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DYNAMIC SIMULATION OF GAS SUSPENSION CALCINER (GSC) FOR ALUMINA

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Abstract

Training of plant operational personnel is becoming more important today than ever, to sustain high availability and productivity of high capacity equipment.

The Gas Suspension Calcination process for production of Smelter Grade Alumina is very easy to operate and control regardless of calcining capacity. But increasing calcining capacity of single GSC units exceeding 4500 tpd of SGA makes it increasingly costly to lose operating time.

The process dynamics of GSC units are very fast with some true response times in fraction of seconds. To train GSC operators, FLSmidth has developed a dynamic Calciner Simulator which serves the primary purpose of training both new operators, as well as maintaining the skills of experienced ones.

The dynamic Calciner Simulator has been developed from supply of more than 75 Pyro process simulators by FLSmidth to the global cement industry. The first Calciner Simulator for Alumina will be commissioned in Australia later this year.

Introduction

As demonstrated over many years the Gas Suspension Calcination (GSC) process for production of Smelter Grade Alumina is very easy to operate and control regardless of calcining capacity.

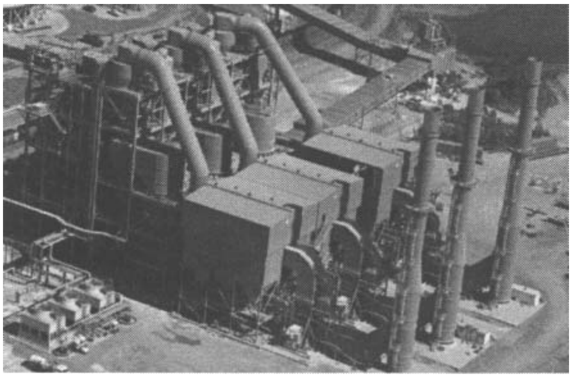
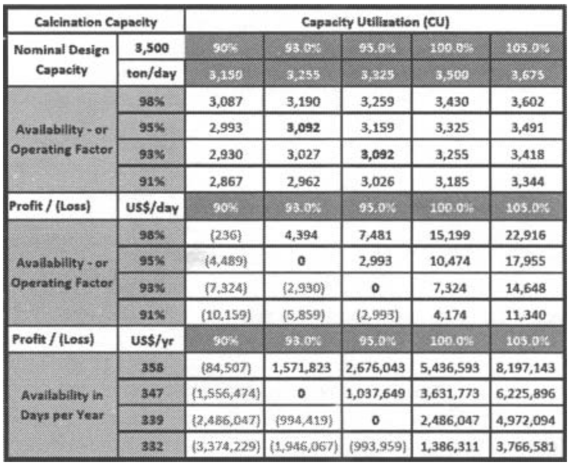


Figure 1: 3 x 4500 tpd GSC Units at QAL, Australia

However, when the GSC operating factor exceeds 98% as is the case in some GSC units, very little opportunity is left for the operator to gain actual hands on shut-down and start-up experience.

With calcining capacity of single GSC units now exceeding more than 4500 tpd of SGA a day, it also becomes more and more costly to lose operating time owing to unnecessary calciner down time. This is especially so, if the Bayer circuit can process more bauxite, liquor and red mud as illustrated in Table 1 below, assuming:

1) SGA production of 1,125,000 tonne per year;
2) SGA Sales Value: 275 US$/ton;
3) SGA production cost: 230 US$/ton;



Calcination Capacity		Capacity Utilization (CU)				
Nominal Design Capacity	3,500	90%	93.0%	95.0%	100.0%	105.0%
	ton/day	3,150	3,255	3,325	3,500	3,675
Availability - or Operating Factor	98%	3,087	3,190	3,259	3,430	3,602
	95%	2,993	3,092	3,159	3,325	3,491
	93%	2,930	3,027	3,092	3,255	3,418
	91%	2,867	2,962	3,026	3,185	3,344
Profit / (Loss)	US$/day	90%	93.0%	95.0%	100.0%	105.0%
Availability - or Operating Factor	98%	(236)	4,394	7,481	15,199	22,916
	95%	(4,489)	0	2,993	10,474	17,955
	93%	(7,324)	(2,930)	0	7,324	14,648
	91%	(10,159)	(5,859)	(2,993)	4,174	11,340
Profit / (Loss)	US$/yr	90%	93.0%	95.0%	100.0%	105.0%
Availability in Days per Year	358	(84,507)	1,571,823	2,676,043	5,436,593	8,197,143
	347	(1,556,474)	0	1,037,649	3,631,773	6,225,896
	339	(2,486,047)	(994,419)	0	2,486,047	4,972,094
	332	(3,374,229)	(1,946,067)	(993,959)	1,386,311	3,766,581

Table 1: Gross Profit and Loss Opportunities.

If the Operating Factor decreases from 95% to 93% (at 93% Capacity Utilization) due to lack of operator training, the loss of just 8 days production, will incur a loss of US$ 994,419 to the refinery per year.

Or, if due to sufficient operator training, the Operating Factor can be increased from 93% to 95% and the Capacity Utilization can be increased to 100% based on improved market conditions as well, the gross profit will increase with US$ 3,631,733 per year.

The above examples illustrates that to sustain high availability and productivity of high capacity equipment, training of plant operational personnel is more important today than ever before.

Furthermore, the training needs to be done without exposing the refinery to undue risk which can be done by using a Dynamic Process Model Simulator.

In summary improved operator training can provide the following benefits:

- Reduced and improved handling of incidents such as plugging;
- Improved Safety of operation with less stops;
- Maximize Capacity Utilization to meet demand;
- Maximize the Operating Factor at all times;

- Improved quality by more stable operation;
- Minimize down time and cost;

Needles to say, in addition to operator training - proper plant and equipment maintenance is also required in order to maximize return on the assets installed.

To train GSC operators, FLSmidth has developed a dynamic Calciner Simulator which serves the primary purpose of training both new operators, as well as maintaining the skills of experienced operators.

The dynamic Calciner Simulator described in this paper has been developed from operational experience, theoretical principles and the supply of more than 75 dynamic calciner process simulators by FLSmidth to the global cement industry.

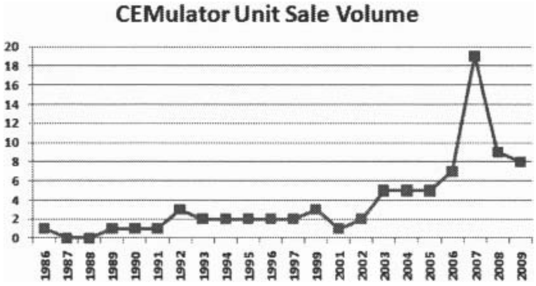


Figure 2. CEMulator unit sales volume: 1986 to 2009.

As seen in Figure 2 the sales of such simulators to the cement industry have increased over the past decade. FLSmidth did experience a sales volume reduction in 2008 and 2009 due to the global economic conditions, but sales are expected to be at the 2007 level in the near future.

The first dynamic Calciner Simulator to be described in the remainder of this paper, will be delivered to Australia for a new 3500 tpd GSC unit before it is started-up and commissioned later this year.

Gas Suspension Calciner Process Flow Sheet

Many processes are involved in the calcination of alumina hydrate. When the moist hydrate enter the GSC system it encounters hot gases from combustion of fuel and the calcination reactions. The purpose of the venturi and the first two cyclone stages is to utilize this heat for drying, pre-heating and pre-calcination of the hydrate. The foremost processes are heat- and mass-transfer and solids separation.

The hydrate is partly calcined in the riser duct to the second pre-heater cyclone, but will continue to react in the next section, which is the calciner furnace and holding vessel. The fuel is injected into the furnace and combusted to achieve the necessary furnace temperature. The hot combustion gases entrain the partially calcined alumina into the Holding vessel, where sufficient retention time is provided to reach the final degree of calcination and alumina quality (LOI, SSA and alpha phase). Again heat transfer is important, but in combination with a calcination model and a combustion model that can handle both natural gas and heavy fuel oil. The central point is however to develop a model that reliably predicts the quality of the calcined alumina in response to the operating conditions imposed. The FLS calcination model is built on the experience and know how gathered since the first GSC was put into operation in 1986, and incorporates modeling of the degree of calcination as well.

The cooling section (C01, C02, C03 and C04) is used for recovery of heat from the hot calcined alumina. This is efficiently done by using four cyclones. The counter-current flow obtained with four (4) cyclone stages of co-current flow in series is providing a high thermal efficiency with respect to cooling the alumina and simultaneously pre-heating the combustion air. Again modelling heat transfer as well as solids separation becomes paramount.

The last section of the GSC system comprises a fluid bed cooler, which will reduce the alumina temperature from approx. 180 °C to a temperature low enough for the alumina to be transported with a belt conveyor. However, this process will not have any significant influence on the overall heat consumption of the GSC system.

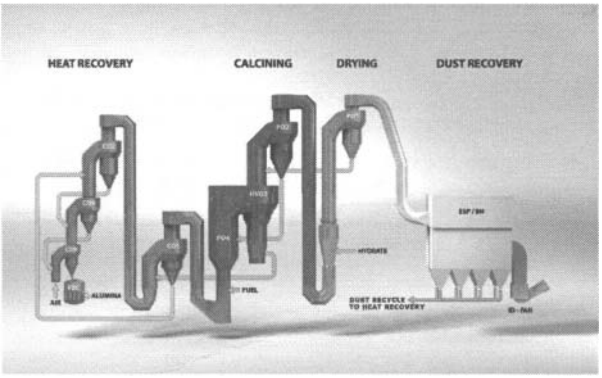


Figure 3. FLS Gas Suspension Calciner (GSC) flow sheet.

The Gas Suspension Calciner is straightforward to control with the following control loops:

- Production Rate controlled by Hydrate Feed Rate;
- Alumina Quality controlled by Calcination Temperature;
- Calcination Temperature controlled by Fuel Flow Rate,
- Alumina Discharge Temperature controlled by Cooling Water Flow Rate to Fluid-bed Cooler;
- Excess Oxygen controlled by Exhaust Gas ID-fan;

The control parameters for the closed-loop process simulator can be altered as the parameters in the plant DCS. Tuning these loops will enhance the closed-loop dynamic response of the process even further in the direction of truthful plant dynamic behavior.

The control strategy is to keep the Hydrate Feed Rate and thus Production as stable as possible and then modulate the Fuel Flow to maintain the Calciner Furnace temperature. This offers the advantage of a rapid control response as the manipulated variable (Fuel Flow) and the measured control variable (Furnace temperature) is situated in the same vessel.

Dynamic Process Modeling of the GSC

The aim of the simulator was to create a dynamic model that also corresponded with our steady state model when solving the time-dependence mass, energy and momentum equations. Building the model thus allowed us to simulate starting and stopping the equipment, but also to introduce changes in any variable to model different operation scenarios.

In general constructing a model can be approached in different ways. It can be either:

- Fully theoretical, derived from first principle and theoretical properties
- Semi- empirical, using first principles and derived model parameters by comparison with plant data
- Fully empirical, derived by correlating input and output data.

The FLS model is semi empirical, solving the dynamic balance equations to reach steady state, but utilizes the considerable FLS know-how about process and operation of the GSC to obtain the right model response in comparison with observed behavior.

Some of the process dynamics of Gas Suspension Calciners are very fast with some true response times in fraction of seconds, such as accelerating the particles discharged from a cyclone into the down-stream riser duct as described below. Once particles are dispersed into the flowing gas stream in the Cyclone Riser Duct, each particle in the gas suspension is accelerated by the flowing gas until each particle reaches its steady state velocity which depends on the gas velocity and the particles terminal velocity. The time needed for each particle to reach their steady state velocity can be estimated by solving the equation of motion for each single sized particle. The vertical upwards flowing particle velocity relative to the gas velocity, at time t>0, assuming that the Stokes drag law applies, is:

$$Uo = [dp^2 (\rho_p - \rho_g)\, g / 18\mu]\,(1 - \exp[-18t/dp^2\rho_p]) + Uio \exp[-18t/dp^2\, \rho_p] \quad (1)$$

The calculated particle velocity (please see list of symbols below) is shown in Figure 4.

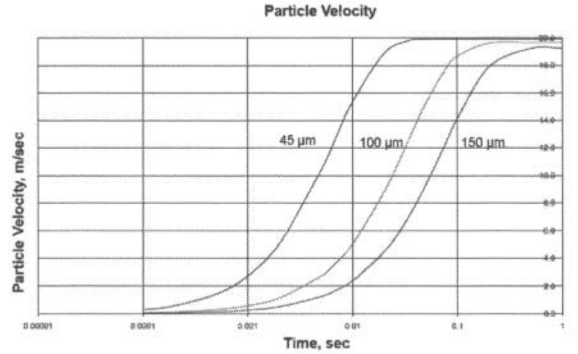


Figure 4. Particle Acceleration in a Vertical Riser Duct.

From the above figure it can be seen that a 45 micron particles reaches its steady state velocity (= gas velocity less its terminal velocity) in less than 0.1 second, while a 150 micron particle reaches its steady state velocity (= gas velocity less its terminal velocity) in less than 1 second.

Finally the operator observed process dynamics are further slowed down by the sampling frequency of the DCS.

While the dynamic response of thermocouples is measured in minutes, the alumina quality like SSA is measured in hours, owing to the turnaround time of alumina samples through the laboratory.

Still other parts of the plant never reaches a true steady-state such as the outer part of the refractory lining being exposed to the ambient temperature cycle covering 24 hours per day and seasonal cycles over the entire year.

In all, the FLS model is a mathematical analogy of the process generated by applying the principle of conservation of mass, energy and momentum. It can be used in real time simulations, thus improving the predictability and flexibility of plant operation.

Model equations – An Example

The mass and heat balance models are derived from first principle:

Accumulation = Input – Output + Generation (2)

In other cases a force balance is used as in the example of the pressure drop over a cyclone stage including its up-stream riser duct (heat exchange & separation stage):

$$0 = p_{in} - p_{out} - \Delta p \quad (3)$$

The pressure drop Δp is determined by summing five pressure drop components associated in the separation vessel:

Pressure drop due to acceleration

$$\Delta p_{sus} = \frac{(F_{g,in} + F_{dust} + F_s)\cdot v_2}{A_1} - \frac{(F_{g,in} + F_{dust})\cdot v_1}{A_1} \quad (4)$$

Pressure drop in the riser pipe bend

$$\Delta p_{rpb} = 0.5k_{rpb}(1 + \frac{F_{dust} + F_s}{F_{g,in}})\rho_{g,2}v_2^2 \quad (5)$$

Pressure drop due to rise pipe area change

$$\Delta p_{rpa} = 0.5(1 + \frac{F_{dust} + F_s}{F_{g,in}})\rho_{g,2}\left(v_3^2 - v_2^2\right) \quad (6)$$

Pressure drop due to friction

$$\Delta p_{cyc} = 0.5k_{cyc}\rho_{g,3}v_3^2 \quad (7)$$

Pressure drop due to gravity

$$\Delta p_{grav} = \rho_{g,3}gH + M \cdot g / A_{out} \quad (8)$$

The total pressure drop will thus be expressed as the summation of the contributors:

$$\Delta p = \Delta p_{sus} + \Delta p_{rpb} + \Delta p_{rpa} + \Delta p_{cyc} + \Delta p_{grav} \quad (9)$$

Below the dynamic response to a step change in the ID-fan speed can be seen on the outlet suction pressure from the dedusting filter and cyclone P01 respectively.

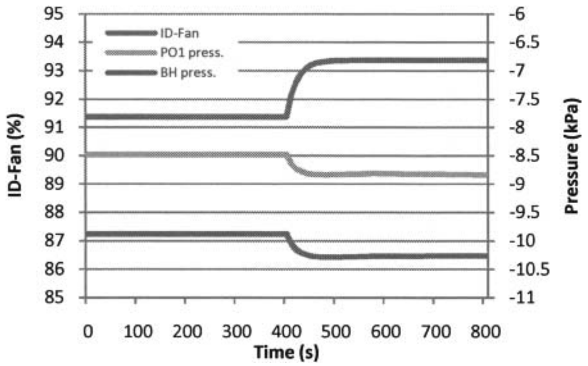


Figure 5. Dynamic response in relative suction pressure to change in ID fan speed.

Implementation of Dynamic Model Results and Validation

The overall pressure profile model prediction at steady-state is compared below with the resulting pressure profile calculated by the independent steady-state design model, which in turn has been verified against practical GSC plant operation:

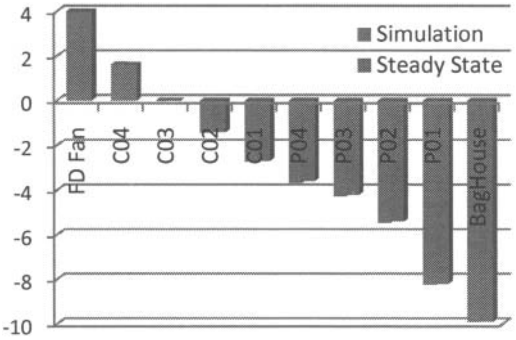


Figure 6. Pressure Profile at Nominal Production with 0% deviation relative to absolute pressure of 101,325 kPa.

As can be observed from Figure 6, a reasonable accurate convergence is obtained from the model when applied at nominal production of the GSC.

But to be of use to the operator, the model must also provide a reasonably true response over the entire GSC capacity range as demonstrated below in Figure 7 at 50% Turn Down ratio.

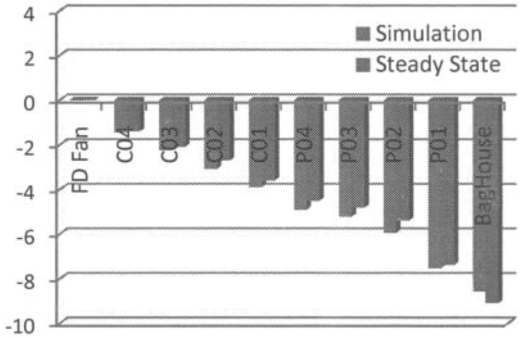


Figure 7. Pressure Profile at 50% Turn Down ratio with 0,2% deviation relative to absolute pressure of 101,325 kPa.

However, matching the stationary steady-state response shown above is a necessary criteria, but insufficient to qualify the dynamic model as applicable for training operators!

Needless to say, if a dynamic simulator model does not respond dynamically in a way that the operator can recognize from the real plant dynamic response observed from the DCS, the dynamic model will surely be abandoned and not used.

This raises the very important issue of proper model validation. We are of the opinion that the response of the dynamic process model must be tested and verified by our experienced GSC commissioning engineers in order to be qualified as a valid training tool – and thus applicable in the Training Simulator.

Training Simulator System Structure

To cover the needs for conducting simulation based training the FLSmidth training simulator consists of 4 program modules. The modules that are illustrated in Figure 8 covers:

- **Dynamic model and solver**, simulating the dynamic process behavior;
- **Soft PLC**, simulating control loop actions and equipment unit/sequence interlocking behavior;
- **Simulator**, control of the training communication between instructor and trainee, etc.
- **DCS** (Distributed Control System), enables risk free trainee operator interaction;

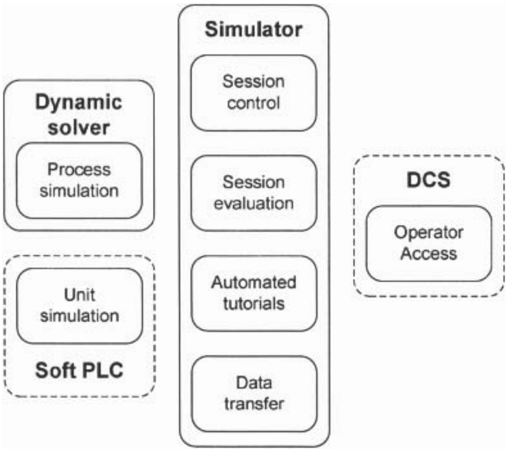


Figure 8. Simulator program structure split in program modules (dashed lined boxes can be standard FLSmidth setup or Honeywell).

In the Dynamic solver module the process dynamics are simulated. This includes the heat, mass and momentum balances and will represent the fast as well as the slow dynamic behavior in the GSC system based on mass, component and energy holdup. At FLSmidth we use the gPROMS, solver which is a state of the art dynamic solver delivered by PSE based in UK.

The Soft PLC module is where unit simulation is hosted. As in a true plant control system setup the PLC holds the process and plant information defining the operating state of the process. For this purpose PLC programs are uploaded in the Soft PLC. These programs are modified to simulate the physical equipment responses such as a starting motor. Besides the FLSmidth standard Rockwell Soft PLC setup a solution supporting Honeywell Soft PLC's are also supplied.

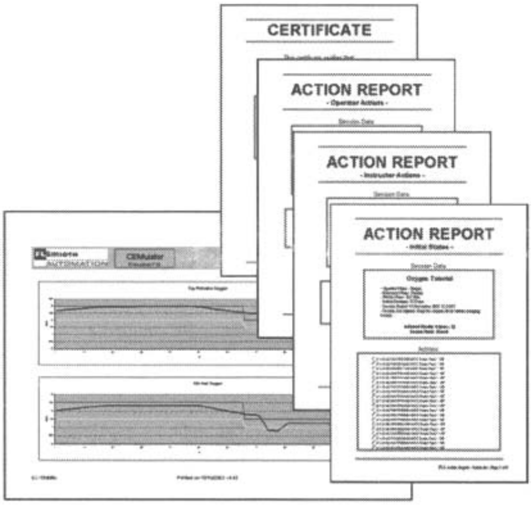
In the Simulator module all the programs used to set up the simulation is hosted.

The first area covered by this module is the Session control, where the Instructor can interact with the simulation session allowing control of the following:

- Start/Stop/Pause session
- Simulation speed - accelerate process responses if needed
- Disturbances – offset on demand
- Input parameters – external inputs/definitions
- On line evaluation
- Text messages

Secondly the Simulator module includes online and offline Session evaluation.

In the online Session evaluation the Instructor can monitor the current performance of the Trainee throughout the session. In offline evaluation the completed sessions are presented as reports representing evaluation objective trends and action reports. These reports can be used to evaluate the performance of the Trainee and dig into what learning areas that needs focus of the instructor.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ACTION REPORT

ACTION REPORT

ACTION REPORT

Figure 9. Example of action reports and session plots representing the offline session evaluation.

Next in the Simulator module is the automated Tutorials. Tutorials are prerecorded sessions including session control events like the action described in online session control. These can be used to uniform the training as events will have exactly the same timing for all Trainees, which results in that evaluation of two Trainees can be compared. The messages included in Tutorials are used to support the training and can therefore be used to ensure that all Trainees learn the same procedures covering startup, hot standby and shutdown.

Finally the Simulator module includes the data transfer between the other modules. The main data transfer is synchronizing the Soft-PLC and Dynamic solver so that all process data is updated in the PLC as well as all motor states and set-points in the dynamic solver. This module also ensures that the Soft PLC and Dynamic solver are aligned when restoring a saved session.

In the Distributed Control System (DCS) objects are presented to the Trainee just as in a real DCS. Here object trending, alarm handling, set-point changes and the remaining features covered by the DCS will be available.

In the FLSmidth standard solutions the in-house developed DCS named ECS (Expert Control and Supervision) is used, but the simulation setup also supports a solution using Honeywell Experion DCS as operator interface.

Common for all setups are the need for interaction from the Trainee and Instructor through their different stations. Figure 10 and 11 illustrates the accessibility needed for these two stations.

Figure 10. The program module access from the Trainee station.

From the trainee station the Trainee can make some of the basic session controls such as start/stop/pause and send messages. To ensure focused training the Trainee must be able to monitor the evaluation throughout the session. As the natural environment for an operator is in the DCS the Trainee's main access to the simulation will go through this interface to do control, monitoring and error tracking.

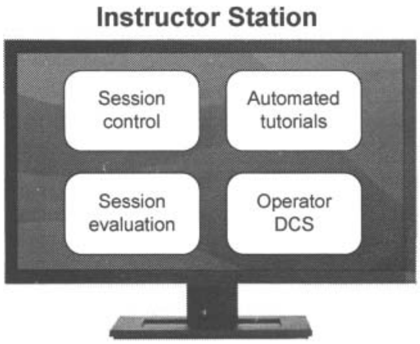

Figure 11. The program module access from the Instructor station.

The instructor station will act as a base for the Instructor. Here the full palette of session control must be available so that the Instructor in addition to the Trainee control can introduce disturbances, change input parameters and evaluation objectives on line. During training preparation the Instructor can use the tutorial editor to tailor make training sessions to the upcoming training needs. While undertaking the training the Instructor will also need to access the Operator DCS to fine tune the tutorials. The DCS can also be used during the session to monitor the current Trainees sessions during training.

FLS Experience with Training Simulator

In the cement industry the trend is that sufficient and documented training of operators is becoming a growing demand from local authorities. A recent example is the requirement for documented training in cement industry in USA. The reason for these demands is not only for the purpose of plant and staff safety, but also a requirement for implementation of a sustainable production.

In addition to the increased use of alternative fuels and focus on emissions, the current situation also raises demand for the operators to get the right skills by simulator training. Subsequently, this training results in more continuous and optimal plant operation with economical benefits to follow.

In the cement industry we have successfully developed an array of standard simulation solutions, which can be purchased as off the shelf applications for fast delivery. The trend is that these are sufficient to cover the needs for training in most organizations, while specific plants tend to need minor adjustments for the process to look more like the specific plant.

Back in the pioneers days in the 1980's the simulator was sold to specific plants. This trend has changed today where we still deliver half of our simulators to specific plants, but an increased interest from global companies is to purchase simulators for corporate training centers.

Apart from the CEMulator units sold externally there are 70 internal licenses spread across FLSmidth where the use varies from training to assistance in development of high level control standard solutions.

Conclusion

Increase in calcining capacity of single GSC units, sometimes exceeding 4500 tpd of SGA, makes it costly for the refinery to lose operating time. When at the same time the GSC operating factor exceeds 98%, as experienced in some GSC units, very little opportunity is left for the operator to gain actual hands on shut-down and start-up experience.

The Dynamic Calciner Simulator for SGA production developed by FLSmidth, will provide the Alumina refinery with the option of a risk free training of its new and experienced operators.

In the cement industry the trend is that sufficient and documented training of operators is becoming a growing demand from local authorities as more and more focus is placed on sustainable production and ensuring environmentally constrained emissions.

Consequently FLSmidth has experienced a surge in supply of training CEMulator units to the global Cement Industry, a demand that may come from the global Alumina Industry in the not so distant future.

List of Symbols

Symbol	Definition	Unit
F_s	Solid Mass flowrate	kg/s
$F_{g,in}$	Gas Mass flowrate	kg/s
F_{dust}	Solid entrained in gas flow	kg/s
υ_1	Gas velocity at inlet of riser pipe	m/s
υ_2	Gas velocity at outlet of riser pipe	m/s
υ_3	Gas velocity in cyclone	m/s
A_i	inlet area of riser pipe	m2
A_{out}	outlet area of cyclone	m2
K_{rpb}	Friction constant	-
k_{cyc}	Friction constant	-
$\rho_{g,2}$	Gas density at outlet of riser pipe	kg/m3
$\rho_{g,3}$	Gas density in cyclone	kg/m3

M	Solid hold up	kg
Δp	Pressure drop	kPa
p_{in}	Inlet pressure	kPa
p_{out}	Outlet pressure	kPa
H	Height of cyclone	m
g	Gravity	kg/m2
Δp_{sus}	Pressure drop of acceleration	kPa
Δp_{rpa}	Pressure drop of changed area	kPa
Δp_{rpb}	Pressure drop in the riser pipe bend	kPa
Δp_{cyc}	Pressure drop in the cyclone	kPa
Δp_{grav}	Pressure drop through gravity lift	kPa
U_o	Rel. particle velocity at t>0	m/s
d_p	Particle diameter	mm
ρ_p	Particle density	kg/m3
ρ_g	Gas density	kg/m3
t	Time	s
μ	Gas viscosity	kg/s m
U_{io}	Rel. particle velocity at t=0	m/s

References

1. B.E. Raahauge,et al.: "Application of Gas Suspension Calciner in Relation to Bayer Hydrate Properties", The Australasian Institute of Mining and Metallurgy, 1981 Annual Conference, Sydney NSW, 1981.
2. B.E. Raahauge,et al.: "Energy Saving Production of Alumina with Gas Suspension Calciner", 111th AIME Annual Meeting, Dallas,US,1982.
3. T.A.Venugopalan,"Experience with Gas Suspension Calciner for Alumina", Proceedeings 1st International Alumina Quality Workshop, pp 53-66, (1988).
4. S.Wind and B.E.Raahauge: "Energy Efficiency in Gas Suspension Calciners (GSC)",TMS Light Metals, pp 235- 40, (2009).
5. J.Ilkjaer, L.Bastue and B.E.Raahauge:"Alumina Calcination with the Multi Purpose Calcine", TMS Light Metals, pp 107-111, (1997).
6. R.K. Jonas:"Design and Training Improvements through the use of Dynamic Simulation", TMS Light Metals, pp 63-67, (2004).