Nickel and Cobalt 2005-
Challenges in Extraction and Production

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SYMPOSIUM ON NICKEL AND COBALT

Nickel and Cobalt 2005-Challenges in Extraction and Production

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Symposium Organized by the Non-Ferrous Pyrometallurgy Section of the Metallurgical Society of The Canadian Institute of Mining, Metallurgy and Petroleum

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Foreword

This volume is a compilation of papers from 6 sessions presented at the International Symposium on the Extraction of Nickel and Cobalt in Calgary, Alberta, August 21-24, 2005. The symposium was held in conjunction with the 2005 Conference of Metallurgists. Both the symposium and these proceedings were sponsored by the Non-Ferrous Pyrometallurgy Section of The Metallurgical Society (Metsoc) of the Canadian Institute of Mining and Metallurgy (CIM).

The papers contained in this book originate from 11 countries on 5 continents. The main categories include industry trends, updates on operating plants, new developments in extraction technology and applied research to support future processing developments. The range of specific topics covered in this book reveal the wide interest in nickel and cobalt processing within the metallurgical community.

Much has changed in our industry since the 1997 Nickel/Cobalt symposium in Sudbury. The threat of low-cost nickel production from limonite ore has yet to be realized and long-standing technologies continue to dominate the industry. However, significant improvements to these processes have undergone recent development and they will be the cornerstone for new production from upcoming projects. Anticipated new production of cobalt has not materialized as a result of challenges in treating limonite ore and slow rebuilding of the African cobalt industry. The above factors, combined with a strong global economy driven by China, have created one of the most exciting periods in the nickel/cobalt industry. The economic outlook for nickel/cobalt producers is very positive, as many companies aim to fill the current supply shortfall.

We would like to thank the authors for sharing their experiences and the Metallurgical Society of the CIM for providing a forum for exchanging knowledge.

We wish to acknowledge the much needed assistance of Elaine Garces of HG Engineering and Ronona Saunders of Metsoc in assembling the proceedings. We would also like to thank Inco and Falconbridge for their support of our effort efforts.

J. Donald
R. Schonewille
Editors

Calgary, Alberta, Canada
August 2005

Editors' Biographies

Jeff Donald received both his Bachelor's and Master's degrees in Materials and Metallurgical Engineering from Queen's University at Kingston, Ontario in 1993 and 1995, respectively. He received a Ph.D. in extractive metallurgy from the University of Toronto in 1997. He joined Inco Limited in 2001 after gaining broad experience in consulting engineering, research and development, and operations. He is presently focusing on projects that enhance long-term company value as Senior Process Engineer in Process Engineering and Strategic Studies at Inco Limited, based in Mississauga, Ontario.

Ron Schonewille studied Chemical Engineering at the University of Toronto, starting in 1986. His graduate research projects were in the field of nickel and copper matte converting. He completed his Ph.D. research in 1994 and started working for Falconbridge Ltd near Sudbury, Ontario the same year. For the first 10 years at Falconbridge he worked in the Metallurgical Technology group, focusing mainly on strategic technology developments for the extraction of nickel and cobalt from sulphide and laterite ores. In early 2004 he moved over to the Falconbridge Nickel Smelter to lead six sigma improvement projects. Ron is presently working in the operations group within the smelter.

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Dynamic simulations for off-gas systems design

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ABSTRACT

Off-gas systems often become the limiting factor in production increase and environmental projects. Any upgrade or new off-gas project needs to address control instability issues, instabilities that can result in safety hazards, significant loss of system capacity and/or emissions to the environment [1]. In addition, the design engineer must optimize system configuration and equipment size for the new operating conditions, to have a technically feasible and economically viable project. Dynamic simulations can be used for addressing both the control stability and the design optimization issues. This paper illustrates how the dynamic simulation of transient processes and of their control system can be used in "real life" situations for these purposes, presenting the example of an electric furnace off-gas system design.

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INTRODUCTION

The design and operation of metallurgical plants in most parts of the world is now governed by productivity, reliability, efficiency, safety and environmental issues. As a consequence, the metallurgical processes must be tightly controlled.

The off-gas system of any pyrometallurgical plant plays a major role in how well the plant operates, and its control system has to ensure that [1]:

- It maintains a gas stream within the cleaning equipment design capabilities.
- The system is controllable and operates within a safe range. Combustible gases and dusts must be handled safely.
- The method of furnace pressure control for the primary gas system must not result in unsafe gas leaks or puffings into the workplace.
- The downtime is minimized.

The intent of this paper is to explore the capabilities and advantages of using the dynamic simulation of off-gas systems for the purpose of investigating the feasibility of controlling the system operation, the performance of the system controls, and for overall system design optimization.

In other words, it addresses issues related to "slow transients" of off-gas systems, transients that can be controlled. The issue of using dynamic simulations for "fast transients" (furnace pressure surges, etc.) was addressed in a previous paper, [1].

The information presented in this article is based on a real case project regarding the modernization of the off-gas system of Groupe pour le Traitement du Terril de Lubumbashi's (GTL) cobalt electric furnace in the République Démocratique du Congo. At the date of presenting this paper, the new system is being commissioned.

OFF-GAS SYSTEM TRANSIENTS

As outlined in the previous paper [1], there are four distinct causes of transients in the off-gas system of a metallurgical furnace:

- Changes in equipment status (e.g.: control damper position, fan speed, etc.)
- Changes in the generation rate of process gas evacuated from the furnace by the gas handling system (e.g.: uneven feeding rates, non-uniform feed moisture, combustion pulsation, etc.)
- Equipment failures (e.g.: leakage of a water cooled element into the furnace, wall bank collapse back into the bath, etc.)

- Operation of systems outside their design ranges (e.g.: excess coke feeding, fan surging at low flow rates, etc.)

Some of these upsets have a high rate of change of the controlled process parameters (such as a furnace pressure, etc.) and they cannot be controlled. Safety devices, such as pressure relief devices, have to be installed to protect the equipment and the operators.

Other upsets have a low rate of change, within the capabilities of the system controls, and this is the topic for discussion in this paper.

DYNAMIC SIMULATION OF “SLOW” TRANSIENTS

The dynamic simulation of a system’s transients (“fast” or “slow”) is the representation of the time-dependent operation of the real system being modeled.

In case of an off-gas system of a metallurgical furnace, the typical controlled parameter is the pressure in the furnace or in the hood. Usually, transients with a rate of pressure change less than 2.5 kPa/sec can be followed by a normal control system. Dampers or the fan variable speed drive can effectively control these transients, [1].

The design of such a control system requires the definition of:

- The gas distribution system and of the time-dependent flow and pressure distribution in the system.
- The control strategy
- Equipment performance characteristics (e.g.: dampers, fan, controllers, etc.)
- Tuning parameters of the controllers

As the consequence, the dynamic simulation must represent accurately all these items. The typical approach follows these main steps:

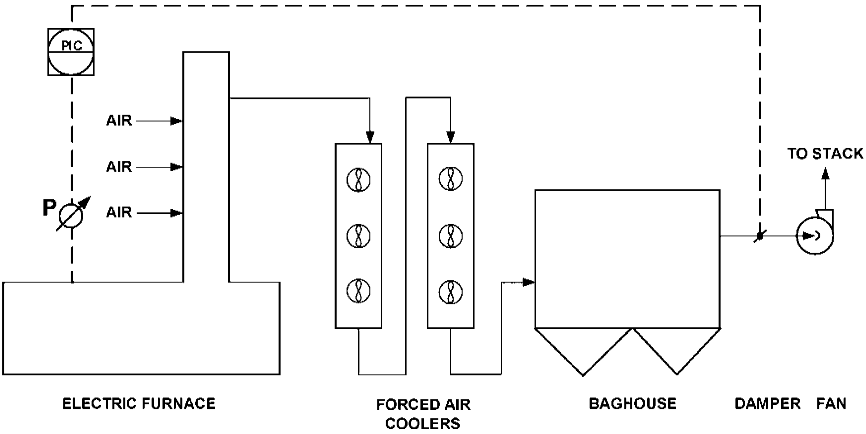
- Data collection and definition of design basis and assumptions.
- Development of the mathematical models of all the four items mentioned above.
- Development of the dynamic simulation model, typically using commercial software.
- Validation of the model
- Analysis, using the model

The next sections address some of these steps, referring to an actual project.

OFF-GAS SYSTEM

The scope of the project was the modernization of the off-gas system of a 30 MW cobalt electric arc furnace in Africa, processing slag remained from an old copper operation. The nominal operating power is 26 MW. Metallurgical coke is used as the reducing agent. The furnace is operated continuously, with several slag and metal tappings per day.

The furnace off-gas, rich in carbon monoxide and zinc vapour, is combusted in a sealed, vertical refractory lined combustion chamber located on the top of the furnace, above the off-take hole in the furnace roof. Combustion air is supplied to the chamber by dedicated fans. The combustion products are sent via a "horizontal" refractory lined duct to two forced-air coolers, and then to a baghouse, exhaust fan and exhaust stack.



The schematic diagram of the system is presented in Figure 1.

Figure 1 – Existing System (Schematic Diagram)

Severe solid deposits occur in the “horizontal” refractory-lined duct and in the forced-air coolers, deposits that limit the operating power of the furnace and require frequent shut downs for cleaning. Consequently, the production rate of the plant is limited.

Our preliminary feasibility study suggested the following main modifications:

- Replace the existing vertical refractory-lined combustion chamber with a water-cooled chamber equipped with an air gap close to the furnace mouth for rapid combustion of the combustibles in the off-gas.

- Replace the existing refractory-lined duct and forced-air coolers with a combination of water-cooled duct, spray cooler and air-cooled duct, complete with provisions for emergency dilution air.

The furnace pressure was suggested to be controlled by a new damper installed immediately downstream of the spray cooler.

The schematic diagram of the proposed system is presented in Figure 2.

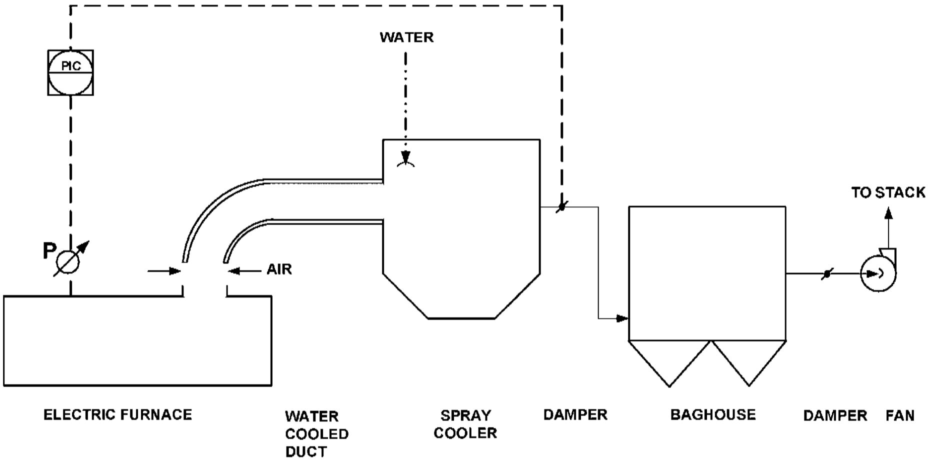


Figure 2 – New System (Schematic Diagram)

The objectives of these modifications are to reduce the number of shut downs and to allow the operation of the furnace at the nominal 26MW.

Several issues had to be resolved before finalizing the design:

- Determine if it is feasible to control the furnace pressure across the gap, taking also into consideration that any pressure change in the new, open, water-cooled combustion chamber affects the combustion process, too (i.e.: the flow rate of combustion air aspirated through the gap).
- Design optimization of the size of the gap, of the size of the control damper and of the control system tuning parameters.

The only possible approach in solving these issues was to develop a dynamic simulation model of the system.

MATHEMATICAL MODEL

The mathematical model must describe:

- The transient process(s) being investigated
- The equipment performance characteristics
- The control system

Process

The relevant processes governing the operation of an off-gas system are the gas generation rate and the flow of gases in the system. Changes of any of them leads to a change in the system pressure distribution, and consequently to a change of the controlled variable that has to be brought back to the set point by the control system.

Gases are compressible fluids. However, the author suggests that a quasi-incompressible treatment of gases steady-state or transient flow provides good accuracy for engineering purposes at small gas velocities (i.e. less than 20% of Mach number in that gas), as encountered in metallurgical off-gas systems. This represents an improvement compared to a full incompressible treatment, often used in off-gas designs

The quasi-incompressible treatment of flow of gases assumes that the off-gases are incompressible at low velocities, but it corrects the gas density in the section of duct under consideration, for the gas average pressure and temperature, accounting for the gas pressure and temperature drop in that section. This approach is followed for all the sections of the entire system.

Using Euler's coordinates frame of reference, the flow of an incompressible, viscous fluid through a fixed control volume is described by the Navier-Stokes equation:

$$\frac{D\overline{w}}{Dt} + \frac{1}{\rho}\,\text{grad}\,\overline{p} = \frac{1}{\rho}\overline{F}_g + \frac{\mu}{\rho}\nabla^2\overline{w} \qquad (1)$$

where ρ is the fluid density, kg/m^3

μ is the fluid dynamic viscosity, Ns/ m^2

$\overline{F}_g$ are the body forces (such as due to gravity)

$\overline{p}$ is the pressure vector, Pa

$\overline{w}$ is the velocity vector, m/s

$\frac{D}{Dt}$ is the substantial derivative

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \text{ – Laplace operator}$$

$$\text{grad} = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \text{ – gradient operator}$$

t is time

Ignoring the body forces (e.g.: gravity, etc., not relevant for gases), adding a "turbulent" viscosity, using the average density, and integrating over the length L under investigation, we obtain an equation that describes the pressure difference across L:

$$\frac{p_2 - p_1}{\rho_{av}} = \int_L (\nu + \nu_T) \frac{dw^2}{dx^2} dx - \int_L \frac{dw}{dt} dx - \int_L w \frac{dw}{dx} dx \qquad (2)$$

where: $\nu = \frac{\mu}{\rho}$ is the kinematic viscosity

The use of an average density over the length L can be justified mathematically (contact the author for details).

The terms on the right hand of the equation (2) can be expressed in an "engineering" form to allow the calculation of the pressure difference between two points located at the distance L. They represent respectively the friction and minor pressure loses, the pressure difference required for the "time" acceleration of the column of fluid and the pressure difference caused by the "convective" acceleration due to the change of the cross flow section area and/or of the gas parameters between the two points.

The "engineering" form of equation (2) becomes:

$$p_1 - p_2 = \left(K_f + \sum K_i\right) \frac{w_{av}^2}{2} \rho_{av} + L \frac{dw_{av}}{dt} \rho_{av} + \frac{w_2^2 - w_1^2}{2} \rho_{av} \qquad (3)$$

where: $K_f = 4f \frac{L}{D_i}$ is the friction pressure drop coefficient;

f is Fanning's friction factor;
D_i is the inside diameter of the pipe, m;

$\sum K_i$ is the sum of the local (minor) pressure drop coefficients;

w_{av} is the average gas velocity, based on the actual flow rate at the average pressure and temperature over the length L, m/s.

Pressure variations in the furnace freeboard are caused by gas accumulation (or removal) in that volume due to an imbalance between gas generation rate and gas flow rate out of the freeboard, into the off-gas system. Assuming that the ideal gas law applies, the relationship between the rate of gas accumulation (or removal) and the rate of pressure change is:

$$\Delta q_{accum} = \frac{22.4\ V}{R_u \cdot T_{av}} \cdot \frac{dp}{dt} \left[\frac{Nm^3}{sec} \right] \tag{4}$$

where: V is the volume of the freeboard, m^3;
p is the pressure in that volume, Pa.

Consequently, the pressure evolution in the furnace freeboard can be determined as follows:

$$p_f = \frac{22.4\,V}{R_u \cdot T_{av}} \int \Delta q_{accum} \cdot dt \tag{5}$$

Thus, the mathematical model used for the dynamic simulation of the transient quasi-incompressible flow of off-gases in each section of the system uses the equations (3) and (5). The respective differential and integral equations are solved numerically by the dynamic simulation software. The difficulties consist in correcting the average density after each calculation step of the pressure and temperature drop in that section for a quasi-incompressible treatment of the flow. As a consequence, the capability of using the results from one calculation step as an input for the next calculation step, without creating an “algebraic loop”, represents a main requirement for the capabilities of the dynamic simulation software package.

Other process phenomena included in the mathematical model of the system:

- Combustion at the gap
- Pressure drop at the gap, on the furnace off-gas and on the air sides, including the calculation of the excess combustion air.
- Energy balance at the gap and the temperature of the gases mix at the inlet of the water-cooled duct.
- Heat transfer to the water and air cooled ducts and the average temperature of gases in each section.
- Energy balance of the spray cooler and the required spray water for the desired outlet temperature of gases.
- Travel time of a gas “plug” from the furnace to the fan (i.e.: any change in the gas generation rate/gas flow rate affects the pressure in the furnace both directly through the change of accumulation and indirectly, due to the change of the fan operating point).
- Expected time-dependent operating point/pressure rise of the exhaust fan as a function of the fan performance curve and of the system characteristic (pressure drop as a function of the flow rate), etc.

Equipment Performance

Mathematical models of the performance characteristics of various pieces of equipment must be included in the dynamic simulation model to describe the performance of the respective equipment in response to time-dependent changes of the operating conditions.

Typical pieces of equipment in this category encountered on off-gas systems are:

- Fans: static pressure rise vs. inlet flow rate.
- Dampers: pressure drop across the damper vs. flow rate and position of damper blade.

Usually, characteristic curves are obtained from the equipment manufacturers and regression equations are derived for the respective curves, equations used subsequently in the model to describe the performance of the respective piece of equipment. The same approach was used for the project under consideration.

Control System

The existing system is set up to control the furnace pressure using a proportional-integral-derivative digital controller, aiming to control the furnace pressure at -15 Pa(g). The derivative function is disabled. The same furnace pressure set point was also desired for the new installation.

The control element is a 750mm butterfly damper located in the inlet duct of the exhaust fan. The damper has a full stroke time of approximately 53 seconds.

The controller uses the typical ISA PID algorithm, set-up as follows:

$$U_N = U_{N1} + \Delta U_N \tag{6}$$

$$\Delta U_N = P\left[(\varepsilon - \varepsilon_1) + \frac{T}{I}\varepsilon + \frac{D}{T}(\varepsilon - 2\varepsilon_1 + \varepsilon_2)\right] \tag{7}$$

where: U_N = controller output
ΔU_N = change of controller output from previous sampling interval
T = 2.0 sec. sampling time interval
P = 0.5 proportional gain
I = 10.0 sec. integration (reset) time
D = 0.0 sec. derivative time
ε = SP – PV current error
SP = -15Pa set point
PV = measured value of process variable
ε_1 = error at the previous sampling interval

The controller uses a normalized current error in respect to the range of the pressure transmitter:

$$\varepsilon = \frac{\mathrm{SP} - \mathrm{PV}}{\mathrm{R}} \tag{8}$$

where: R = 2000 Pa, range of pressure transmitter.

The dynamic simulation model uses the same algorithm and the same tuning parameters as the existing controller, as the base case. It also accounts for the travel time of off-gases from the furnace to the exhaust fan. Thus, the change of the operating point of the exhaust fan is delayed by this travel time.

The model also includes an analogue proportional-integral (PI) controller, for comparison purposes. The mathematical algorithm of the analogue controller is:

$$\mathrm{U_N} = \mathrm{P}\left(\varepsilon + \frac{1}{\mathrm{I}} \int \varepsilon \, \mathrm{dt}\right) \tag{9}$$

where: $\varepsilon = \frac{\mathrm{SP} - \mathrm{PV}}{\mathrm{R}}$

R = 2000 Pa

The tuning parameters of the analogue controller (PI) are the same as of the digital controller.

DYNAMIC SIMULATION MODEL

Once the mathematical models of all the processes and system components are available, the dynamic simulation model that would solve them can be developed using a suitable software package.

For the project under consideration, the objective was to generate a tool which could be used both for the analysis of these processes in transient regime, and assess the feasibility of controlling the furnace pressure across the gap, in the new configuration of the off-gas system.

The software package used was the European Simulation Language. ESL has a graphic interface which allows the user to build the model by using icons and blocks, defining their attributes and then interconnecting them, as required to “write” graphically the respective mathematical equations. The package includes differentiating, integrating and Laplace transforms which allow the description of processes and process controls in transient regime. After the model is built graphically, a program code in ESL language is generated automatically. Subsequently, the code can be translated and executed in Fortran 77. The results are presented either in graphical form or in tabular form. Any parameter in any point of the system can be monitored as a function of time or of another parameter.

The model for our project included modules for:

- Combustion calculations (both, off-gas and coke).
- Pressure drops/pressure distribution for each section of the off-gas system
  - Gap
  - Combustion chamber and water-cooled duct
  - Spray cooler
  - Duct between spray cooler and baghouse
  - Baghouse and duct to exhaust fan
  - Exhaust fan outlet duct and exhaust stack
- Performance of control damper
- Performance of the exhaust fan (to establish its operating point at each moment in time)
- Furnace pressure control loop.

A modelling technique was developed to allow the use of the output parameters at one calculation time step (e.g.: pressure, temperature) as input data for the next calculation time step. In this way, the compressibility effects (variation of density and of actual velocity with pressure and temperature) can be accounted for and the "engineering" form of the equation (3) describing a quasi-incompressible flow can be solved for each section of the off-gas system.

The graphical representation of the main routine of the model is presented in Figure 3.

For a given feed rate and composition of the furnace off-gas and coke (i.e.: furnace power), the model calculates automatically the impact of the variation of the draft (negative pressure) in the combustion chamber on various parameters, i.e.:

- When the furnace pressure increases, the control damper opens more to reduce the pressure in the combustion chamber and consequently in the furnace, to bring back the furnace pressure to the set point.
- The decrease of the pressure in combustion chamber increases the aspiration of combustion air, which, at its turn:
  - Increases the flow rate of gases through the system and modifies the operating point of the exhaust fan.
  - Decreases the temperature of gases.

- Decreases the amount of spray water required to maintain a constant temperature of gases at the outlet of the spray cooler. This also modifies the flow rate of gases to the fan.
- Changes the density of gases.

The model of the furnace pressure control loop uses the same tuning parameters and valve stroke time as the existing system.

Other features of the model include:

- Accounting for gas travel time.
- The capability to use a digital (as the existing one) or analogue controller
- The capability to generate disturbances of furnace pressure or of gas generation rate.
- The use of actual operating performance data for the existing exhaust fan.
- The use of actual operating performance data for control dampers.
- The impact of the change of combustion gases temperature with the excess air (i.e.: combustion chamber suction pressure) on the convective acceleration term of the pressure drop in combustion chamber, etc.

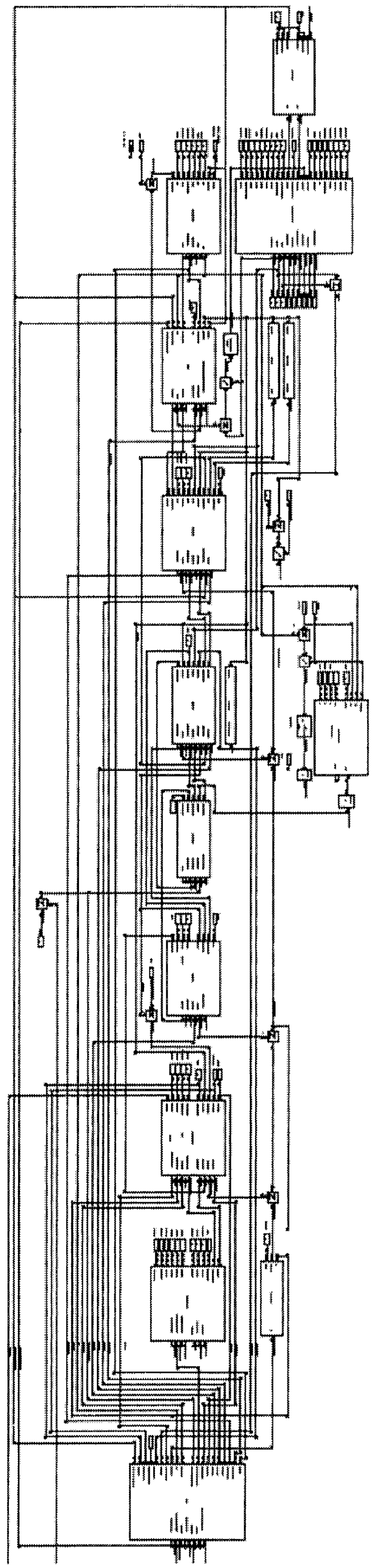


Figure 3 – Graphical Representation of the Main routine of the Model

MODEL VERIFICATION

The accuracy of the model was verified by performing calculations "by hand" for certain modules and comparing the steady-state results with those given by the model, for the same input data.

The verification indicated that the results of the "hand" calculations are the same as the model results.

RESULTS

The model was run for the following operating conditions:

Furnace Power	26 MW
Target excess combustion air	250% ÷ 270%
Furnace pressure set point	-15 Pa
Pressure controller tuning parameters	same as existing
Control damper full stroke time	same as existing (53 sec)
Control damper size (3 options)	30 in, 36 in, 42 in

Step changes of furnace pressure (25 Pa) (refer to Figure 4) and of gas generation rate in the furnace (10%) were tried. In both cases the model indicated that the furnace pressure would be brought back to the set point, but after a long period of time (refer to Figure 5).

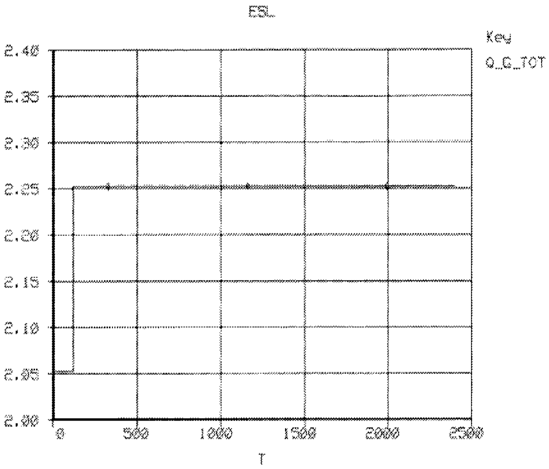


Figure 4 – Step-Change Perturbation of Gas Generation Rate
(10% at 120 second Simulation Time)

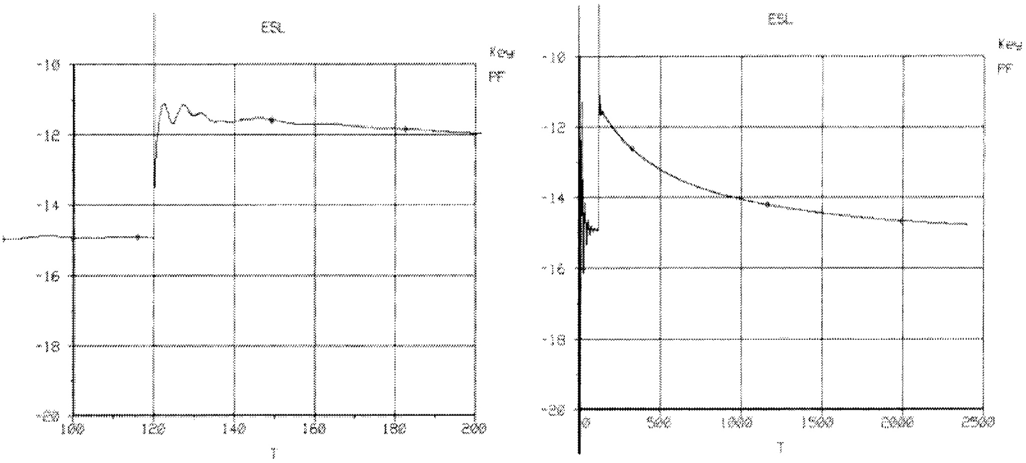


Figure 5 – Furnace Pressure Response to a 10% Step Change of Gas Generation Rate (30 in Control Damper)

Other results:

- The response time of the control system using the existing set-up parameters was too slow. This refers to both the full stoke time of the control damper (53 sec.) and to the tuning parameters of the furnace pressure controller.

Thus:

  - The control damper needs an actuator with a full stroke time smaller than the existing 53 seconds.
  - The tuning parameters of the controller need to be adjusted in field to give a faster response.

- A control damper close to the size of the duct diameter would be only a little open at the furnace nominal power, if the fan inlet damper is fully open (refer to Figure 6). This would give a poor control of the furnace pressure, and possibly no control at all, at low furnace power.

Thus:

  - Either a smaller control damper must be used or,
  - The position of the fan inlet damper has to be adjusted to keep the control damper in the controllable range.

Alternately, a variable speed drive could be installed on the fan motor, for the same purpose. The variable speed drive option would have the advantage of allowing the fan inlet damper to be in fully open position or even the complete removal of the damper, reducing the total pressure drops and saving electrical energy.

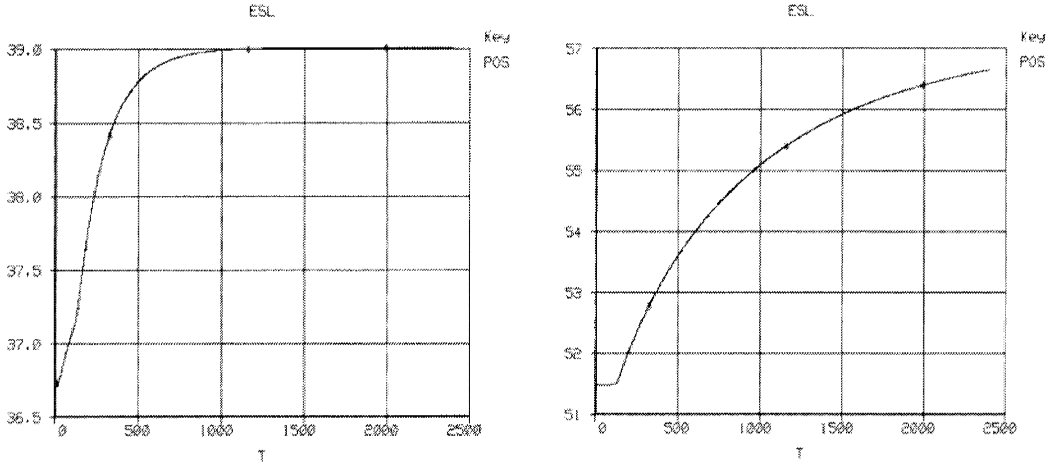


Figure 6 – Position of a 42 in (left) and of a 30 in (right) Control Damper Responding to a 10% Step Change of Gas Generation Rate, at Nominal Furnace Power

- The gap width selected initially was too small for providing enough combustion air and, at the same time, controlling the pressure in the furnace in the required range. Thus, the final design provided for a bigger gap, with the width as resulted from the analysis for optimum operation.
- It seems that an analogue controller using the same tuning parameters as a digital controller would provide a faster response (refer to Figure 7).

Alternately, the rate of response of the digital controller could be increased by reducing the sampling time interval, increasing the proportional gain, etc.

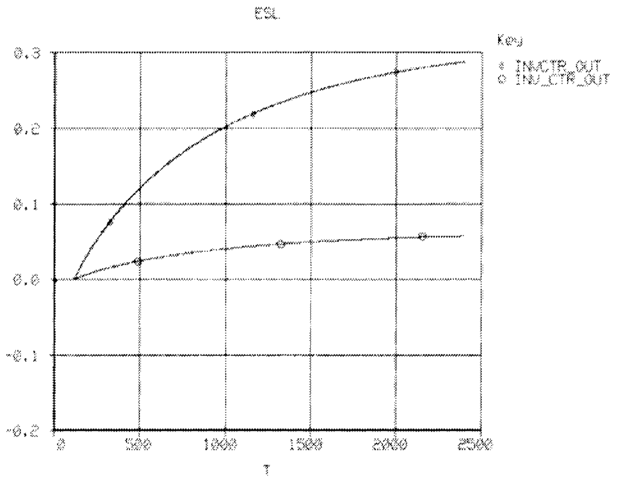


Figure 7 – Response of Analogue (INVCTR_OUT) and Digital (INV_CTR_OUT) Controllers to a 10% Step Change of Gas Generation Rate

CONCLUSIONS

The increasing demands on modern gas handling systems in respect to capacity, productivity, reliability, operability and safety require state-of-art engineering approaches and tools to be used in the design process. These demands require system designers to properly understand and control transient behavior of these systems, and dynamic simulations are becoming a necessity.

The project presented in this paper illustrates the usefulness and necessity of using dynamic simulation techniques for feasibility investigation and for design optimization. Both the controls and the system design optimization can benefit from the use of dynamic simulations and sometimes, there is no other way to solve design issues of the more and more demanding such systems.

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