A holistic approach to control and optimization of a PGM concentrate flash drying unit

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Journal Paper

Synopsis

Global trends stipulate the need to optimize existing assets while reducing environmental impacts. This paper illustrates the procedure that was followed to achieve such goals at one of the coal burning flash dryer units at an Anglo American smelter. An in-depth study of the process and related literature led to the development and installation of a revised control philosophy. This system includes modifications to the existing regulatory control structure as well as a hybrid rule-based and model-predictive advanced process control (APC) layer.

Since commissioning of the APC, this flash dryer's average throughput has increased by more than 6%, despite higher feed moistures. Furthermore, even though coal consumption has increased slightly, operating efficiency has improved by close to 5%. This was made possible by improving stability of the drying column outlet temperature by approximately 40%, which in turn enabled selection of a more optimal setpoint. Recent data has shown that APC utilization now exceeds 95%. This is indicative of a successful controller installation with good site acceptance. The same philosophy has therefore since been rolled out to most of the other flash dryers in the group.

Keywords
flash dryer, platinum processing, model predictive control, expert system.

Introduction

Platinum processing can be divided into concentrating, smelting, and refining operations (Figure 1)[1,2,3]. Given the temperatures (matte up to 1 485°C, slag up to 1 700°C) at which the smelting furnaces operate, and the consequential risk of hydrogen explosions, it is imperative for safe and efficient operation that they receive a consistent, uninterrupted supply of bone-dry (<0.5% H_2O) concentrate[4]. Anglo American Platinum employs several independent flash dryers at its three smelter complexes (Table I)[5] to keep the furnace feed silos adequately filled with such concentrate. These flash dryers require relatively frequent maintenance, and hence it is important to maximize their throughput in order to allow for sufficient downtime to do maintenance without jeopardizing furnace feed supply. Hot gas that is used for transport and drying of concentrate in the flash dryers is produced by coal-burning hot gas generators, which should be operated as efficiently as possible to minimize the specific cost of the coal and environmental impacts associated with coal combustion[6].

This paper discusses how, driven by these requirements and motivated by optimization successes at similar flash dryers[7], a holistic approach was followed to achieving these objectives through the development and implementation of an advanced process control (APC) system for flash dryer no. 2 at Anglo American Platinum's Waterval smelter.

Flash drying

Solid materials are dried when entrained volatile liquid, most notably water, is removed by means of evaporation. Flash dryers (also referred to as pneumatic dryers) represent one of many types of drying equipment that exist in industry[8]. These dryers dry solids (which should typically consist of particles that are less than 1 mm in diameter) by dispersing the particles into an upward flowing stream of hot gas, resulting in extremely short contact times. Other than platinum concentrate, typical products that are dried in flash dryers include ores, coal, clays, food products, and chemicals. These can be in the form of slurries, pastes, sludges, filter cakes, powders, or granules. Table II lists various strengths and weaknesses associated with flash drying[9].

Process flow diagram

Figure 2 illustrates the process flow of the flash dryer under consideration for this study. Using manually operated overhead cranes, concentrate (containing 12% to 18% moisture)

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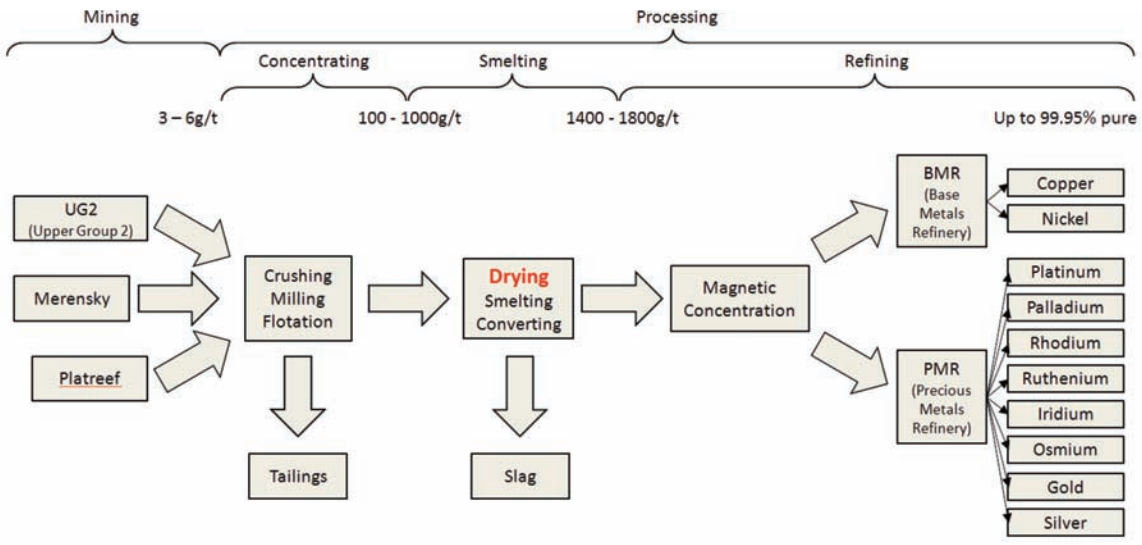

Figure 1—Platinum processing overview

Table I

Anglo Platinum smelter capacities

	Waterval	Mortimer	Polokwane
Smelting capacity	650 kt/a	180 kt/a	650 kt/a
Flash dryers (Moisture removal capacity)	2 x 6 t/h 1 x 12 t/h	1 x 6 t/h	2 x 12 t/h
Furnaces	2 x 34 MW	1 x 18 MW	1 x 68 MW

is fed into the concentrate feed hoppers from the concentrate stockpile. From here it is continuously transported with screw feeders onto the concentrate conveyor that delivers it to the back-mixer where it is mixed with a portion of the previously dried concentrate. This mixture is fed into the vertical flash drying column through the disintegrator, where it is pneumatically conveyed by hot gas that flashes off the moisture. The hot gas is generated in the hot gas generator (HGG) which operates by combusting coal on a fluidized silica bed. Heated fluidizing air that passed through this bed combines with air that is sucked in through the HGG chimney prior to being fed to the flash dryer. Air flow through the HGG and flash dryer is jointly achieved by a fixed speed induced draft (ID) fan at the outlet side of the flash dryer that sucks the air through the system and a fluidizing fan that forces air into the system through the HGG bed. After drying, the concentrate is separated from the air by means of two cyclones, a multi-clone and a baghouse[10].

Controller objectives

Anglo American Platinum is in the business of producing platinum safely and profitably. The flash drying operations can contribute to this goal by drying as much concentrate as possible using the least amount of coal without harming the environment, equipment, or people. Therefore successful optimization of a flash dryer is measured according to the following key performance indicators (KPIs).

Table II

Strengths and weaknesses of flash drying technology

Strengths	Weaknesses
Intimate contact with gas stream	Loss of power will cause product to fall into dryer base
Efficient transfer of drying energy	Attrition and impact may cause size reduction
Ideal for heat sensitive, explosive or reactive products	High electricity costs for fans and dust collection
Small physical footprint	May not be suitable for products with a high degree of bound moisture.
Flash tube is flexible, can be routed within plant constraints	May be susceptible to high wear if improperly accounted for
Low maintenance - few moving parts	

Maximize concentrate throughput (process objective)

Consistently maximizing concentrate throughput provides for optimal utilization of flash drying capacity, and should provide more opportunities to run with only some of the flash dryers on a site at any given time. This reduces operating cost (coal, electricity, wear and tear), improves maintenance scheduling, and ensures uninterrupted furnace feed supply. Since throughput is impacted by concentrate moisture, it is best to consider throughput by means of moisture removal rate in addition to concentrate feed rate.

Minimize specific coal consumption (process objective)

Specific coal consumption (*SCC*) is calculated according to Equation [1]. Reducing the amount of coal required to remove a ton of water from the concentrate has cost-saving and reduced environmental impact implications. Actual coal feed rate is unfortunately not measured, hence it has to be approximated by using screw feeder speed. It should be noted

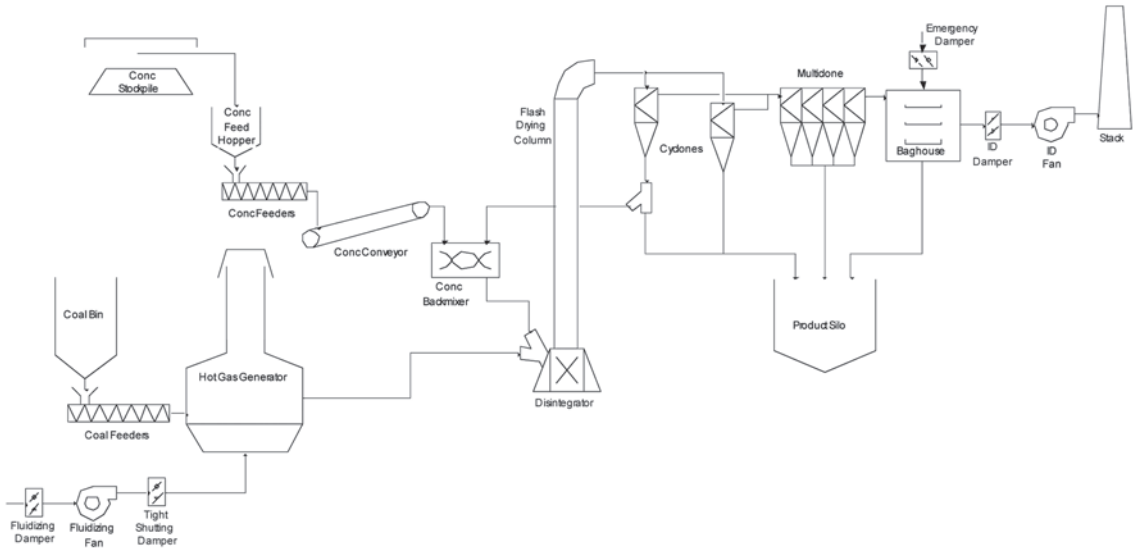

Figure 2—Flash drying circuit process flow diagram

that when combined with the concentrate throughput KPI, this KPI does not necessarily imply that absolute coal consumption will decrease, only that any increase in coal should be proportionally less than the corresponding increase in concentrate.

$$SCC = \frac{M_{CC}}{M_{WR}} = \frac{M_{CC}}{M_{CD}.X_W} \quad [1]$$

where

M_{CC} = mass of coal consumed
M_{WR} = mass of water removed
M_{CD} = mass of concentrate dried
X_W = mass fraction of water in concentrate (measured daily).

Stabilize dryer outlet temperature (process objective)

Dryer outlet temperature is the best available indication of moisture content in the dried concentrate[11]. According to design and considering the boiling point of water, it must always be kept above 100°C to avoid excessive moisture entering the furnace feed silo. Whenever this requirement is not met, concentrate feed is immediately stopped. This impedes throughput, wastes coal as a result of operating the HGG without drying, and increases wear on the feed belts[7]. In addition, a dryer output temperature significantly in excess of 100°C denotes wasted energy, which should rather have been absorbed during drying, and poses a risk to the baghouse which has limited resistance to high temperatures.

It follows that the optimum setpoint (SP) for the drying column outlet temperature is the lowest possible value above 100°C that will allow a sufficient margin to accommodate the minimum achievable variation in the temperature. Hence, a more stable temperature (with less variation) enables selection of a more optimal setpoint without increasing the risk of concentrate feed stops. This contributes to maximizing the water removal capacity of the dryer, supporting the concentrate throughput KPI, due to an increased temperature differential across the column, which is indicative of how effectively the generated energy is utilized in order to drive off the moisture[12].

Stabilize HGG bed temperature (process and safety objective)

A minimum HGG bed temperature of 600°C is required to maintain combustion in the HGG. Loss of combustion constitutes production losses and additional cost due to low pressure (LP) gas that is required to restore combustion. Furthermore, should the HGG bed temperature reach 1 200°C, the silica bed will sinter, resulting in several days' production loss. In order to avoid these scenarios, it is imperative to stabilize and maintain the HGG bed temperature in the region of 900°C. However, there is some scope to let this temperature drift in favour of stabilizing the flash dryer outlet temperature.

Maintain minimum air to coal ratio (safety objective)

Ensuring sufficient air to combust all coal fed to the HGG will help to minimize the risk of incomplete combustion, which can potentially lead to carbon monoxide buildup and/or coal accumulation on the bed. An increased coal concentration in the bed will result in a rapid bed temperature rise once adequate oxygen is provided. Such temperature spikes have been one of the main causes of sintered beds in the past. Since neither actual air nor coal feed rates are measured, this metric can only be approximated by calculating the air damper position relative to the coal feeders' speed. Considering a 6 month window of historical data (see Figure 3), during which no bed sintering incidents occurred, it was observed that this ratio averages 40%, therefore it is believed that a low limit for this ratio of 40% provides a sufficient safety margin.

Process improvement through process control

In general, chemical and minerals processing plants exist so that certain raw materials (e.g. wet concentrate) can be transformed into desired products (e.g. dry concentrate) through the application of available sources of energy (e.g.

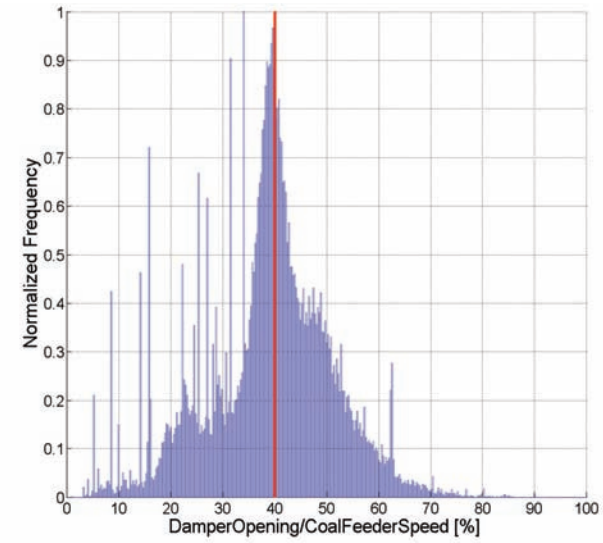

Figure 3—Histogram plot showing the distribution of approximated air to coal ratio for a six month period

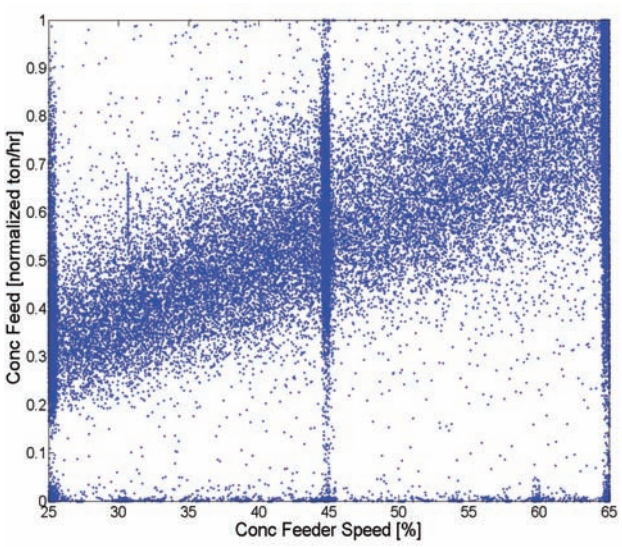

Figure 4—XY plot showing the variance in concentrate feedrate for any given concentrate feeder speed recorded over a six month period

coal combustion). Process control is applied to help achieve this general goal while ensuring safety, quality, environmental, operational and economic requirements[13].

Regulatory control

The flash dryer in this study was originally controlled by three proportional-integral-derivative (PID) controllers:

- Coal feeder speed to HGG bed temperature (*SP* = 900°C, positive gain)
- Concentrate feeder speed to dryer outlet temperature (*SP* = 115°C, negative gain)
- Fluidizing damper opening to dryer outlet temperature (*SP* = 125°C, positive gain).

Note that the concentrate feed and fluidizing damper are used to control the same temperature but to different setpoints. This unusual arrangement has been chosen in an attempt to cater for the frequent occurrences of concentrate feed interruptions. These typically result in a rapid increase in the dryer outlet temperature to far above 115°C, and consequently the damper will start to close as it approaches and exceeds 125°C. A relatively low damper high limit essentially disables the damper PID controller during normal operating conditions as it simply saturates at that level. Requirements like these can be addressed much more elegantly by a multivariable APC system.

A further limitation of the original control strategy was that it excluded the concentrate feed rate measurement. Since such a strategy is based on the assumption that feed rate is exactly defined by feeder speed, which, despite being a good approximation in the case where feed rate is not measured, is not accurate (see Figure 4). This was addressed by introducing a new cascaded PID controller scheme that manipulates the concentrate feeders to achieve the desired mass flow that is required to maintain a desired flash dryer outlet temperature (Figure 5).

Advantages of this new cascaded PID controller include:

- Better flash dryer outlet temperature control due to the reduction in non-linearity of the process through the inclusion of additional process knowledge (compare 3 PID with 4 PID on Figure 8 and Figure 9)
- Better feed disturbance detection and rejection due to the more direct measurement of the concentrate feed rate, especially when the feed hopper runs empty
- Better use of the entire range of the concentrate feeders. Prior to installing the new PID controller, these feeders had a relatively low high limit to avoid chokes in the downstream ducting; however, that limit could now be relaxed in favour of the more appropriate, and intuitive, high limit on the concentrate mass flow.

In addition to the PID controllers, the regulatory control layer also contains various interlocks that intervene, by interrupting the coal, air, and/or concentrate supply, to protect equipment and site personnel in event of significant disturbances that can result in temperature spikes, inadequately dried product, excessive torque requirements, etc. Such interlocks have been carefully selected during various design and risk assessment processes and must always remain active irrespective of the selected control scheme.

Advanced process control

Following a thorough investigation of the process, it was evident that the existing base layer control strategy is inadequate to realize the full potential of the process. Despite initial improvements, the process still exhibited high levels of instability that led to frequent process interruptions and hence reduced throughput (notice the frequent occurrences of dryer outlet temperatures that are more than 5°C below setpoint when not under APC control in Figure 9). This can be explained by the interaction that exists between process variables, e.g. coal feed and fluidizing damper adjustments not only affects HGG bed temperature but also HGG outlet temperature and hence drying column outlet temperature, as well as the dead times that are present as a result of, for example, a long feed conveyor belt. The resulting instabilities necessitated the selection of conservative operating regions and hence the process could not be operated at maximum efficiency. Consequently, an APC strategy that would primarily stabilize the process despite the presence of interaction and delays and furthermore improve throughput

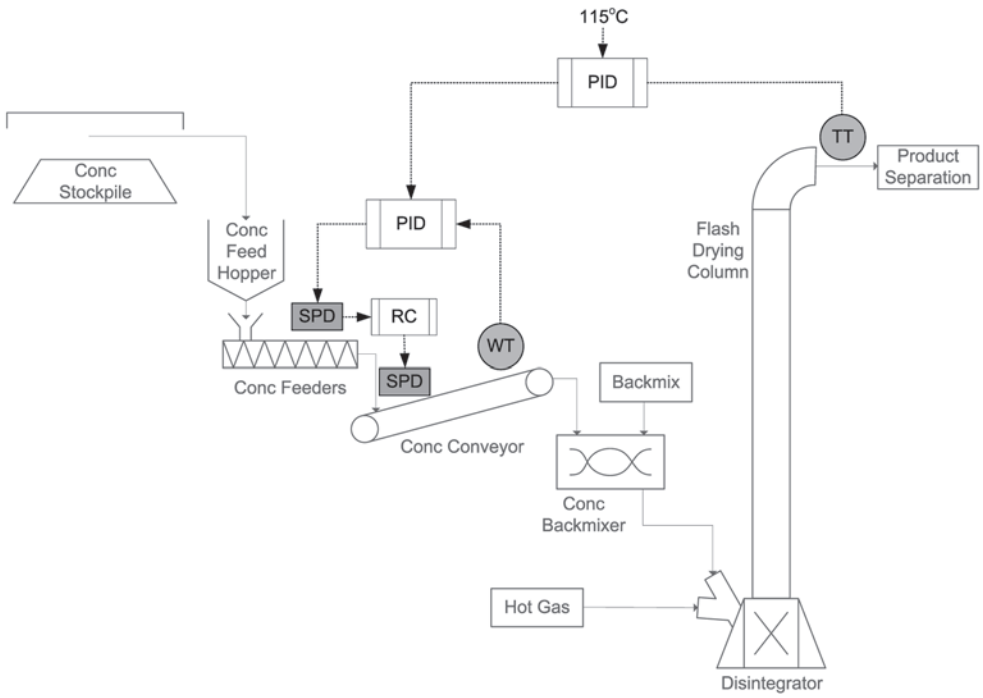

Figure 5—New concentrate mass flow PID controller (WT = weightometer, TT = temperature transmitter, RC = ratio controller, SPD = speed)

and efficiency was introduced. The APC system was deployed using Anglo Platinum's Expert Toolkit (APET)[14] that has been integrated with Aspen Tech's DMCplus® software.

Dynamic Matrix Control (DMC)

DMC is a derivative of model-predictive control (MPC), which is widely used (more than 10 000 current applications) in the petrochemical industry[15]. The past decade has, however, also seen a significant increase in applications to minerals processing and other industries as is shown in the work by Schuster and Kozek[16] which describes the implementation of a constrained MPC algorithm on an industrial drying process. Le Page, Tade and Stone[17] compared PID, DMC, and STC (self-tuning-control) in the regulation of a calciner furnace temperature. Here it was shown that DMC delivered the best performance, closely followed by an optimized PID controller. Similarly, Altafini and Furini[11] discuss how model-based control was applied to an industrial starch flash dryer in pursuit of improved regulation robustness. Tay[15] reports on an operation that deployed MPC to de-bottleneck a dryer process. The immediate value that was generated justified a plant-wide rollout. Cristeaa, Baldeaa, and Agachia[18] tested the applicability of MPC on an industrial batch dryer. Through simulation it was shown than MPC holds clear potential to improve the operation of such a process. Results from an initiative to develop a MPC controller for an infrared dryer also indicated that, through its proper handling of process interactions, such a controller produces good results for setpoint tracking of the moisture and temperature of the exit material, while effectively rejecting measured and unmeasured disturbances[19]. Substantial benefits have also been derived by deploying DMC on crushing[20], milling[21], flotation[22], boiler[23], and batch reactor[24] processes in the platinum group metals (PGM) industry.

The DMC algorithm uses linear step-response models that are obtained either through physical step tests (as done for this study) or through theoretical approximations, to predict the future behaviour of each controlled variable (CV) based on the past moves in each manipulated variable (MV). Knowing the future trajectory of each CV and considering targets, limits, priorities, and allowable move sizes, a quadratic programming optimization algorithm is used to determine the optimal future moves for each MV that will minimize the overall controller objective function[25,26,27]. Equation [2] shows the general form of this objective function[16].

$$J(n_c, n_p) = \sum_{i=1}^{n_p}\sum_{j=1}^{n_y} \delta_j(k)\left[\hat{y}_j(k+i/k) - w_j(k+i)\right] + \sum_{i=1}^{n_c}\sum_{j=1}^{n_u} \lambda_j(k)\left[\Delta u_j(k+i-1)\right]^2 \quad [2]$$

where

n_c = control horizon

n_p = prediction horizon

n_y = number of CVs

n_u = number of MVs

k = time of calculation, typically current time

$\delta_j(k)$ = penalty on j[th] CV error at time k

$y_j(k+i/k)$ = predicted value for j[th] CV at time $k+i$ as calculated at time k

$w_j(k+i)$ = Reference value for j[th] CV at time $k+i$

$\lambda_j(k)$ = penalty on j[th] MV movement at time k

$\Delta u_j(k+i)$ = change in j[th] MV at time $k+i$

System identification

Based on the process inputs and outputs (see Figure 6), the defined KPIs, and the existing instrumentation, the following controlled variables (CVs) were selected:

- HGG bed temperature
  - To ensure downstream stability and sufficient energy for the drying
  - To maintain sufficient heat to sustain combustion
  - To avoid sintering the silica bed
  - In support of the HGG bed temperature stabilization KPI.
- HGG outlet temperature
  - To ensure maximum energy transfer to the dryer
  - To avoid damage to the hot gas transfer ducting
  - In support of the concentrate throughput maximization KPI through ensuring a maximum temperature differential between hot gas and wet concentrate.
- Dryer outlet temperature
  - To ensure adequate drying of the concentrate
  - To avoid energy wastage or damage to the baghouse
  - In support of the concentrate throughput maximization KPI through ensuring a maximum temperature differential across the column and avoiding feed interruptions
  - In support of the dryer outlet temperature stabilization KPI.

Furthermore, the following MVs represent the only automated handles currently available to the operator and/or control system:

- Coal feed—through adjusting the coal feeders' speed. More coal will increase the HGG bed temperature, and subsequently the HGG and dryer outlet temperatures as well. Penalizing more coal in the controller objective function supports the specific coal consumption minimization KPI
- Fluidizing air supply—through adjusting the fluidizing damper position. More air will cool down the HGG bed. Furthermore, since less air will be sucked in via the HGG stack, the HGG and dryer outlet temperatures should in theory also increase; however this relationship could not be confirmed on this particular flash dryer. Ensuring an appropriate low limit for the fluidizing damper position supports the minimum air to coal ratio maintenance KPI
- Concentrate feed—through adjusting the concentrate mass flow setpoint. An increase in feed will not affect the HGG, but will absorb more drying energy and therefore reduce dryer outlet temperature. Rewarding more concentrate in the controller objective function supports the concentrate throughput maximization KPI.

The following potential MVs were not considered in this phase of the controller:

- Back-mixing ratio. It is believed that the amount of previously dried concentrate that is mixed with the wet concentrate has an insignificant effect on the over-performance or throughput of the drier. This is because this recycled concentrate already contains virtually no water and is essentially already at the drying temperature. Therefore, other than ensuring that the minimum recycling ratio that is required to avoid blockages in the back-mixer or disintegrator is maintained, not much can be achieved through manipulating the back-mixing ratio
- ID fan damper position. The ID fan is responsible for transport throughout the dryer and product separation equipment. Manipulating its feed damper can have various unintended effects on the lifting capacity in the dryer and/or the separation efficiency in the cyclones or baghouse. These potential consequences outweighed the potential benefits of including this MV, and hence it was excluded.

Disturbance variables (DVs) that act on the process include the following:

- Coal quality (composition, calorific value, moisture content) and size distribution. This variable is not measured

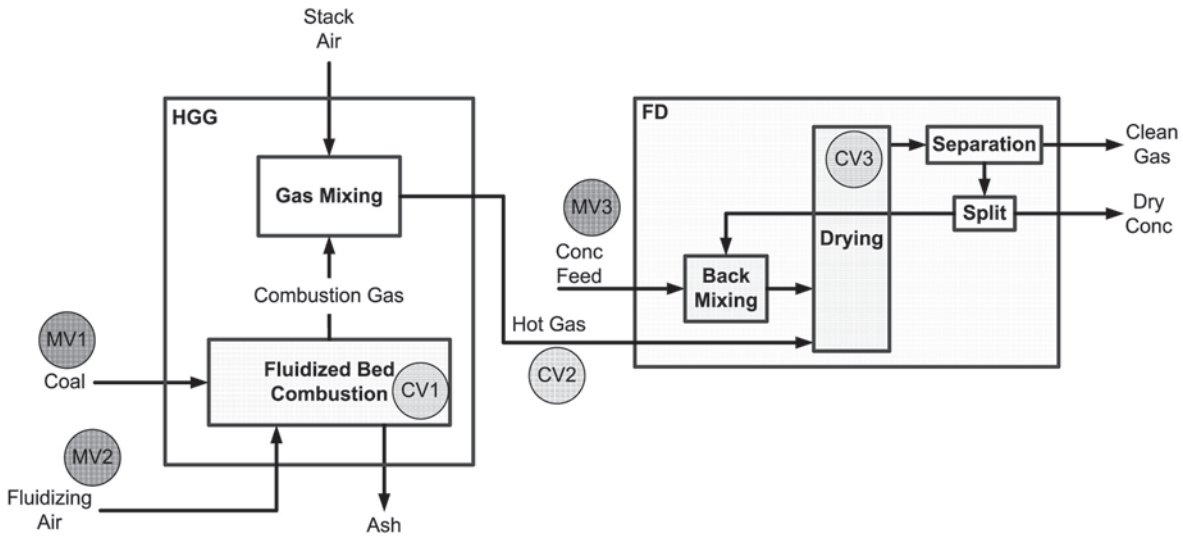

Figure 6—Process inputs and outputs

- Ambient temperature and humidity. These variables can be measured, but since they change much slower than the other process variables, it's rather difficult to derive a useful relationship between these variables and the controlled variables[10]
- Concentrate moisture. This variable is recorded only daily and can therefore not be used in real-time control
- Concentrate feed hopper level. This variable is not measured.

In order to identify the exact process dynamics (dead times, time constants, and gains), step tests had to be performed where all three temperature PIDs were set to manual while the different MVs were manipulated individually and the CV responses were recorded. Step testing the flash drying circuit proved rather difficult given the high frequency of significant disturbances (most notably the feed hopper tends to run empty, but also other unmeasured disturbances in the coal supply and concentrate moisture) that result in sudden considerable ramps in the various CVs (often exceeding 20°C per minute). Given the relatively small acceptable CV ranges, combined with considerable dead times and slow dynamics, it is essentially impossible to wait long enough between steps to allow for full time to steady state. Consequently, all the process responses were modelled, using DMCplus®, as pseudoramps (see Figure 7). Pseudoramp control variables allow the DMC controller to control relatively long settling-time processes (where there is a large disparity in CV time constants and where very long open-loop response times are present) without considering steady state control issues. The feedback correction of such variables is handled by combining a contribution from the bias prediction error term with a contribution from the rate-of-change of the bias prediction error term[27].

Tuning the DMCplus® controller is an iterative process of adjusting the various parameters (Table III) in the DMC algorithm in order to achieve the desired controller performance in terms of the defined KPIs, setpoint tracking, and disturbance rejection.

Rule based intervention control

Chen *et al*[28] describe how expert system-detected process conditions can be used to adjust the model parameters of a DMC implementation. Likewise, the chosen control technology, APET combined with DMCplus®, makes it possible to deploy powerful hybrid control solutions that leverage the best characteristics of different control algorithms. High levels of uncertainty and nonlinearity in the flash drying process, combined with frequent disturbances, soon highlighted the need for certain intervention control measures. The needs for these measures are detected in APET by means of process state expressions and are then either implemented by adjusting settings in DMCplus® or by overriding its control action altogether. All process state

Table III

Key tuning parameters of the DMCplus® controller

General	MVs	CVs
Filtering	Move suppression	Limit rankings
Limits and Targets	Maximum moves	Steady state equal concern errors
Models (mainly delays and gains)	Steady state costs	Ramp rates, horizons and rotation factors

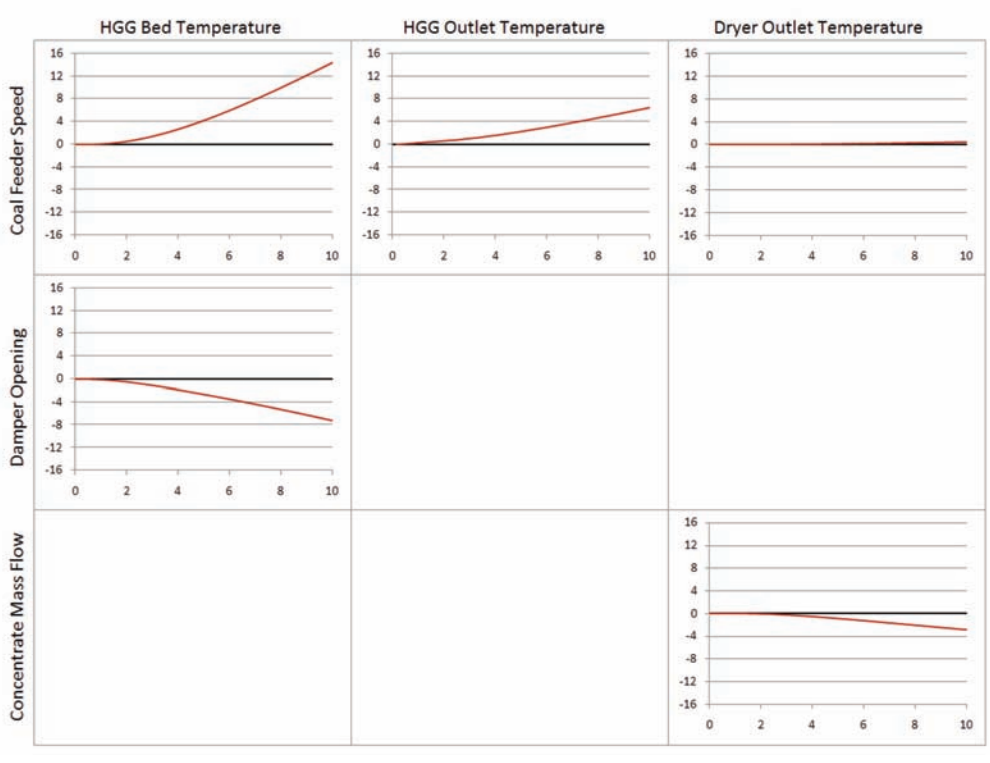

Figure 7—Open loop process response model matrix as deployed. Time axes are in minutes

Table IV

Process states, their calculation and resulting intervention control

Process state	Calculation	Intervention
Extreme low dryer outlet temperature	Dryer outlet temperature below target and predicted to drop below 100°C within less than 2.5 minutes	Cut concentrate feed rate to minimum
Extreme high HGG bed temperature	Average HGG bed temperature exceeds 925°C and predicted to exceed 930°C in less than 2.5 minutes or an individual HGG bed temperature exceeds 1 000°C	Cut coal feeder speed to minimum
Concentrate feed disturbance	Concentrate feed conveyor is running but its mass flow PID is not positive setpoint tracking (PV < (SP – margin))	Set DMCplus® windup flag to prevent further concentrate feed rate increases
Concentrate feed stopped	Concentrate feed conveyor not running	Set DMCplus® windup flag to prevent further concentrate feed rate changes
Coal feed stopped	Coal feeders not running, tight shutting damper closed or fluidizing fan stopped	Set DMCplus® windup flag to prevent further coal feeder speed changes
Dryer outlet temperature below target	Dryer outlet temperature < target	Set DMCplus® CV ramp rate to more aggressive value
HGG bed temperature close to target	Target - 20°C < HGG bed temperature < Target + 7°C	Tighten DMCplus® coal move suppression
Air to coal ratio too low	Damper opening / coal feeder speed < 40%	Increase damper low limit

Table V

Summarized results

Metric	Change	Statistical significance	Content
Plant utilization	52.9%	N/A	Neutral
APC utilization	56.6%	N/A	Good
Increase in concentrate dried	6.3%	99.9%	Very Good
Increase in moisture removed	8.6%	99.9%	Very Good
Increase in coal consumed	3.4%	99.9%	Bad
Reduction in specific coal consumption	4.7%	N/A	Very Good
Reduction in HGG bed temperature stability	20.8%	N/A	Neutral
Increase in dryer outlet temperature stability	39.4%	N/A	Good

calculations are governed by a persistence requirement (the condition needs to consistently exist for a specified period of time, typically 15 seconds, before action will be taken) to avoid reacting on insignificantly short spikes in the measurements. Table IV lists the details of the process states that have been defined, how each is calculated, and what intervention measure is taken.

Results

In order to evaluate the performance of the newly installed control strategy, process data was collected throughout the project, starting just prior to step testing, throughout commissioning and including a few months post-handover to ensure sustained improvement. In total, 290 days' data was considered, during which the flash dryer was operated just more than half of the time. Table V shows a summary of the results. During this time, when the plant was running it was under APC control for 56.6% of the time. It can be seen that, while under APC control, the process performs significantly better. This is highlighted by an 8.6% improvement in average moisture that was removed per hour. Furthermore, the 4.7% improvement in specific coal consumption (units of coal used to remove one unit of moisture) outweighs the slight increase in overall coal consumption.

To analyse temperature stability, the daily average control error was calculated. This pointed out that HGG bed temperature became somewhat less (20.8%) stable, while the drying column outlet temperature is now significantly more (39.4%) stable. Note that this is a direct consequence of the controller design, in which HGG bed temperature is allowed to drift slightly in order to achieve more stable downstream conditions. Figure 8 and Figure 9 shows the difference in

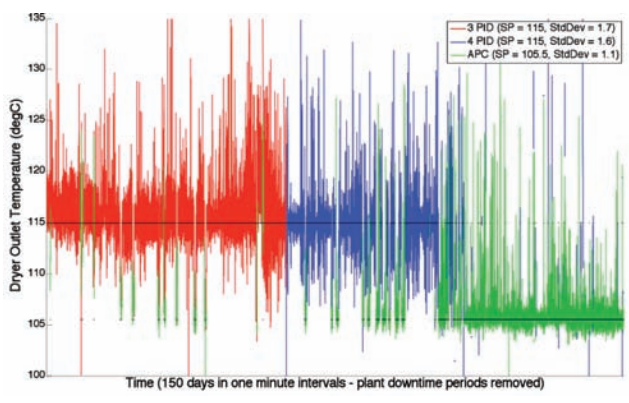

Figure 8—Time series plot of dryer outlet temperature during the different control strategies

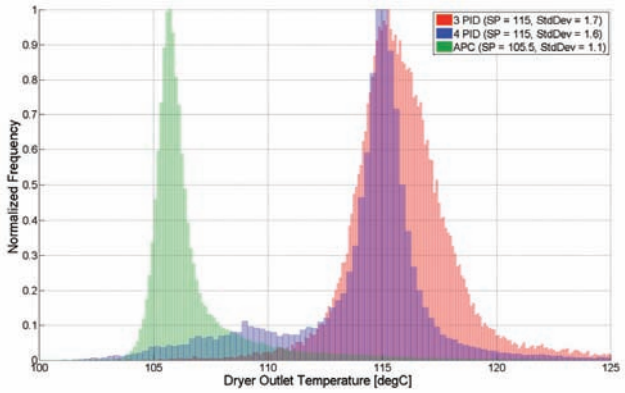

Figure 9—Histogram plots illustrating the improvement in stability and different operating regions for the dryer outlet temperature using the different control strategies

stability and operating region of flash dryer outlet temperature corresponding to the different controller strategies, namely original (3 PID), original plus cascaded concentrate mass flow controller (4 PID), and APC.

Conclusion

Recent data has shown that APC utilization now exceeds 95%. This is indicative of a successful controller installation with good site acceptance. The same philosophy has therefore since been applied to most of the other flash dryers in the group as well.

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