APCO: THE AUTOMATED PRECIPITATION CIRCUIT OPTIMISER

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ABSTRACT

The Automated Precipitation Control Optimiser (APCO) is an Expert System that delivers the process engineer's 'Holy Grail' of Bayer process control: rapid, science-based optimisation of input parameters to maximise production of quality product. APCO embeds 25 years of fundamental research from the joint industry-funded AMIRA P521-521D projects within a dynamic precipitation model to predict liquor yield, the particle size distribution and the soda content of the product. The Optimiser can be customised to any equipment configuration, including bypasses, split seeding, classification and inter-stage cooling. It dynamically models the responses to changes in flow, temperature, supersaturation, seeding rates etc., and has the potential to be integrated into existing on-line process control systems.

In this paper we describe the development and main features of APCO, and demonstrate its performance with a generic plant design that includes all the elements of a typical modern Bayer precipitation circuit. We demonstrate the power of the system with a surprising example of how a key parameter may track adversely after a process change before eventually resolving positively. With innovative use of surrogate models, APCO is superior to existing simulators and a must for every process engineer's toolbox.

1. INTRODUCTION

With computers and computational platforms becoming increasingly more powerful, the modelling and simulation of Bayer precipitation has progressed from modest beginnings to a level where it has become an integral part of the process management toolbox. Originally, gibbsite precipitation simulation tools were based on various custom-built platforms developed by different alumina refineries for their respective gibbsite precipitation operations, for example, Alcoa's dynamic precipitation model (Stephenson and Kaprun, 2013), Worsley's BRAHMA steady-state precipitation simulator (Antrobus and Hiralal, 2002) and Rio Tinto Alcan's HYPROD (Audet and Larocque, 1993). More recently, a range of generic process simulation tools, such as Aspen (Langa et al., 2016; Andrade and Islam, 2012), and SysCAD (Balde et al., 2018; Islam, 2014) have found applications in modelling gibbsite precipitation. A significant attraction of Aspen and SysCAD has been their ability to integrate gibbsite precipitation modelling with other alumina refinery operations, delivering a comprehensive plant-wide process model. SysCAD has built a broad database of material properties targeted specifically at the Bayer process, making it easier to apply their models for different alumina refineries. However, an important drawback of these existing tools is that it takes significant modelling expertise and simulation time to generate predictions of precipitation process responses that are useful for process engineers and plant management.

By introducing a novel surrogate model-based approach, the rapid Automated Precipitation Circuit Optimiser (APCO) is an innovative new approach to precipitation circuit modelling. The aim of the developed APCO software is to provide alumina plant process engineers with a simulation tool to rapidly predict responses of the precipitation circuit to changes in its inputs. Using the simulated predictions, the APCO accurately estimates the maximum yield that can be achieved under given precipitation conditions.

2. METHODOLOGY

The methodology used for the development of APCO software is presented by a workflow diagram in Figure 1.

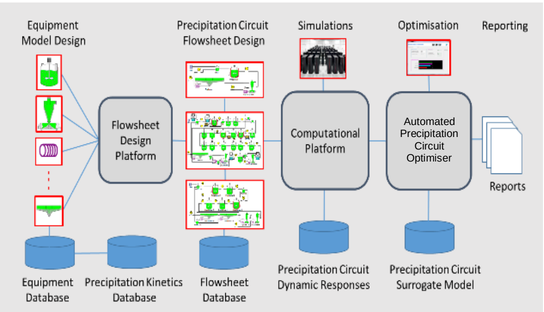

Figure 1. Framework for model-based Bayer precipitation circuit optimisation

The main framework consists of three stages. First, a model flowsheet design stage is followed by a computation stage that provides dynamic responses of the precipitation circuit. In the final stage, the software embedding a full precipitation circuit surrogate model is built to enable its rapid optimisation.

Numerical models of different equipment represent basic building blocks of the model flowsheet design stage. An example of a dynamic precipitation circuit model, utilising the gibbsite precipitation kinetics obtained through extensive experimental work, was presented previously by Bekker at al. (2017). In that case, a Simulink computational platform (2018) was used to predict dynamic responses of a generic precipitation circuit.

The APCO software enables the user to rapidly acquire predictions of precipitation circuit steady-state responses under different operating conditions, and thereby determine optimal values of various control parameters.

As shown in Figure 2, to conduct a meaningful optimisation the user specifies the feed rate and impurities, puts limits on the available seed filtration rate, and sets desired product quality parameters, for example targeted product particle size, and maximum soda and fines content. Taking into account the specified precipitation circuit inputs, the optimiser estimates the optimal values of a range of control parameters that maximise the precipitation yield. The set of optimisation parameters can include a range of process handles, such as cyclone cut-size and bypass, temperature, and agglomeration section bypass.

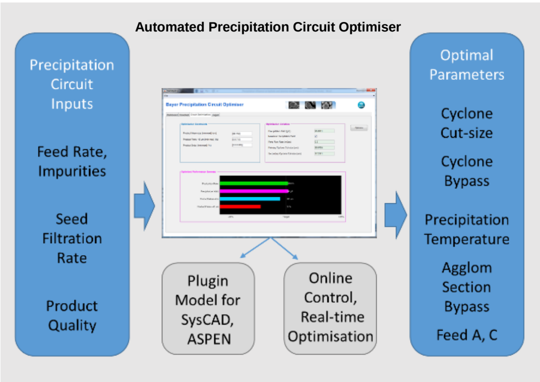

Figure 2. APCO schematic

The developed framework can also easily be adapted as a plugin precipitation circuit model for other modelling platforms, for example Aspen and SysCAD, or as an embedded rapid optimisation algorithm for online plant control and real-time process optimisation.

The APCO software interacts with the user through three main parts: (i) dashboard (Figure 3), (ii, #73) flowsheet (Figure 4), and (iii) optimiser (Figure 5).

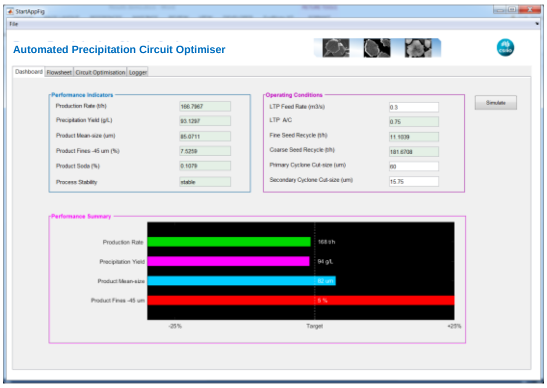

Figure 3. APCO dashboard

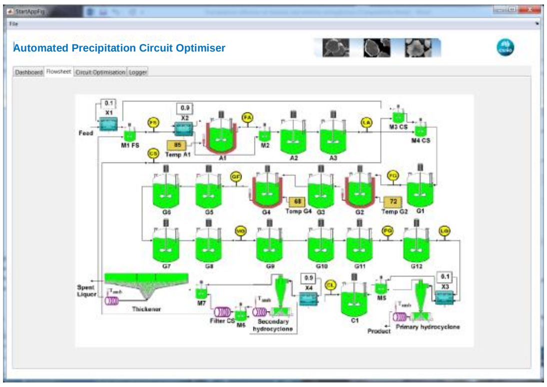

Figure 4. APCO flowsheet

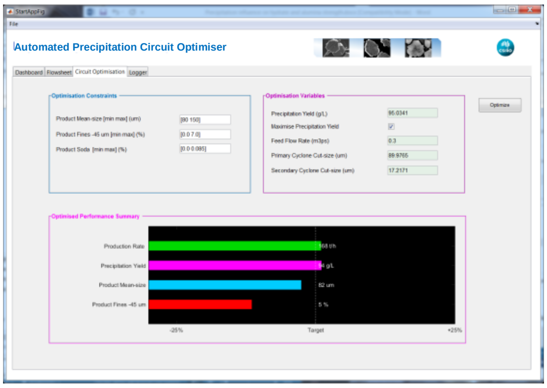

Figure 5. APCO optimisation

3. RESULTS AND DISCUSSION

The APCO software can be used in three main modes (i) direct simulation, (ii) productivity optimisation, and (iii) sensitivity analysis.

3.1 Direct simulation

The direct simulation mode, displayed in the APCO's Dashboard panel, delivers a numerical solution for the chosen precipitation circuit inputs. They include the feed rate and

impurity levels, hydrocyclone bypasses and cut-sizes, temperatures in various precipitation tanks, and values of A, C, and S in the feed.

In contrast to most standard simulators, the APCO's model prediction is available immediately. Its predictions include hydrate particle size distributions (PSD) in a range of 1-400 µm, with a resolution of 150 size intervals matching the Coulter Counter accuracy. The model predicted PSDs in the main precipitation streams are shown in Figure 6 for a feed rate of 1000 m^3/h, and a primary and secondary cut-size of 95 µm and 12 µm, respectively. A list of APCO predicted output variables is shown in Table 1. The circuit instability parameter is a measure of the circuit's unsteadiness. Parameter's values of less than 0.05 indicate a steady-state operation.

Table 1. APCO predicted precipitation circuit output variables

Variable name	Dimension
Circuit instability	-
Yield as Al_2O_3	g/L
Liquor productivity Al_2O_3	g/L
Product rate as $Al(OH)_3$	t/h
Soda in product as Na_2O/Al_2O_3	%
Product mean size as $d_{4,3}$	µm
Product fines -20 µm	%
Product fines -45 µm	%
Product coarse +150 µm	%
Solids in first agglomerator	g/L
Alumina in first agglomerator	g/L
Solids in first growth tank	g/L
Alumina in first growth tank	g/L
Solids in last growth tank	g/L
Alumina in last growth tank	g/L
Fine seed mean size as $d_{4,3}$	µm
Fine seed rate as $Al(OH)_3$	t/h
Coarse seed mean size as $d_{4,3}$	µm
Coarse seed rate as $Al(OH)_3$	t/h
Spent liquor rate	m^3/h
Spent liquor alumina as Al_2O_3	g/L
Spent liquor caustic, Na_2CO_3	g/L
Spent liquor soda as Na_2CO_3	g/L
First agglomerator PSD	Vol,%
First growth tank PSD	Vol,%
Last growth tank PSD	Vol,%
Fine seed PSD	Vol,%
Coarse seed PSD	Vol,%
Product PSD	Vol,%

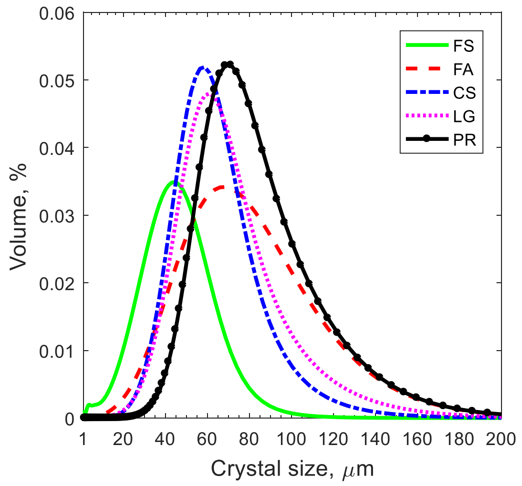

Figure 6. Hydrate PSD in the main precipitation circuit streams, where FS is fine seed, FA first agglomerator, CS coarse seed, LG last growth precipitator, and PR product

3.2 Productivity optimisation

In the optimisation mode, APCO maximises the precipitation yield by estimating the optimal values of a selected set of control variables for given precipitation circuit inputs. These inputs include the feed rate, concertation of impurities, and a set of upper and lower bounds on chosen process parameters, such as the seed filtration rate, product particle size, maximum soda and fines content.

An example of yield optimisation outcomes is shown in Figure 7 to Figure 11. Yield is calculated as ΔA, which is the difference between alumina in the feed and spent liquor.

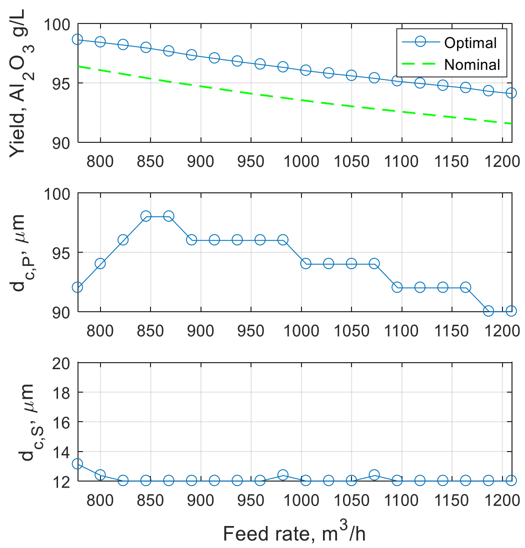

Figure 7. Optimal and nominal yields and optimal primary and secondary cyclone cut-sizes for different feed rates. Nominal $d_{c,P}$=60 µm and $d_{c,S}$=20 µm

Control parameter values for primary and secondary cyclone cut-sizes, $d_{c,P}$ and $d_{c,S}$, were optimised for different precipitation circuit feed rates. A set of the optimisation bounds used in optimisation is shown in Table 2, with the circuit responses shown in Figure 7 to Figure 11.

In the yield plot of Figure 7, the dashed line is the yield achieved with the nominal non-optimal control parameters, with $d_{c,P}$=60 µm and $d_{c,S}$=20 µm. As shown, a much higher yield is achieved with the optimised values of the cyclone cut-sizes. To maximise the yield, different classification strategies, i.e. different values of the cyclone cut-sizes, need to be used for different feed rates.

Table 2. Optimisation bounds for the precipitation circuit output variables

Optimisation bounds
Circuit instability < 0.05
Soda in product as Na_2O/Al_2O_3 < 0.12 %
Product fines -45 µm < 6 %
Product mean size as $d_{4,3}$ > 78 µm
Fine seed rate < 14 t/h
Coarse seed rate < 600 t/h

Optimisation bounds can be chosen for any of the precipitation circuit output variables listed in Table 1.

Corresponding fine and coarse seed filtration rates are shown in Figure 8 for different liquor feed rates as predicted for a nominal and optimal set of control parameters. The dotted lines in the plots show the bounds as set in Table 2.

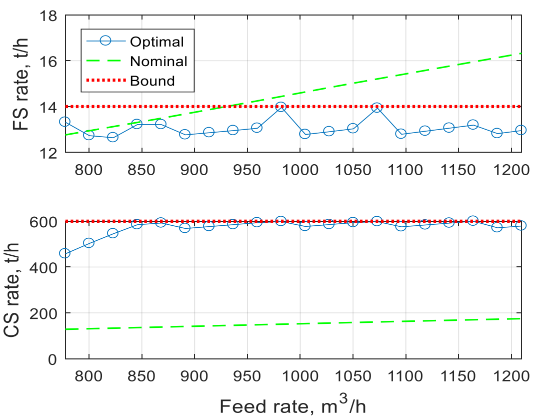

Figure 8. Optimal and nominal fine seed and coarse seed recycling rates for different feed rates

For the optimised set of control parameters, the fine seed rate is kept lower than the upper bound of 14 t/h at any value of the feed rate. In the case of the nominal, un-optimised set of parameters, the fine seed rate exceeds the assumed upper bound for feed rates higher than 950 m^3/h. Predicted circuit instability and product quality responses at different feed rates are shown in Figure 9.

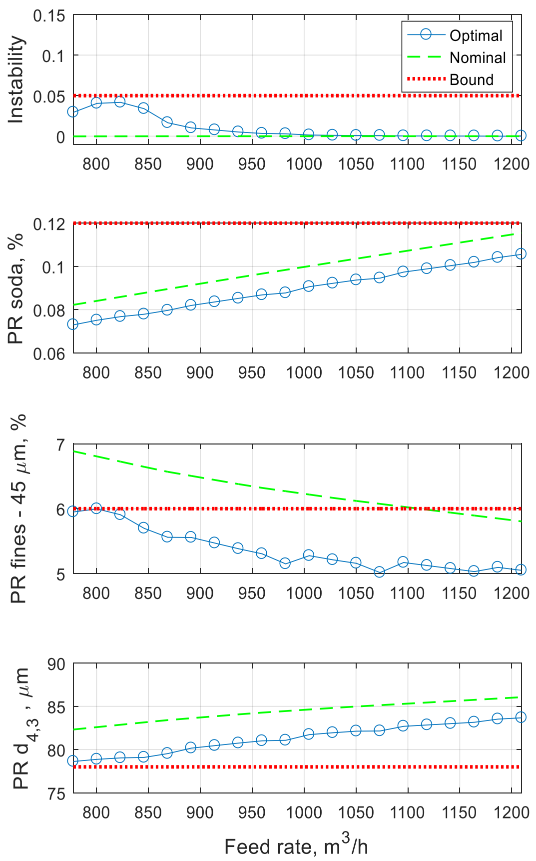

Figure 9. Optimal and nominal circuit instability, soda in product, product fines -45 µm, and product mean sizes for different feed rates

Instability values of less than 0.05 warrant a steady-state circuit operation. Compared to the nominal case, for the optimised control parameters the product soda level is reduced for all feed rates. At the same time, the optimised -45 µm product fines are consistently lower than the upper bound of 6%, whereas for the nominal parameters they exceed the upper bound for most of the feed rate range. The product mean size for the optimal control parameters, while smaller than that for the nominal case, is consistently larger than the mean size lower bound. Most importantly, the optimised control parameter set delivers a maximum yield achievable under given precipitation circuit feed conditions.

In Figure 10, the liquor productivity and product rate are compared for a nominal and optimal set of control parameters for different feed rates. The liquor productivity is calculated as CΔ(A/C), where Δ(A/C) is the difference between the A/C ratio in the feed and spent liquor, and C is the feed caustic concentration.

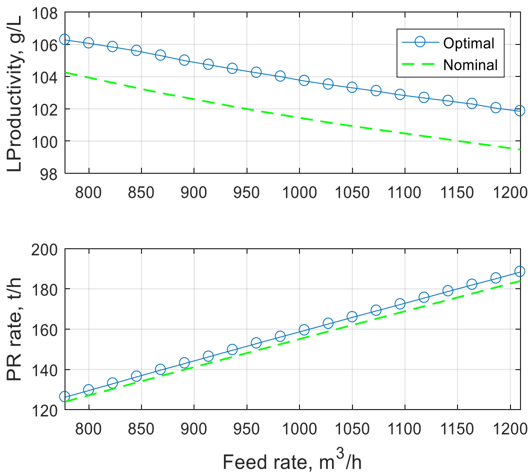

Figure 10. Optimal and nominal liquor productivity and product rate for different feed rates

The liquor productivity for the optimal case is consistently higher, by around 2 g/L, than that for the nominal case.

As shown in Figure 11, an increased liquor productivity in the case of optimised parameters is mainly a result of the increased solids in the growth section of the precipitation circuit. At the same time, the optimal solids in the agglomeration section are either very close to or slightly lower than those of the nominal case.

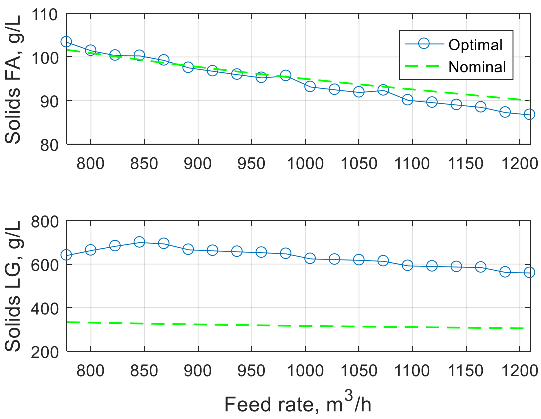

Figure 11. Optimal and nominal solids concentration in the first agglomerator and last growth precipitator

3.3 Sensitivity analysis

In addition to the optimisation, which estimates a maximum precipitation yield, sensitivity of the precipitation circuit output variables, such as shown in Table 1, can easily be analysed within the APCO's framework. Shown in Figure 12 are the yield and product mean size sensitivities as visualised in a 3-D space around a feed rate of 1000 m³/h. In this case, optimal primary and secondary cut-sizes are 95 μm and 12 μm, respectively.

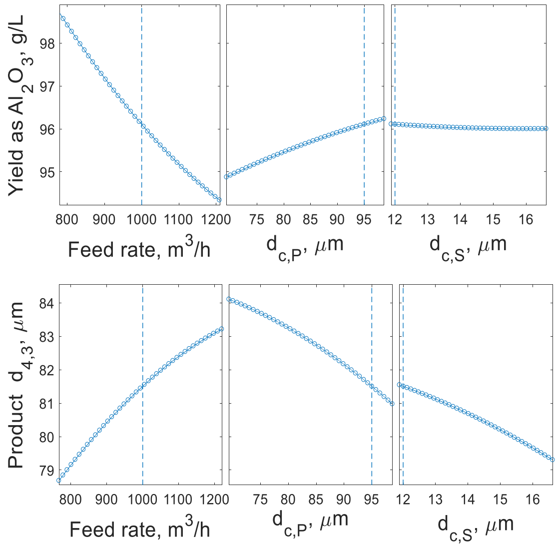

Figure 12. Yield and product mean size sensitivities with respect to the feed rate, and primary and secondary cyclone cut-sizes

The sensitivity plots clearly illustrate opposite trends in the yield and product mean size responses, with the former dropping and the latter raising as the feed rate increases. While the product mean size decreases with increasing primary and secondary cyclone cut-sizes, the yield, however, increases with increasing primary cut-size, but slightly decreases with increasing secondary cyclone cut-size.

4. CONCLUSIONS

Using a novel numerical framework, the Automated Precipitation Circuit Optimiser (APCO) delivers a gibbsite precipitation circuit model that is rapid and significantly more productive than the known precipitation circuit simulators. As demonstrated, in response to the feed rate changes it can optimise the classification parameters that maximise the precipitation yield.

Major advantages of the APCO are its speed, and ease of use and robustness in delivering predictions of the gibbsite precipitation circuit responses to changes in operating conditions.

Potentially it can be integrated within on-line process monitoring and control platforms.

While less tested in the production environment than the more conventional precipitation circuit simulators, the APCO software tool can potentially provide significant benefits to process engineers and plant operation managers.

5. NOMENCLATURE

FR - Feed rate

A - Feed liquor alumina, (Al_2O_3 g/L)

C - Feed liquor caustic, (Na_2CO_3 g/L)

S - Feed liquor soda, (Na_2CO_3 g/L)

FS - Fine seed

CS - Coarse seed

FA - First agglomerator

FG - First growth precipitator

LG - Last growth precipitator

PR - Product

PR soda - Soda in product as Na_2O/Al_2O_3

PSD - particle size distribution

$d_{c,P}$ - Primary cyclone cut-size

$d_{c,S}$ - Secondary cyclone cut-size

$d_{4,3}$ - Volume mean particle diameter

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