

Dynamic Modeling of the Plant Gas System: Process control and design applications

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KEYWORDS

Dynamic Modeling, Process Control, Process Design, Pressure Control, Simulation

ABSTRACT

A development approach and application of a high fidelity dynamic model is presented for a large industrial plant, characterized by strong interaction of the production units with fast dynamics and sharp unexpected changes of the process pressure. The model is designed using a general-purpose process simulator extended with custom components for modeling of specific features of the plant pressure relief devices. The model was created for the existing plant configuration and future process modifications. Due to complexity of the plant units, the model is built as a multilayer dynamic flowsheet, containing up to four nested levels of sub-flowsheets. In order to provide a realistic simulation, sequences for plant events and process interlocks were also included in the model. The resulting model has been used for development and evaluation of the advanced control strategies for both the existing and modified processes under different scenarios of its behavior. On the process side, the model was utilized for reconstruction and analyzing of emergency situations and for evaluation of the vent system redesign options.

1. INTRODUCTION

Dynamic modeling is a valuable tool for evaluation of plant operating conditions and control strategies. High fidelity dynamic simulators, developed for the process industries in the last decade, provide a solid basis for accurate modeling of the dynamic transitions [1]. Nevertheless, development of custom

components (for specific features of the process and measurement system) is often needed to provide a realistic model of the plant [2], [3].

This paper presents a development approach and application of a dynamic model for the plant off-gas system, characterized by the complex structure and strong interaction of the production units with fast dynamics and sharp unexpected changes of the process pressure. The model was developed in several phases using a Hysys dynamic simulator [4]. Initially, the model for the existing plant configuration, in nominal operational mode, was created; i.e. the plant emergency pressure relief devices that required custom modeling were not included. This model was validated using the plant data historian and was used for evaluation of the process dynamics and improvement of the existing control system. Then the model for the thermal oxidizer unit (a redesign option to decrease plant emissions) was added. This model was used in the design of the advanced control strategies for the modified process and thermal oxidizer itself. These strategies were tested for various scenarios of plant events and the expected plant unit interactions were evaluated. Finally, as the confidence of Plant Manufacturing grew, the model was extended with the custom pieces of the pressure relief devices (existing and new projected ones) and was used for development and justification of the plant vent system redesign.

2. PLANT PERFORMANCE AND CONTROL ISSUES

A general schematic of the process is given in figure 1. The plant has three electric arc furnaces, used for the production of elemental phosphorus. The reaction products coming off the furnaces are primarily phosphorus vapor and carbon monoxide gas. At the gas processing units, the phosphorus is condensed and separated from the carbon monoxide in the condenser after particulate is removed from the stream in the electrostatic precipitator. The carbon monoxide is directed to a common header and conveyed further to a rotary kiln, where it is used as the primary fuel in calcining phosphate ore in preparation of its use in the furnaces. Excess gas is flared. In the near future a thermal oxidizer will be constructed to process the excess carbon monoxide gas, thereby removing the flare most of the time.

The described structure creates a highly interactive environment for pressure control in the system. Pressure control of the furnace off-gas is critical to the safe and efficient operation of the plant. A surge of the furnace pressure propagates quickly to the common header causing disturbances in the work of both the kiln and parallel furnace units. On the other hand, the kiln load changes immediately lead to the header pressure disturbances, impacting the performance and pressure control of all parallel furnaces.

The dynamic modeling project was undertaken to get a better understanding of this and several other plant control and performance issues. Due to the fast, interactive dynamics of the process, the quality and speed of response of a control system are vital for plant performance. Using dynamic simulation is an easy and reliable way to test potential process control improvements (decoupling of the loops, gain scheduling, feedforwarding) before implementing it into the real plant. The other important control issue for the plant is a transition from the legacy system to the newer DCS. The dynamic modeling can help to answer the question how the scan rate and speed of response of a new system will effect the quality of control.

The process redesign option for decreasing of emissions is to install a thermal oxidizer, replacing the flare in the normal operational mode. Because of strong interactions between furnaces, flares, thermal oxidizer and kiln, design issues with the proposed thermal oxidizer and dynamics of the off-gas header are of great interest. Some of the issues to explore are: how to maximize carbon monoxide use in the kiln, what is the maximum pressure in the system under a given set of upset conditions, how quickly must the thermal oxidizer react to prevent flaring. The main items for dynamic modeling in this part of the project were: (a) create a dynamic model of the thermal oxidizer (TO) unit and develop its control system, providing stable TO performance under the changing input load; (b) modify a control strategy for the common header pressure to take into account TO as an additional interacting element; (c) evaluate performance of the whole, modified process (with new strategies) under different scenarios of the plant behavior, including abnormal and emergency situations.

An improvement in the pressure-relief system performance is a key plant safety issue. It is also related to plant emissions. The pressure-relief devices of the existing system were designed using steady state conditions, while the real values of the device-relieving pressure and capacity are dynamic in nature (depend, particularly, on the pressure impulse dynamics). Therefore, the first answer that can be given by dynamic simulation is to evaluate the real values of relieving pressure and relieving capacities for the devices and the overall system at various intensity and shape of the pressure impulses. The subjects of interest for the vent system include: if air is inadvertently introduced into the off-gas system, what pressures would be expected by the resulting deflagration, and how the pressure-relief devices interact during a pressure excursion. The next task is to use the dynamic model to modify the system. Particular items for modeling are: (a) create the model of a new pressure relief device and test its behavior before implementing it into the real plant; (b) using the simulation, evaluate different configurations of the vent system, consisting of new and existing devices; (c) define an optimal relieving point for the new device.

3. DEVELOPMENT OF THE DYNAMIC MODEL

The model was developed using the general-purpose Hysys process simulator. The custom components for modeling of specific features of the pressure-relief devices were created using spreadsheet calculations and Hysys User Variables (Visual Basic programming). The model was built in two versions, basic and extended. The basic version is a model for the existing plant configuration in the normal operational mode, with the thermal oxidizer unit connected (which can be easily turned off to give the current process layout). The extended version contains, in addition, a vent system model, including the existing seals and new ones planned to be installed.

3.1 MAIN FEATURES OF THE MODEL

Due to complexity of the plant, the model is built as a multilayer dynamic flowsheet, containing up to four nested levels of sub-flowsheets. The main flowsheet, shown in figure 2, contains unit operations for the common header (piping, valves, condensate traps), simplified model of the kiln, and sub-flowsheets for the furnaces/ processing units and thermal oxidizer. The furnace/ processing unit flowsheet includes, in turn, sub-flowsheets for its component and pressure-relief devices (seals). This multilayer solution provides simplicity in reading and navigation through the model and flexibility of its development and

modification. Particularly, the seal models can be easily repositioned along the process or switched on/off to analyze alternative structures of the pressure-relief system.

The plant piping system has a fundamental impact on the process dynamics. Since the simulator currently does not support dynamic unit operations for the pipe segment, it was modeled using combination of a separator, simulating the pipe volume, and valves for the pipe resistance. The valve sizing was carried out using plant steady state data for one- (gas) or two-phase (liquid-gas) flow. In order to provide correct calculation of the pipe resistance in transition from one- to two-phase flow, the variable valve opening and additional dynamic element, lag transfer function, were used.

The model includes also a part of the plant control system. The controllers and valves were implemented using simulator unit operations. The valve and actuator characteristics were defined according to plant data (design and experimental), and the tuning parameters of controllers were set equal to the real plant ones. The main process interlocks were programmed using the simulator Event Scheduler. The Event Scheduler was used also for modeling of plant events, such as pressure excursions, load changes, and process equipment going down in emergency situations. A combination of these features, complemented with custom models of the plant seals (see section 3.2 below), provides a highly-realistic environment for studying plant behavior and testing of the new control strategies and process design options.

3.2 CUSTOM MODELS OF THE PRESSURE RELIEF DEVICES

The existing plant seals are primarily of two types: gravity-weighted and fixed-cap ones. In the first type, the seal is broken (opened) when the lifting force, provided by the pressure under the moving bell, becomes higher than the bell weight. In the second one, the bell is not moving and the seal is opened when the pressure under the bell is high enough to push out all liquid from the space under the bell (inner space of the seal) into the space between the outer surface of the bell and the seal tub (outer space of the seal). The new seal is a fixed-cap type with improved capability of resealing and liquid-gas separation.

The model for the gravity-weighted cap seal includes a bell lifting model and equivalent pipes and valves. The bell-lifting model describes the motion of the seal bell resulting from the balance of the forces acting on it. The calculated bell position is used then to get the value of the seal opening and further calculate the relief flow rate through the seal. An equation for the bell velocity $V(t)$ can be written as

$$M \cdot dV(t)/dt + K_R \cdot V(t) = (P_{In} - P_{Top}) \cdot S_{Bell} - W_{Bell} \quad (1)$$

or in a standard form of a first order filter

$$T_v \cdot dV(t)/dt + V(t) = K_v \cdot ((P_{In} - P_{Top}) \cdot S_{Bell} - W_{Bell}) \quad (2)$$

where

M is a mass of the bell,

K_R is a friction resistance coefficient,

P_{In} and P_{Top} are the pressure values under the bell and on its top, respectively,
 S_{Bell} and W_{Bell} are the bell top area and bell weight, respectively.
 $T_v = M / K_R$ is the time constant for a first order filter,
 $K_v = 1 / K_R$ is the gain for a first order filter.

The bell position $H(t)$ is calculated then by integrating $V(t)$, taking into account a mechanical restriction H_{max} on the bell lifting,

$$H(t) = \int V(\tau) d\tau, \quad \text{with constraints } 0 \leq H(t) \leq H_{max} \quad (3)$$

The boundary conditions for the bell velocity are

$$V(t) = 0 \text{ IF } (H(t)= 0 \quad \text{AND} \quad dV(t)/ dt \leq 0) \quad (4a)$$

$$V(t) = 0 \text{ IF } (H(t)= H_{max} \quad \text{AND} \quad dV(t)/ dt \geq 0) \quad (4b)$$

The term $K_R * V(t)$ in Eq.(1) is a friction-resistance force causing the bell to suspend finally when the main forces acting on the bell, weight and pressure difference, are equalized. K_R is the tuning parameter of the model. Since the mass of the bell is known, it is more suitable to use T_v (see Eq (2)) instead of K_R . This time constant has a physical meaning of approximately one third of the time needed for the equalized system to stop. The bell position calculated according to equations (1)-(4) is converted then into opening percent of the equivalent valve, sized according to the friction pressure drop of a seal assembly. Finally, the flow rate through the seal is calculated in the simulator using the current seal pressure difference and the valve characteristics.

The model for the fixed-cap seal includes a model for the dynamics of a liquid accumulation in the seal tank. It is implemented using simulator unit operations, and the custom calculations for the seal state variables. The seal state variables define: (a) the seal operating mode (Open, Closed, Open with no liquid column), (b) opening/closing the pseudo-valves controlling the gas path and liquid inlet/outlet to the seal tank, (c) pressure drop and height of gas-liquid column in the seal, (d) direction of the seal flow (pressure relief or suction).

The equations for the “seal open” conditions are given below, where formula (5a) works for opening the seal at the direct pressure relief (high process pressure), and equation (5b) is a vacuum relief condition,

$$((P_{In} - P_{atm}) > W_{AboveSkirt} / A_{outer}) \quad (5a)$$

OR

$$((P_{atm} - P_{In}) > W_{AboveSkirt} / A_{inner}) \quad (5b)$$

Here, P_{In} (P_{atm}) is a seal (atmospheric) pressure, $W_{AboveSkirt}$ is a weight of liquid above the seal skirt (low edge of the bell), and A_{outer} (A_{inner}) is a cross section area of the outer (inner) tub space.

The level of clear liquid H_0 in the seal is calculated as

$$H_0 = L_{AboveSkirt} + \max (DH_{outer} , DH_{inner}) \quad (6)$$

Here $L_{AboveSkirt}$ is a tank liquid level above the seal skirt in equilibrium (when $P_{In} = P_{atm}$), and DH_{outer} (DH_{inner}) is the current deviation of the level from the datum line in the outer (inner) space of the seal tub. The values $W_{AboveSkirt}$, $L_{AboveSkirt}$, DH_{outer} and DH_{inner} in equations (5) and (6) are calculated using the current liquid balance in the seal tank, seal geometry data, and the process pressure value.

Fractional liquid holdup K and Fraude number, Fr , are calculated using superficial velocity of the gas V , a free-fall acceleration g , and H_0 :

$$K = 1/(1 + Fr^{1/2}) \quad (7)$$

$$Fr = V^2 / (g * H_0) \quad (8)$$

The level H_0 and liquid holdup K are used then to determine the height of a gas-liquid mixture in the seal tub, which controls the seal pseudo-valves. The values Fr and V are also used in the criterion calculations for transition between two-phase (liquid-gas) flow regimes, employed in the model of the new seal.

The models include features of abnormal seal functioning, such as incomplete closing of the seal and ignition reactions. Incomplete closing of the moving bell, after the seal has opened, results in the intake of air into the gas system. As a result, the carbon monoxide gas may have an ignition reaction with the air that can cause a pressure and temperature rise in the piping system. An ignition of the gas can be modeled for both types of seal in situations when ambient air suction occurs due to insufficient resealing with liquid.

4. MODEL APPLICATIONS

The resulting model, providing an accurate evaluation of the dynamic transitions for both the existing and modified processes, has been used for development of advanced control strategies. On the process side, the model was utilized for reconstruction and analyzing of plant emergency situations and for evaluation of the design options (location and parameters of new pressure relief devices) to improve plant performance and safety.

4.1 DEVELOPMENT AND TESTING OF THE CONTROL STRATEGIES

There is pressure control on each furnace to maintain furnace backpressure, pressure control on compressor outlets to maintain compressor pressure, and pressure control in the common header. At the current process configuration, the fuel supply to the kiln is controlled by varying the flare pressure setpoint, thus indirectly affecting CO flow to the kiln (in this case, the RSP signal shown in figure 1 goes to the flare pressure controller). Unfortunately this control adjustment has the adverse affect of upsetting the upstream pressure controllers, particularly, the nearest upstream controller at the compressor outlet. The model for the current process configuration was utilized to demonstrate the effect of adding dynamic feedforward between the flare pressure control valve and the compressor outlet pressure control loop. In the simulation, step testing was performed for the effects of both the flare

valve and the compressor outlet valve on the compressor outlet pressure. The results of the step testing were used to set the feedforward gain and the feedforward lead/lag. Closed-loop pressure response for a typical flare pressure setpoint adjustment was compared with and without feedforwarding. The feedforward reduced the upstream pressure excursion by 60%. Additional reduction in the excursion was limited by the directionally nonlinear response.

In the modified process with thermal oxidizer (TO) unit, replacing the flare in the normal operational mode, the header pressure controller manipulates the off-gas flow to the TO as shown in figure 1. The flare pressure controller serves as a back up controller to prevent an uncontrolled pressure rise in the header under the rapid changes of process conditions. The modified control strategy has to maintain the kiln demand for the fuel, taking into account the constraints on TO pressure and capacity values. Therefore, the overriding control scheme is used for calculation of the header pressure controller setpoint. The TO pressure constraint takes part in overriding only when the TO's own resources on its pressure control are exhausted. The suggested strategy was prototyped using Hysys unit operations, and the controllers were tuned via simulation. The dynamic simulation revealed a significant interaction between the pressure at the TO reactor and the pressure drops at the TO scrubbing trains. A number of control system configurations and actuator locations were tested to find the appropriate scheme to give proper decoupling: a fast response to the reactor pressure changes, while holding the scrubber pressure drops at the nominal levels.

In the resulting configuration, controllers were tuned to provide an acceptable performance in a wide range of the TO load and header pressure changes. The test scenarios were suggested by Plant Manufacturing and contained the typical flow variations to the TO in the normal and emergency modes. The upset scenarios included the kiln-fuel interlock trip with three furnaces running and the kiln losing feed with three furnaces running. The normal simulated process transitions are the timed off-gas flow transitions and typical continuous gas flow variations.

The worst case scenario simulation, a kiln-fuel interlock trip with three furnaces running and TO in a standby mode with half of its capacity available, is presented in figure 3. It shows that in this case the flaring can't be avoided completely due to two main reasons: (1) a very sharp drop in gas consumption – in about 20 seconds the kiln load (red dashed line) goes from full load to zero, (2) time is needed for the TO to gain full capacity – the flat part of the flow curve to the TO (blue dotted line) at the time interval 1800 to 1870 seconds, when the TO starts taking a full load. At this moment the flaring flow rate (blue solid line) goes to zero. The pressure in the common header (black solid line) during all the transitions, including the period of the kiln going back to full load, was controlled within acceptable margins. In this way, the furnace pressure control disturbances were tolerable. The values of the TO reactor pressure and the scrubber pressure drops (not shown here) were also within normal limits.

As a result of test runs, additional control problems were identified. Particularly, the modified process has a much higher level of interaction in the common header than the existing one due to the piping shortcut at the point of TO connection (see figure 2). In this situation, variations of the #3 furnace load will have a much higher impact on header pressure, and this can cause excessive interaction between the pressure controllers of the individual lines and the header pressure controller. This results in deterioration of the flow control to the kiln. The other problem is a variable process gain. Both the suggested and currently used strategies have the primary loop of the header pressure control receiving a

set point from the kiln firing control system. Therefore, the controlled pressure value varies widely, depending on the kiln demand for off-gas, and the plant gains for the pressure controllers, these being linked in the off-gas header, are variable. This can cause worsening of control. It was observed in simulations, and in the real process, that compressor pressure control response may become sluggish at high header pressures, and oscillatory at low values (for the header pressure control the situation is reversed). Potential advanced control strategies that might be used to address these problems are: (a) decoupling (or multivariable predictive) control to alleviate the pressure controller interactions, (b) gain scheduling for the header-linked controllers. This will be done at the phase of DCS system implementation for the modified process.

With pressure response in the off-gas header being very fast, of particular interest is the effect of controller scan rate on the extent and duration of pressure excursions. Earlier dynamic simulations suggested a very fast, dedicated controller was necessary to best control the excursions. Improvements in DCS execution speed in recent years have raised the question of whether the older dedicated controllers, with spare parts issues, are still necessary, or could control be moved within a slower high-capacity, multiloop controller. To test this, control execution in the simulation was slowed and the response to a typical pressure excursion was measured. For the case studied, maximum excursion was less than 0.5% higher with settling time essentially unaffected. This small difference is believed due to the slower controller not catching the beginning of the excursion as quickly; the remainder of the control response can be made equivalent with tuning. The simulation justified replacing the older controllers.

4.2 PROCESS PERFORMANCE AND DESIGN APPLICATIONS

The original reason to develop a dynamic model of the vent system was to analyze pressure profiles in the off-gas system after an incident that caused equipment damage. Minor alterations in the process, over the years, raised concerns that the off-gas system might not be adequately protected. Besides, the potential process sources for the incident had to be investigated. The main suspected reason was variation in composition of one of the furnace feed streams. The simulation provided an estimation of the feed inconsistencies potentially causing this effect. The maintenance improvements, based on these estimations, helped to decrease a risk of the accidents. Generally, the simulations demonstrated sufficient protection of the process in the abnormal situations. Nevertheless, the additional design step has been undertaken to augment the process safety.

The dynamic model is being used to modify the plant venting system. The model of a new pressure relief device was created and its behavior was tested before installation. Using simulation, the different configurations of the vent system with the new device were evaluated and then optimal parameters of the seal were determined. Particularly, the optimal relieving points were estimated for the furnace/processing units depending on the furnace capacity and dynamics (volume and resistance) of the units.

The responses of the existing and the modified vent system have been compared extensively by simulation. These at the most probable levels of furnace pressure excursions. Two typical magnitudes, moderate and severe, and several shapes of the pressure impulse (rates of the pressure rise), were simulated in different combinations. As a typical example, the simulation run results for the moderate value of the furnace pressure excursion are given in figures 4 and 5. The plots present the pressure

profiles for different points along the furnace/processing unit. The new system has shown superior performance, providing 10-12 % less of the peak system pressure with a more favorable (safe) sequence of the relief devices opening and higher resealing capabilities. The modified system has been successfully implemented for one of the furnaces. The results of its functioning are close to those predicted in simulation. An implementation of the modernized vent system is currently under way for two other furnace units.

5. CONCLUSIONS

The dynamic model of the plant gas system, exemplifying strong interaction of the production units with fast dynamics of the process pressure, is presented. The model is built using standard unit operations of the general-purpose process simulator and custom components. These components for modeling of the plant pressure-relief devices were created using spreadsheet calculations and Visual Basic programming. The model has been used in the development and testing of control strategies for the existing and the modified processes. The process performance application of the model resulted in the successful implementation of a new, redesigned plant vent system.

Due to its modular structure, the model can be extended with more detailed models of the furnace and kiln areas that will make possible the simulation of the gas system for the whole facility. This will provide the venue for solving the interconnected plant performance problem, such as maximizing the off-gas usage in the kiln and optimization of the kiln gas system control.

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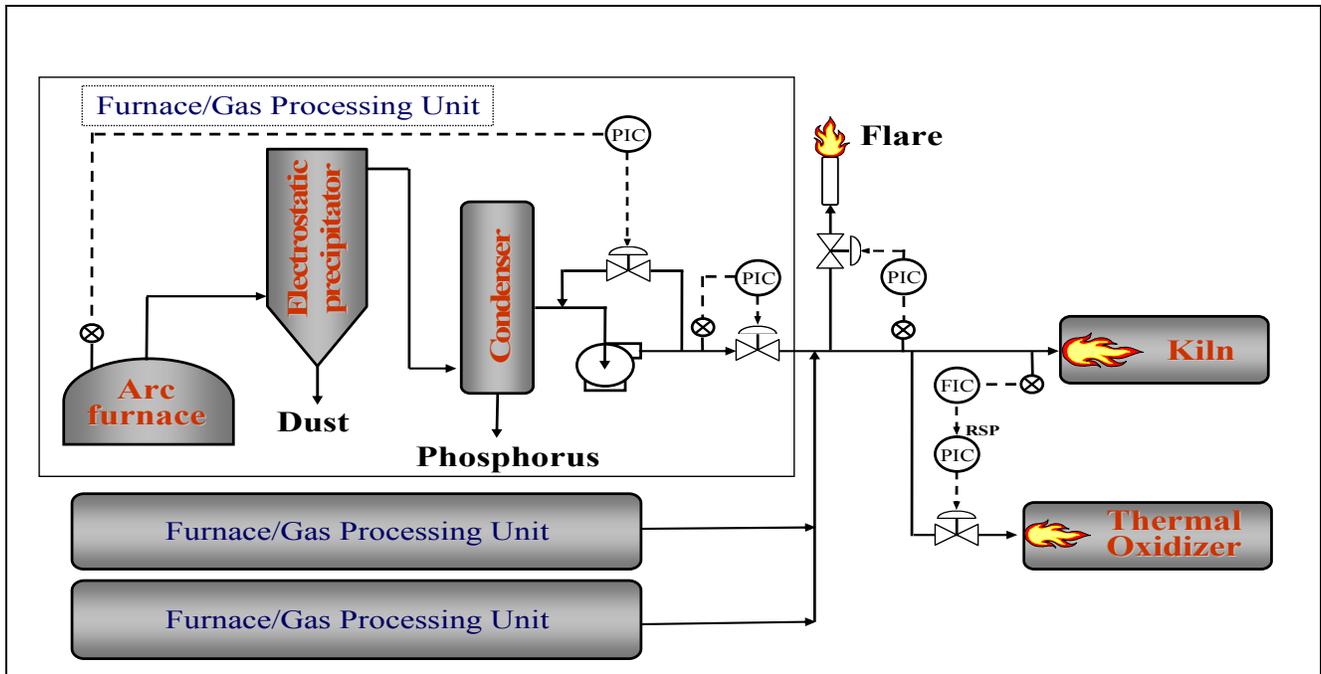


FIG. 1 PLANT GAS SYSTEM

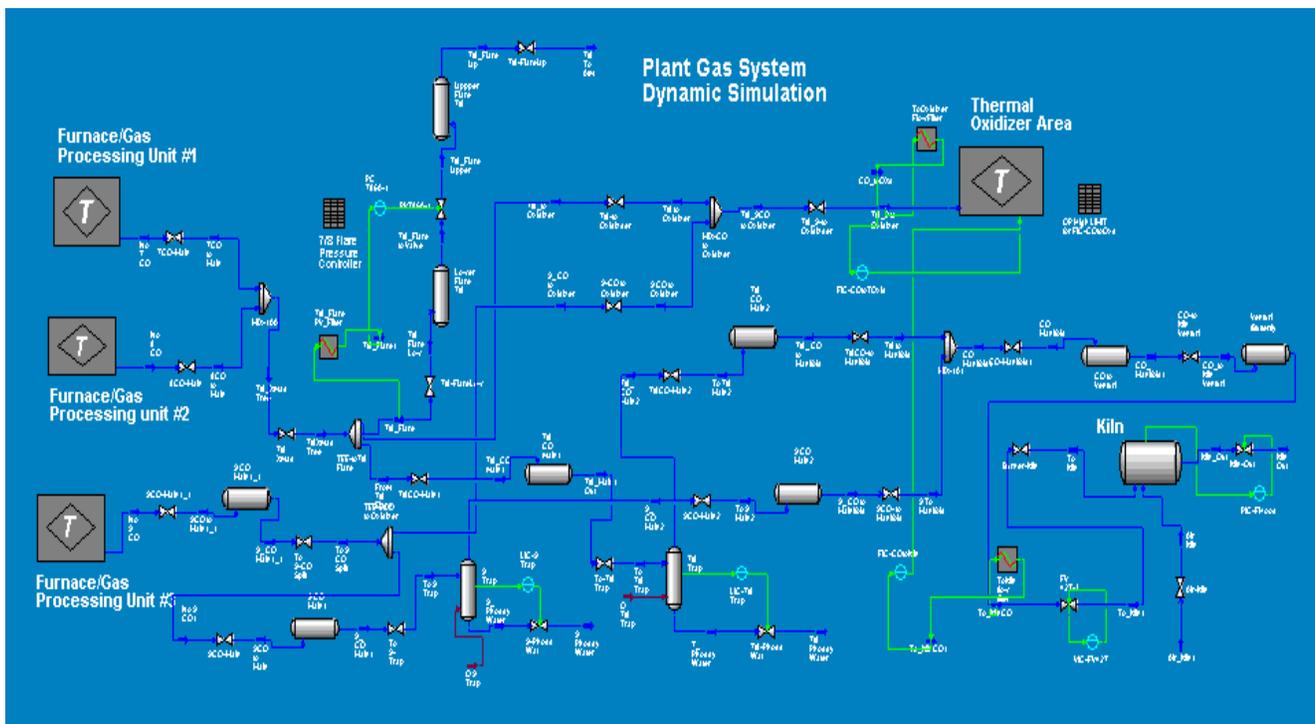


FIG. 2 MAIN FLOWSHEET OF THE MODEL

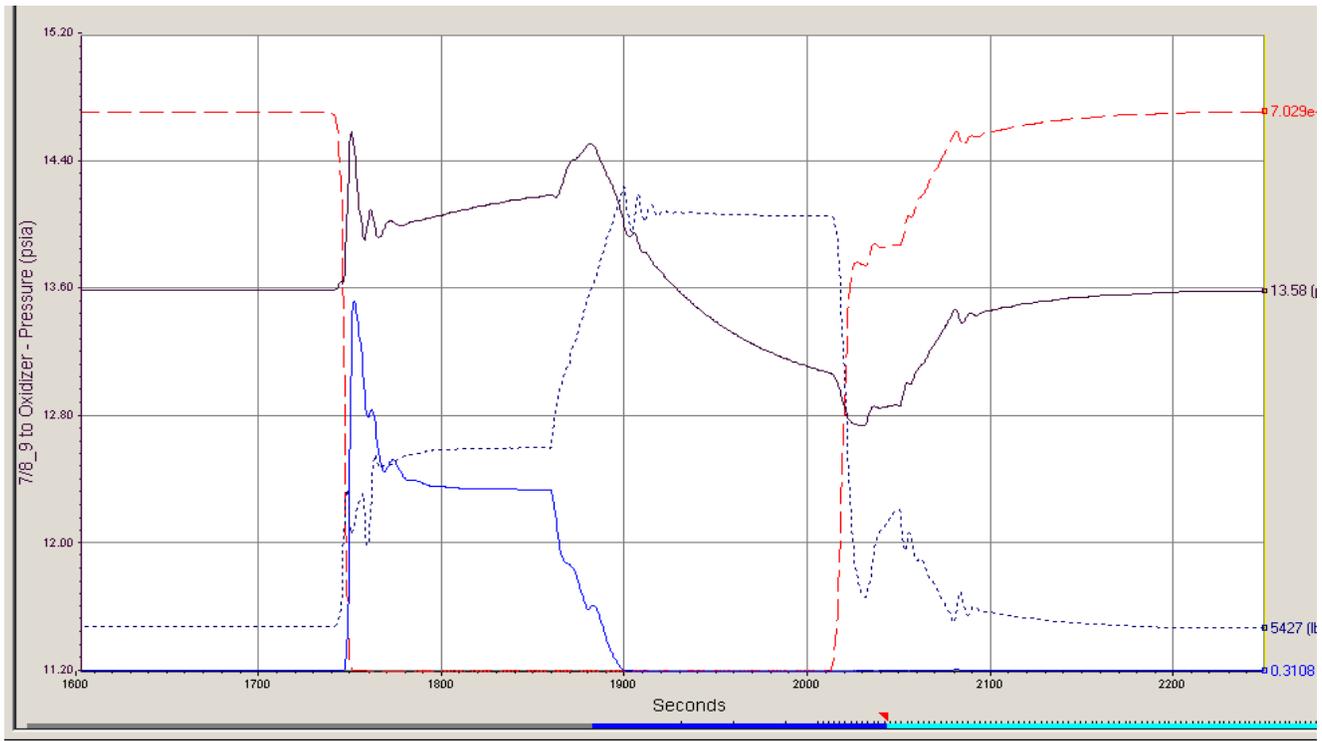


FIG. 3 SCENARIO: THE KILN FUEL INTERLOCK TRIP WITH THREE FURNACES RUNNING

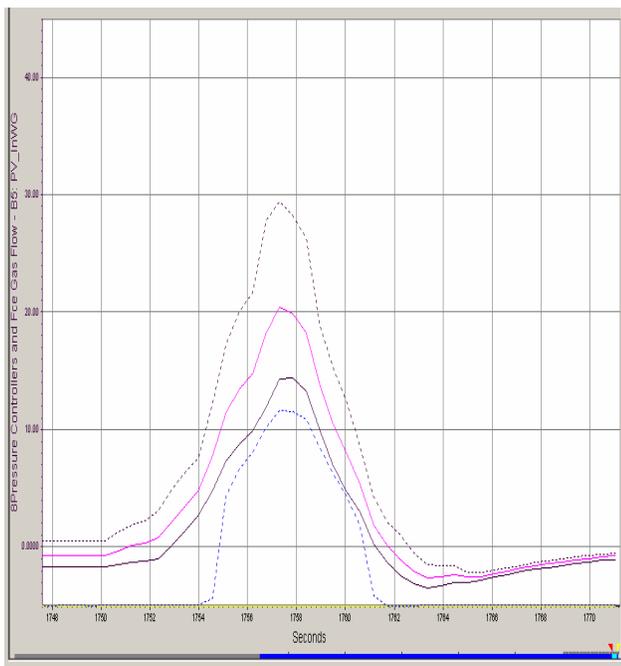


FIG. 4 EXISTING VENT SYSTEM

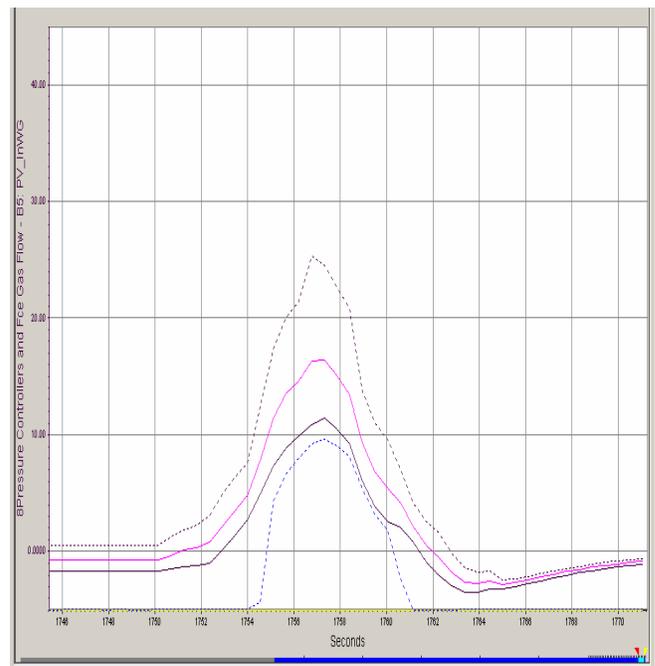


FIG.5 MODIFIED VENT SYSTEM

