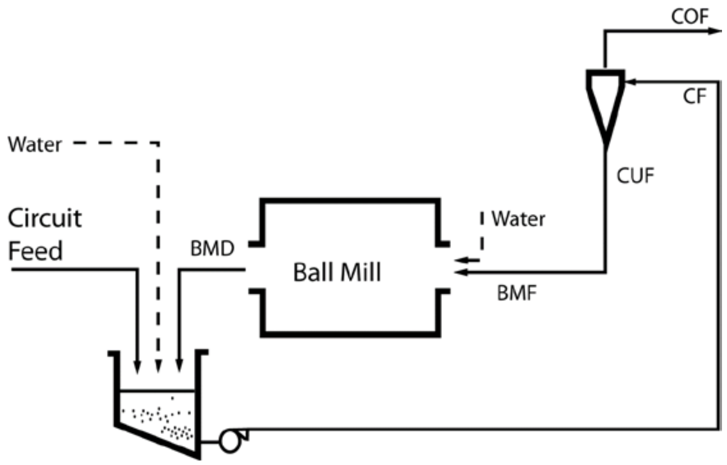

Figure 1 – Typical reverse configuration ball mill circuit flowsheet.

Sieve (μs)	Ball Mill Feed (CUF) Cumulative Wt% Passing	Ball Mill Discharge (BMD) Cumulative Wt.% Passing
850	87.3	90.9
600	81.8	86.5
425	74.8	80.6
300	66.1	73.1
212	57.0	64.9
150	44.4	52.9
106	30.9	39.3
75	19.3	26.5
53	12.8	18.7
38	9.5	14.5

Table 1 – Example plant sample data for CSE calculation.

USING CSE IN PRACTICE AND DESIGN

Armed with CSE as a fast, low-cost metric for evaluating the effect of operational changes on the performance of the classification system, plant metallurgists can run trials to prove to themselves and their colleagues what operating schemes are best. Circuit designers can use the CSE metric as a way of evaluating and guiding a circuit modelling and simulation exercise, essentially performing the same trials as the plant metallurgist but on the computer.

From practical experience it has been found, and previously published, that for pump/cyclone classification systems there are three major steps which can be taken to maximise CSE 1.) increase circulating load ratio, 2.) reduce cyclone feed % solids, and 3.) utilize modern, high-performance cyclones (McIvor 2017). However, these steps cannot be taken blindly. Instead the changes should be engineered to take into account the constraints of the pump and piping, desired circuit cut size, and target ball mill % solids. For example, if the plant metallurgist simply added water to the cyclone feed, depending on the control system, it is possible the circulating load would build beyond the capacity of the existing apexes causing roping or the cyclone overflow P80 to shift finer than target. Making changes to the target circulating load ratio, target grind size, and cyclone water balance are all covered by the Metcom training system and other publications (McIvor 1988b, 2011). Additionally, new software tools are available (Metcom Streamline™) which simplify the pump and cyclone system re-engineering process in the context of ball mill circuit optimisation. With a single, good quality ball mill circuit survey, the plant metallurgist, process consultant, or circuit designer can generate a Streamline™ model and quickly find the practical limit of CSE attainable for a given circuit along with the required changes to pump speed, water balance, number of cyclones to operate, and cyclone fitting sizes (vortex and apex) needed.

CASE STUDIES

Increasing circulating load ratio

An iron ore concentrator operating a fine grinding (P80 = 25 µ) pebble milling circuit closed with hydrocyclones historically operated at a circulating load ratio of about 180 per cent. A plant test, with the assistance of Metcom, was run to evaluate the effect of increasing circulating load ratio on classification system efficiency and milling circuit performance. The pebble milling circuit was specially designed for rigorous, detailed plant surveys. Sample points all allowed for full stream cuts, and a pebble mill circuit new feed slurry volumetric flow rate measurement tank was utilised (Figure 2) to precisely measure circuit tonnage by means of volumetric flow rate, % solids, and solids SG. This tank, located above the cyclone feed pumpbox allowed for momentary diversion of slurry from the primary mill for timed-volume measurements by means of a pneumatic ram pushing a mining hose. Pneumatic drain valves at the bottom of the tank allowed for quick return of the feed to the circuit by gravity into the cyclone feed pumpbox. By repeating this measurement of new feed rate multiple (20+) times, before, at midpoint, and after the survey, an accurate volumetric flow rate of new slurry into the pebble milling circuit was obtained.

In addition to the rigour expended in capturing good samples in the plant, laboratory analyses were conducted in duplicate, with survey-dedicated sieve sets, all calibrated to a master composite sample, so any sieves replaced could be evaluated in comparison to the previous one in use. A 25cm diameter laboratory ball mill, with a standardised ball charge, was utilised to measure the batch grindability of cyclone underflow (grams/revolution new -25 µ produced) as a measure of the ore resistance to breakage for each survey.

This test line had been used for many historical surveys to evaluate a number of proposed plant changes, so a database of 11 historical surveys was available to calculate an average circuit production rate and classification system efficiency. The 11-survey historical average circulation load ratio was 179 per cent, and the average CSE, at 25 µs, was 77.1 per cent. The average cyclone overflow grind was 85.1 per cent - 25 µ. Pebble mill circuit F80 for the 11 survey historical average was 681 µm.

Following the pump and cyclone modifications to increase circulating load ratio, circuit survey data indicated circulating load ratio increased to 311 per cent while the cyclone overflow grind was very close to the historical average at 84.6 per cent -25 µ. F80 was also close to the historical average at 663 µm.

Table 2 shows the key survey parameters, CSE metrics, and performance effects of the higher circulating load ratio test as compared to the 11-survey historical baseline.

CSE, at the higher circulating load ratio had increased to 85.1 per cent; a 10 per cent higher (relative) value than the historical average (77.1 per cent). In general, the relative increase in CSE translates to the same relative increase in circuit production rate if all else is the same (grind, ore hardness, mill grinding efficiency). In this case, production rate of new -25 µ material increased from 46.1 to 57.4 mt/h (dry basis), or a relative 24 per cent increase. Only a portion (about 10 per cent) of this increase can be attributed to the increased circulating load. The remainder of the improvement comes from the improved mill grinding efficiency. Mill grinding efficiency was measured to be between 7 and 12 per cent higher than the historical average. While mill grinding efficiency was not the focus of this trial (CSE was), the standard grindability being lower (harder) in the test versus the baseline indicates that the media (pebbles) may have been better sized for the harder ore being processed that day. Mill percent solids, the other key variable in mill grinding efficiency, were nearly identical to the historical average so this factor can be discounted. In theory, the CSE improvement and Mill Grinding Efficiency improvements should sum to the production rate of new fines improvement. In this case, using the high-end estimate of mill grinding efficiency improvement (+12 per cent) and the CSE improvement (+10 per cent), the sum is close (+22 per cent) to the measured 24 per cent increase in production rate of new -25 µm material. An indication of expected parameter error estimates, using best case survey conditions, is also given in Table 2 (McIvor 1988b).

The higher circulating load ratio did increase the cyclone feed percent solids and bypass of fines to underflow, as expected, but the overwhelming benefit of higher circulating load (ie reduced residence time) resulted in a net improvement in CSE and circuit performance. An evaluation of ‘classifier performance’ in isolation, by means of tromp curve (difficult at these fine grinds), or by looking at bypass or cyclone feed % solids alone, would lead to the improper conclusion that the lower circulating load ratio was better. Instead comparing the 11-survey historical average to the increased circulating load ratio survey showed an improved CSE from 77.1 to 85.1 per cent, a relative increase of 10 per cent attributable to the higher circulating load ratio. Additionally, by measuring the ore grindability and its resultant effect on mill grinding efficiency during the survey the amount of production rate improvement actually attributable to the increased circulating load was more properly quantified so better economic decisions about operations could be made in the trade-off between higher pumping costs and improved circuit performance.

Figure 2 – Slurry volumetric flow rate measurement tank.

	11-survey average	Increased CLR Survey	Units	Estimated error 95% C.I. for best case conditions
Pebble Mill Circuit F80	681	663	µs	<1%
Pebble Mill Circuit P80	21.5	22.0	µs	<1%
Prod. Rate new -25µm	46.1	57.4	dry mt/h	<1%
Pebble Mill Power	2065	2225	kW at pinion	± 2%
Class. System Eff. (at 25µm)	77.1	85.1	%	± 0.5%
Effective Mill Power	1592	1893	kW	± 2%
Std. Grindability Mill Feed	0.478	0.464	g/rev	± 2%
Gr. Rate of +25µm	0.0290	0.0303	mt/kWh	± 2%
Pebble Mill Gr. Eff. (at 25µm)	0.0606	0.0653	mt/kWh per g/rev	± 3.5%
Functional Performance Eff.	0.0467	0.0556	mt/kWh per g/rev	± 3%
Circulating Load Ratio	179	311	%	
Cyclone Feed % Solids (w/w)	22.7	33.4	%	
Cyclone Feed % Solids (v/v)	7.1	11.7	%	

Table 2 – Plant survey results, increased circulating load ratio test. *Estimated errors, McIvor 1988b, Metcom Module 5

Improving water balance and use of high efficiency cyclones

The reader is encouraged to explore the many case studies published by McIvor, et. al. for examples of improving water balance and utilisation of high-efficiency cyclones as additional means of improving CSE.

CONCLUSIONS

The function of the classification system in a ball milling circuit is to maximise the percentage of solids in the ball mill which require more grinding (coarse), and minimise the amount of material that is already at target size (fines). This ensures that the mill energy and volume is best utilised for maximum circuit productivity and efficiency. Classification system efficiency (CSE) is a practical, understandable, and easily implementable measurement of how well a given classification system is performing its function. It can be utilised by plant metallurgists to evaluate the effect of circuit changes on classification performance. It can be used by plant operators to identify potential problems in the classification circuit. It can be used by management to benchmark and identify opportunities for circuit improvements. And finally, it can be used by circuit designers to guide plant design calculations and computer modelling exercises.

ACKNOWLEDGEMENTS

Graciously acknowledged are the management and staff of the following operations for their support of this process development work and their generosity in sharing plant performance results; Kidd Creek, Selbaie, Dome, Tilden, Gibraltar, Clarabelle, Strathcona and Tulawaka. The writers also thank McGill University for ongoing support.

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