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ADVANCED PFBC TRANSIENT ANALYSIS

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ABSTRACT

Transient modeling and analysis of advanced Pressurized Fluidized Bed Combustion (PFBC) systems is a research area that is currently under investigation by the United States Department of Energy's Federal Energy Technology Center (FETC). The object of the effort is to identify key operating parameters that affect plant performance and then quantify the basic response of major sub-systems to changes in operating conditions. PC-TRAXTM, a commercially available dynamic software program, was chosen and applied in this modeling and analysis effort. PC-TRAX's software system includes a library of modular components that describe the dynamic behavior of standard power plant equipment such as pumps, compressors, and gas/steam turbines. These modules are linked together, such that thermodynamic and hydrodynamic information flows between the individual modules to emulate the overall plant configuration. Customized dynamic models have been developed using Advanced Continuous Simulation Language (ACSL) for non-standard components such as carbonizers, fluidized-bed heat exchangers (FBHE), fluidized-bed combustors, solids coolers, and other near-term components found in PFBC power plant systems. These customized ACSL-based modules have been interfaced with the standard TRAX code and used for on-line transient analysis of complete power plant configurations.

This paper describes the development of a series of TRAX-based transient models of advanced PFBC power plants. These power plants burn coal or other suitable fuel in a PFBC, and the high temperature flue gas supports low-Btu fuel gas or natural gas combustion in a gas turbine topping combustor. When it is utilized, the low-Btu fuel gas is produced in a bubbling bed carbonizer. High

temperature, high pressure combustion products exiting the topping combustor are expanded in a modified gas turbine to generate electrical power. Waste heat from the system is used to raise and superheat steam for a reheat steam turbine bottoming cycle that generates additional electrical power. Basic control/instrumentation models were developed and modeled in PC-TRAX and used to investigate off-design plant performance. System performance for various transient conditions and control philosophies was studied.

INTRODUCTION

PFBC is an efficient method of coal combustion and one of the advanced power concepts demonstrated in DOE's Clean Coal Technology (CCT) Program. First Generation technology (PFBC-I) burns coal in a pressurized fluidized-bed combustor (PFBC) to produce a high temperature flue gas referred to as vitiated air. High pressure combustion air is provided by a gas turbine compressor. Particulate matter is removed and the high temperature vitiated air stream is utilized in a modified gas turbine expander to generate electrical power. Waste heat is recovered and used in a steam turbine bottoming cycle that generates additional electrical power. Advanced, or Second Generation, technology (PFBC-II) adds a bubbling bed reactor, or carbonizer, to convert a portion of the coal feed into a low-Btu fuel gas. High temperature vitiated air from the PFBC supports combustion of this fuel in a topping combustor. High temperature, high pressure combustion products from the topping combustor are then expanded in a modified gas turbine. The low-Btu fuel gas combustion increases the working fluid temperatures in the expander and increases the efficiency over that of the PFBC-I technology. A hybrid of the two, the 1-1/2 Generation PFBC, utilizes natural gas rather than low-Btu fuel gas in the

topping combustor. Each of these combined cycle approaches will be referred to in this paper.

PFBC PLANT DESCRIPTION

A simplified schematic of an advanced PFBC power plant concept is presented in Fig. 1. The shaded area of Fig. 1 corresponds to first generation (PFBC-I) technology. The area bordered by the thin broken line corresponds to the second generation (PFBC-II) technology. The 1-1/2 generation PFBC would be realized schematically by replacing the carbonizer fuel gas train with a natural gas stream. These power generating concepts are well known and have been described previously (Robertson, 1989, Horazak, 1994).

MODELING APPROACH

PC-TRAX, the primary tool used in this analysis, is a commercial software product that allows for the dynamic analysis of fossil-based power plants. PC-TRAX consists of a set of modules that describe the dynamic behavior of standard commercial power plant equipment. The individual modules are linked together to obtain the desired plant configuration. Standard PC-TRAX modules were used to model all of the plant control hardware, the gas turbine expander, and most of the steam turbine bottoming cycle, as well as all of the plant valving and piping.

Customized dynamic modules were developed to describe the dynamic behavior of the demonstration-stage process components such as the carbonizer, PFBC, FBHE, and ash cooler. The customized dynamic models were written in Advanced Continuous Simulation Language (ACSL) code and dynamically interfaced with the standard PC-TRAX modules. The customized ACSL modules are supported by FORTRAN subroutines that perform ancillary non-dynamic calculations such as physical property routines. Most of the mathematical models used to develop the customized ACSL code are based on prior work completed by PARSONS and Foster Wheeler Development Corporation (White and Torpey, 1995).

A transient model of a complete commercial-scale power plant must incorporate the thermodynamics, hydrodynamics, and chemistry in sufficient detail to provide accurate performance results during steady-state and transient operation. Additionally, the model must account for mass and energy balances, pressure-flow relationships, velocity effects, and process control and instrumentation. The level of detail must be balanced to yield an effective yet tractable model. The power plant model described in this paper contains the necessary process and control parameters required to produce realistic relative component responses. The following section describes the basic modeling approach used in this study.

PC-TRAX Process Model

A PC-TRAX-based process model is a network of pressure and flow nodes. Pressure nodes calculate pressure based on the flow of material in and out of the nodal volume. Pressure nodes typically describe large volume components such as a steam condenser or deaerator. Flow nodes calculate the flow rate based on the upstream and downstream pressure. Therefore, under most circumstances, flow nodes must be connected exclusively to pressure nodes and vice versa. Flow nodes usually describe small volume elements such as steam turbine sections or steam economizers. Figure 2 shows the flow of thermodynamic and hydrodynamic information between nodes.

The left-hand side of Fig. 3 shows a simple illustration of a heat recovery steam generator (HRSG) component typically found in combined cycle power plants. In the HRSG, high temperature flue gas is cooled through the raising and superheating of steam. Shown in the drawing are the economizer heat transfer surface, a liquid level control valve, a steam drum, and a steam superheater. The right-hand side of Fig. 3 contains a block diagram of the appropriate TRAX modules required to generate a dynamic model that duplicates the HRSG configuration. The appropriate hydrodynamic and thermodynamic information passes between modules by interconnecting flowstreams according to the scheme shown in Fig. 2.

ACSL Process Model

Demonstration-stage process equipment such as the carbonizer and PFBC were coded in ACSL and dynamically interfaced with the standard TRAX-based process model. The individual process components modeled in ACSL use the same pressure-flow relationship described above. However, the modules are often much more complex due to the presence of reducing chemistry and solids-gas hydrodynamics not found in the typical TRAX module. A summary description of the custom ACSL models is given below.

Carbonizer/PFBC. Both the carbonizer and PFBC ACSL models are configured as pressure nodes. Each model can describe either reducing or oxidizing gas/solids chemistry. Solid-gas hydrodynamics including solids entrainment and variable solids particle size distribution are accounted for. Pressure drop is calculated based on the superficial gas velocity. A differential energy balance determines average vessel temperature, thermal energy storage in the vessel refractory, and thermal loss to ambient. A differential equation utilizing the ideal gas law and gas-side material balance determines the average vessel exit pressure. Trace emissions and chemical kinetics are not accounted for.

FBHE. The FBHE is modeled as a pressure node and consists of seven individual fluidized cells, six of which contain heat transfer

surface area in the form of submerged tube bundles, submerged enclosure wall surface, and exposed enclosure wall surface. Convection is the predominant mode of heat transfer for the submerged surface, while radiation is the predominant mode for the exposed surface. It is assumed that there are no solid-gas reactions in the FBHE. Differential energy balances describe the bulk solids-gas temperature of each cell. Pressure drop and absolute pressure calculations are similar to those of the carbonizer/PFBC.

Cyclones/Candle Filter Models. Both of the components are modeled as pressure nodes and the piping that separates them as flow nodes. The cyclone model assumes constant separation efficiency and calculates pressure drop based on the flow rate of gas through the component. The candle filter pressure drop depends on gas flow and cake thickness upon the filter elements. Cake thickness depends primarily on solids loading as well as the trigger pressure set point. Differential equations determine the bulk exit temperature and pressure, thermal energy storage in the refractory, and heat loss to ambient for both vessels.

Topping Combustor Model. The topping combustor, a flow node, was modeled in some of the system configurations described in this paper. The topping combustor model accounts for both oxidizing and reducing conditions. Differential equations determine the bulk exit temperature and pressure and heat loss to ambient. A differential equation determines metal thermal storage losses.

Ash Cooler Model. The ash cooler is modeled as a flow node and utilizes the NTU-effectiveness method to determine solids and water outlet temperatures. It is assumed that there is no energy or material storage. Water flow through the ash cooler is based on the pressure difference between inlet and outlet.

PC-TRAX Control Model

Process control loops were identified based on process constraints such as maintaining constant temperature in the PFBC or constant height in an evaporative steam drum. Individual loop types, or configurations, were based on past experience with conventional power generating system controls. A Scientific Apparatus Manufacturers Association (SAMA) diagram was developed for each control loop. TRAX-based process control models were then developed by linking the appropriate TRAX modules to obtain the desired configuration. All process control and instrumentation model components utilize standard PC/TRAX modules. The standard TRAX module library supports a full complement of SAMA-based control elements. Module types that were used in this study include signal transmitters, various mathematical operators, function generators, three mode controllers (PID), three element controllers, auto-manual stations, and lead-lag elements.

The left-hand side of Fig. 4 shows a typical SAMA diagram of a PID controller used to maintain steam turbine header pressure. The configuration consists of a pressure transmitter, error generator, PID controller element with limit switch, an auto manual station with set point signal tie back, and a control valve. The right-hand side of Fig. 4 shows the appropriate TRAX blocks required to emulate the PID controller configuration. As shown in the figure, there is an almost one-to-one correspondence between the SAMA diagram and the TRAX module configuration.

Following completion of the process model, individual process control models were developed for each of the process control loops and integrated with the process model. The controllers were placed in automatic mode and tuned on-line to determine the appropriate proportional, integral, and derivative gains for the controller. The on-line tuning procedure consisted of initiating set point changes or process upsets followed by observation of the specific control variable response. Controller gains were then tuned to generate the desired control variable response within rate and stability constraints. Figure 5 shows a typical controller and process variable response generated during an on-line tuning procedure.

MODEL RESULTS AND ANALYSIS

The first model developed in this study was a commercial-scale PFBC-II power plant. The model was based on a conceptual design of a 500 MW plant (Robertson, 1989). Master plant control was based on two fundamental assumptions. First, total plant power output for this model was controlled by fresh coal flow to the carbonizer, with the gas and steam turbine controls responding to changes in available thermal input. There was no fuel gas throttling valve. Second, process air flow control was used to maintain a low fuel-to-air ratio in the PFBC vessel. This control approach, referred to as the "maximum efficiency approach," attempts to preserve high cycle efficiency even during plant turndown.

Use of the model showed that the high efficiency control approach developed in this study resulted in significant interaction between the PFBC/FBHE and steam bottoming cycle. This interaction adversely affected plant stability following any plant load changes. The transient results generated were unfavorable but helpful in understanding some basic concepts. A short discussion of this work presented below. This is followed by a discussion of a follow-up study of a commercial 1-1/2 generation PFBC plant model that built upon the lessons learned from the PFBC-II study.

PFBC-II Application

The initial application of the commercial-scale PFBC-II plant model was to "ball-park" a relative response time for a plant load decrease of 10 percent. Figure 6 shows a plot of carbonizer coal flow, carbonizer temperature, and carbonizer pressure for a 10 percent

decrease in coal flow at a rate of 1 percent a minute. Notice that the ordinate is skewed and does not begin at zero. This will result in some exaggeration of plotted values. During the ramp in coal flow, carbonizer temperature is maintained at the set point value of 1,600 °F (870 °C) while carbonizer pressure slowly starts to decrease. The decrease in carbonizer pressure is expected and results from a decrease in gas flow through the carbonizer.

As shown in Fig. 6, approximately ten minutes after the completion of the coal flow ramp, carbonizer temperature begins to oscillate ± 5 °F (± 3 °C) and does not stabilize in the 30-minute period following the completed ramp. The carbonizer pressure is equally unstable. The pressure fluctuations are small, covering less than 5 psi (0.345 bar), but they are nothing like the desired result of a smooth turndown.

The fluctuations in temperature and pressure are the result of uneven air supply to the carbonizer. At first, as the coal flow is decreased, the air flow is decreased by the control system and the carbonizer temperature is maintained. However, several minutes later, air supply is disrupted and the control valve has difficulty maintaining an even temperature reading. As air flow surges, carbonizer temperature and pressure rise (circa time 31,200-seconds) until the control valve manages to limit the excursion. This, however, is followed by a sharp sinusoidal oscillation that the control system fails to damp.

Figure 7 shows a plot of carbonizer coal flow, bulk PFBC temperature, and solids flow through the reheater pass of the FBHE for the transient described above. During the coal ramp period, PFBC temperature remains fairly stable, varying about 8 °F (4.44 °C) from the 1,600 °F (871 °C) set point. The initial dip in PFBC temperature is caused by a decrease in char flow which closely follows the coal ramp. Air flow to the PFBC is decreased (air is bypassed to the gas turbine combustor) by the control system to maintain a constant fuel/air ratio in the PFBC and the temperature rises back to 1,600 °F (871 °C). Following this, however, the PFBC temperature experiences several large sinusoidal temperature excursions.

An interesting feature of Figs. 6 and 7 is that the surge of air flow into the PFBC at time 31,800 seconds, resulting in a marked decrease in PFBC temperature, corresponds to a similar surge in the carbonizer, although the surge of air flow into the carbonizer results in a temperature increase at time 31,800 seconds. This surge is caused by the air bypass valve, which controls the flow of bypass air out of the header and into the topping combustor. The air bypass valve stem position is plotted in Fig. 8, along with coal flow and steam throttle flow. As air is bypassed to the topping combustor, the gas turbine firing temperature drops off, causing decreased steaming in the HRSG steam drum. This immediately results in decreased steam flow to the FBHE, resulting in lower heat recovery

requirements and subsequent lowered heat removal from the PFBC. As steam flow decreases, fewer solids are cooled in the FBHE superheater and reheater passes. Lowered heating in the FBHE returns increased thermal energy to the PFBC through the increased recirculation of hot solid material, which in turn, forces temperature in the PFBC upwards. Attempts to regain PFBC temperature control, through increased air flow to the PFBC, resulted in a continuation of this interaction.

The inability of the carbonizer and PFBC air control valves to damp or control the corresponding temperature swings is a result of a control philosophy conflict. Maintaining both the PFBC air-to-fuel ratio as well as PFBC temperature is unachievable unless a third variable is introduced that decouples PFBC air flow and PFBC bulk temperature. A third variable is needed because the slow, large volume PFBC/FBHE dynamics are out of phase with the rapid dynamics of the gas and steam turbine. Aggravating the situation is the fact that the rapid gas dynamics of the gas turbine can be easily influenced by the addition/subtraction of cold bypass air.

The PFBC and FBHE are large volume vessels (the freeboard volume of the PFBC is several orders of magnitude greater than that of the gas turbine) with significant thermal inertia generated by the pinwheel, or circuit, of circulating solid material. The dynamics of the PFBC/FBHE circuit, heavily influenced by the large thermal inertia and relatively large gas volume, are much slower than the rapid dynamics of the gas turbine. More importantly, the PFBC/FBHE circuit dynamics are much slower than those of the steam turbine (S/T) bottoming cycle, which directly affects PFBC/FBHE circuit performance through heat recovery in the FBHE. Heat removal in the FBHE has a significant affect on the PFBC operating temperature. Additionally, because the HRSG and FBHE both have steam drums, heat removal in the HRSG drum can also have an affect on heat removal in the FBHE superheat circuitry due to either starving or excessive steaming. To obtain adequate plant response, the master control scheme utilized in the PFBC-II study would have to be modified; the coupling imposed by the "maximum efficiency approach" would have to be mitigated.

Model Results of 1-1/2 Generation PFBC Application

A follow-up effort examined a commercial-scale 1-1/2 generation PFBC combined cycle. The 1-1/2 generation PFBC combined cycle approach replaces low-Btu fuel gas generation in the carbonizer of the PFBC-II approach with a stream of pressurized natural gas. Subsequently, natural gas is fired in the topping combustor in lieu of the low-Btu fuel gas. Many of the lessons learned in the initial PFBC-II modeling and control effort were applied in the follow-up model and control scheme development. The overall control approach utilized in this follow-up study did not attempt to maintain a low fuel-to-air ratio in the PFBC vessel. Instead, a variable fuel-to-air ratio was used to maintain PFBC vessel temperature.

Figure 9 shows a plot of the model predicted power output levels for total power, steam turbine power, and gas turbine power output for a turndown in plant load from design levels to 60 percent of design load. Turndown corresponds to a 28 percent decrease in natural gas flow at a five percent per minute rate. As shown, following a smooth turndown, the plant operates at the new 60 percent condition and is then turned up to the original design load condition.

In the model developed here, transients in power output are initiated by modulating the flow of natural gas to the topping combustor. This action sets the power output of the gas turbine. As the gas turbine is turned down, the compressor IGV's close in response to the new load demand. The control system detects a decrease in available process air, resulting in increased PFBC temperature for a given circulation rate and FBHE solids distribution configuration, so it decreases coal flow to the PFBC. (Coal flow and PFBC temperature may also be affected by changes in the FBHE solids distribution configuration.) Less thermal energy is available to the steam turbine bottoming cycle so it "follows" the plant turndown to a new operating point.

An interesting feature of the transient presented in Figure 9 is the irregularity, or bump, in the power generation level immediately following the initiation of the turndown at the 15 minute mark. The bump is most pronounced in the G/T power output level, is less evident for the total power output, and is completely absent for the S/T output. A bump is also evident at the initiation of the turn-up at 70 minutes, although in that case, the bump is in the opposite direction as that of the turndown.

The irregularity in the power output level is a manifestation of the interplay between the rapid dynamics of the gas turbine and the relatively slower dynamics of the PFBC/FBHE arrangement. As the control system brings the gas turbine down in power by decreasing natural gas flow, the control system also begins to close the compressor IGV's. Closing the IGV's decreases the compressor work. In a standard gas turbine combined cycle, this would coincide with an immediate decrease in expander work due to less mass flow through the expander and a slightly cooler firing temperature. However, in this PFBC combined cycle, the compressor and expander are separated by several large volume components. Therefore, the expander power output is maintained until the PFBC/FBHE volumes "decompress," or attain a lower operating pressure (due to decreased mass flow through the vessels). During this time there is a power mismatch between the gas turbine compressor (decreasing in power) and the gas turbine expander (momentarily maintaining power). This imbalance results in a temporary "increase" in gas turbine net power output at the generator terminal.

Figure 10 shows O₂ and CO₂ concentrations in the PFBC flue gas during the transient shown in Fig. 9. Following plant turndown, O₂

levels increase and CO₂ levels decrease due to decreased coal flow rate to the PFBC initiated by the control system during turndown. Although not shown, bulk PFBC vessel temperature was maintained at the desired set point value. Also shown in the figure is the flue gas flow exiting the PFBC. As expected, the flow rate decreases during the turndown and is restored to the design condition following plant turn-up to design load.

Control Approaches of 1-1/2 Generation PFBC Application

The control approach used in generating the transient shown in Fig. 9 was "steam-turbine following". This approach requires that changes in plant load be initiated by the gas turbine, with the steam turbine controller "following" the change to a new power output. Limited independent control of steam turbine power output is also available through the manipulation of FBHE heat transfer surface or solids distribution in the individual heat transfer cells of the FBHE. Steam turbine power output level can also be affected by manipulating the HRSG dampers and/or flue gas bypass arrangement.

The master control scheme can also be configured into a "coordinated" approach. In this case, plant load changes are initiated by the gas and steam turbine simultaneously reacting to a change in load demand. A third control approach is "gas-turbine following". In this approach, plant load demand changes are initiated by manipulation of the steam turbine, with the gas turbine controller "following" the steam turbine transient. Figure 11 plots total plant power output for a turndown to 60 percent of design load for each of these three controller configurations. As can be seen in the figure, a final power output level is attained faster with "gas-turbine following".

1-1/2 Generation PFBC in PFBC-I Operation

A characteristic of the 1-1/2 Generation PFBC power plant is that, in a broad sense, the gas turbine and steam turbine each have separate fuel sources. Thermal input provided by natural gas flow is primarily utilized and converted to electrical energy by the G/T, even though a portion of this energy is rejected and recovered by the S/T. However, the amount of natural gas thermal input recovered and utilized by the S/T is relatively minor when compared to the energy provided to the S/T by coal flow. Thermal energy input provided by the coal feed is mainly used by the S/T, even though a relatively small portion is utilized in the G/T. Recognizing the relative relationships of the G/T and S/T and their corresponding principal source of thermal input, it is possible to formulate a generalized concept in which the G/T and S/T are operated and/or controlled in a quasi-independent manner.

CURRENT WORK

ACKNOWLEDGMENT

REFERENCES

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Figure 1: Simplified Schematic of PFBC Power Plant Concepts

Figure 2: PC-TRAX Hydrodynamic/Thermodynamic Information Flow Scheme

Figure 3 : HRSG Schematic and Block Flow Diagram of TRAX HRSG Model

Figure 4: SAMA and TRAX Model Block Diagram of Header Pressure Controller

Figure 5: Typical Controller Response Following On-line Tuning

Figure 6: Carbonizer Variables for 10% Decrease in Coal Feed at 1%/min

Figure 7: PFBC/FBHE Variables for 10% Decrease in Coal at 1%/min

Figure 8: Process Variables for 10% Decrease in Coal at 1%/min

Figure 9: Power Output for Turndown to 60 % of Design Load

Figure 10: Flue Gas Composition for Turndown to 60 % of Design Load

Figure 11: Power Output for 60% Turndown for Three Control Approaches

Figure 12: Power Output for Individual Cycle Turndown