Dynamic Modeling and Analysis of a Commercial-Sized Second Generation PFBC Power Plant

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Introduction

Advanced, or Second Generation, Pressurized Fluidized Bed Combustion (APFBC) is an efficient coal-based electric power generating concept that has proven feasible in pilot scale application at Foster Wheeler Development Corporation's Livingston, NJ facility[1]. Work is currently underway to extend this success to a demonstration-scale application at the Wilsonville Power Systems Development Facility[2]. These are necessary steps in the commercialization of this technology.

Commercial application of APFBC technology will be utilized most efficiently in a combined cycle configuration. This combined cycle approach has been described, modeled and analyzed at steady-state design conditions[3]. Dynamic models of individual system components, such as the fluidized-bed combustor, have been developed and used to evaluate component transients[4]. These studies have contributed to building a knowledge and information base useful to the APFBC community. What the information base is lacking, however, are dynamic models that describe the total power plant concept as envisioned in commercial combined cycle application.

Objective

The primary objective of this work is to develop a dynamic model describing the process equipment and basic process control and instrumentation of a commercial-scale APFBC combined cycle power plant. Use of the model will enable FETC engineers to cost effectively ask "what-if" questions and to develop quantitative responses to process development concerns. Results generated through dynamic modeling contribute to the growing APFBC knowledge base and benefit the long term goal of commercial application by aiding pilot-scale and demonstration plant design efforts with insight into design and integrated plant operation.

Approach

The first step in developing a dynamic model is completing a steady-state base load heat and material balance. The base load design point configuration utilized a 1,700 ^{o}F carbonizer, 1,600 ^{o}F PFBC, a modified Westinghouse 501F gas turbine, and a 2400/1000/1000 steam turbine bottoming cycle. The state point results of the heat and material balance are used as input into the dynamic model and to design the process equipment. Design data required by the dynamic model include: piping pressure drops, vessel geometry, heat transfer surface areas, gas and steam turbine design conditions, etc. The commercial steady-state modeling package ASPEN™ was used to develop the heat and material balance. The base load configuration uses the "maximum power output" approach and requires coal feed to the PFBC. Base load gross and net power outputs correspond to 465 and 446 MW_e respectively.

PC-TRAX™ is a computer simulation package developed for the dynamic modeling of fossil-based power plant systems and was used as the primary analysis tool in this work. TRAX's software contains the appropriate first principle-based equations to describe the thermodynamics, basic chemistry, and hydrodynamics of standard power plant equipment such as gas turbines, feed water pumps, and steam turbines. The FETC team has incorporated customized dynamic models using Advanced Continuous Simulation Language (ACSL) for pressurized circulating fluidized bed combustors, carbonizers, and other non-commercial components found in APFBC power plant systems. Most of the mathematical models for the ACSL components were developed in earlier efforts and have been described in previous publications[5].

TRAX's software also contains logic and instrumentation models required to model plant process control. A process control approach based on the 100 percent design load configuration was determined and used to identify individual control loops. Scientific Apparatus Manufacturers Association (SAMA) diagrams for each control loop were developed and used to configure controller and instrumentation models. The process control model developed in this manner was then integrated with the process equipment model described above to yield a fully integrated dynamic APFBC combined cycle power plant model. Controller gains were determined through on-line tuning procedures following model integration. Controller and instrumentation modeling with TRAX has been described in previous publications[5].

Results

Following completion of the integrated dynamic model, the model was used to simulate a 100 percent of design load steady-state condition. This step is required to determine the overall "fitness" of the model.

Figure 1 shows a plot of total gross plant power (465 MWe), net steam turbine power (300 MWe), and net gas turbine power out put (165 MWe) for a steady-state 100 percent load condition. As shown in the diagram, steady model performance is observed over the 80 minute interval, indicating stable and acceptable model performance for the steady state condition.

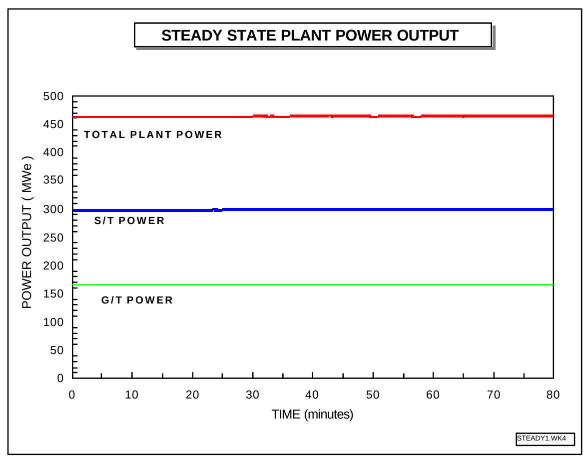

Figure 1 - Steady-State Power Output Values

Figure 2 shows a plot of PFBC cyclone and candle filter exhaust pressure (left ordinate) along with candle filter cake thickness (right ordinate) for the steady-state condition illustrated in Figure 1. Note that pressure is shown on an exaggerated scale for purposes of illustration. As the candle filter cake thickness builds, the cyclone pressure, which is upstream of the filter face, increases due to the affects of restricted flow. The filter exhaust plenum, which is down stream of the filter face, decreases in pressure as the candle filter cake thickness increases due to decreased flow through the vessel. When the filter element trigger pressure is reached, about every eight minutes due to high loading, the candle filter elements are blown-down, the cake is temporarily removed and the cyclone and candle filter vessel pressures briefly returns to the clean element conditions before the next cycle begins.

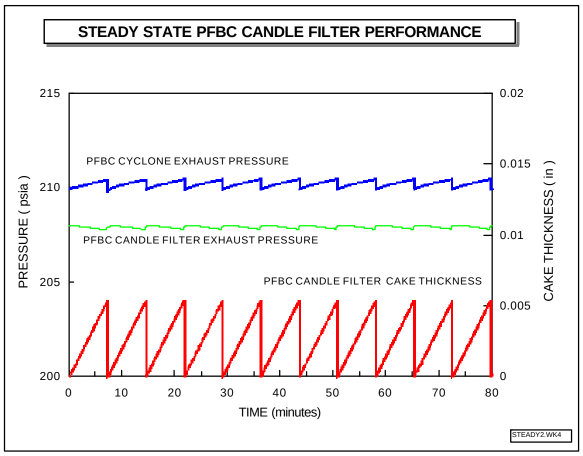

Figure 2 - Steady-State PFBC Candle Filter Performance

Favorable model performance at the steady-state, 100 percent of design load condition allowed for the start of the initial phases of transient application of the model. To start with, several off-design operating points were investigated. Transient responses from the various exercises were evaluated as portions of the model required further debugging. Also, some controllers required additional tuning. Once the model debugging was completed, several transients were investigated and documented. Some of that work is presented below.

Figure 3 shows total gross plant, net steam turbine, and net gas turbine power output for a turndown to 85 percent of design load. Turndown is initiated by reducing carbonizer coal input, which in turn decreases fuel gas flow to the gas turbine, and corresponds to a gross power load change from 465 MWe to 398 MWe. Plant turndown, which is smooth and stable and indicative of a feasible control strategy, is completed at a rate of 4.4 MW/min or 1 percent per min.

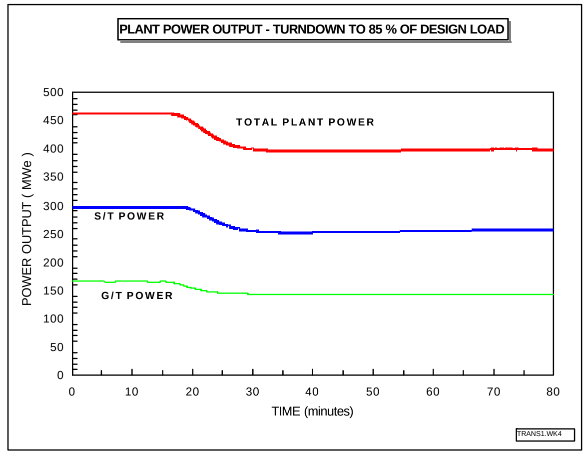

Figure 3 - Plant Power Output for Turndown to 85 Percent of Design Load

Figure 4 shows selected solids flows for the transient shown in Figure 3. Carbonizer coal, char, and sorbent flows all decrease with the transient. This is expected because turndown is initiated and obtained through decreased carbonizer coal feed and carbonizer sorbent and char flows are a direct function of carbonizer coal flow. PFBC coal and sorbent flowrate values initially decrease but soon recover close to design conditions. The “maximum power output” approach uses coal flow to the PFBC to control PFBC temperature. With this approach, coal flow to the PFBC accounts for any discrepancy between PFBC combustible fuel input through carbonizer char generation and process air available for combustion in the PFBC. In the case shown here, a small amount of coal was required to maintain PFBC temperature.

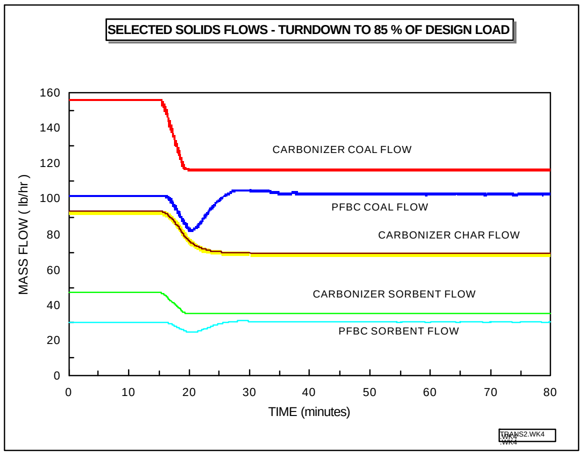

Figure 4 - Selected Solids Flows for Turn Down to 85 Percent of Design Load

Figure 5 shows selected gas-side process temperatures for the transient shown in Figure 3. Carbonizer, PFBC, and PFBC candle filter temperatures are maintained close to their design points. This is expected because these are all controlled variables. However, FBHE solids temperatures for the finishing, secondary, and primary superheater slump with decreased PFBC thermal input. These are uncontrolled process variables and are expected to slump with decreased heat removal rates in the FBHE.

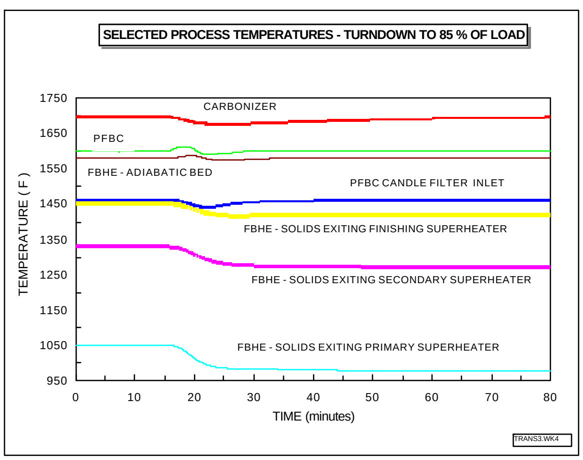

Figure 5 - Selected Gas-Side Process Temperatures for Turn Down to 85 Percent of Design Load

Figure 6 shows selected gas-side process pressures. Like the FBHE solids temperatures, these pressures are uncontrolled variables and are primarily a function of vessel geometry, temperature and process gas flows. As process gas flows decrease with the turndown (gas turbine IGV's partially closing with decreased carbonizer coal feed and decreased gas turbine power output), gas-side process pressures slump as expected. Carbonizer, PFBC, and gas turbine topping combustor pressures all drop uniformly because these vessels are of fixed geometry and have controlled temperatures and therefore drop in pressure due to decreased air supply which affects each vessel more or less uniformly. The FBHE fluidizing air temperature is an uncontrolled variable and varies with circulating solids temperature. Therefore, the FBHE pressure trend is not directly parallel with the other three vessel pressures shown.

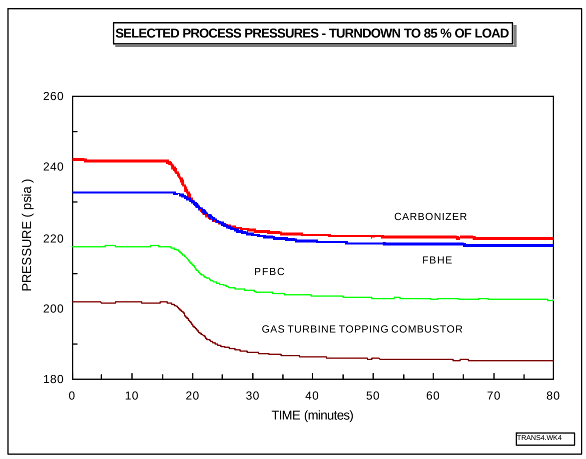

Figure 6 - Selected Gas-Side Process Pressures for Turn Down to 85 Percent of Design Load

Figure 7 shows the following steam-side process pressures: FBHE steam drum, HRSG steam drum and the high pressure steam turbine throttle steam. Drum pressures are not directly controlled, but are primarily a function of vessel geometry, temperature and water and steam flows. As drum steaming decreases due to decreased heat removal rates in the FBHE and HRSG resulting from decreased plant thermal input, the amount of flow through the drums decreases and drum pressures slump as expected. In the steam plant modeled in this study, steam turbine throttle pressure is a controlled variable. Control valves modulate with changing conditions to maintain a constant throttle pressure. As shown in Figure 7, throttle pressure is maintained constant at 2400 psig (2414.4 psia in figure).

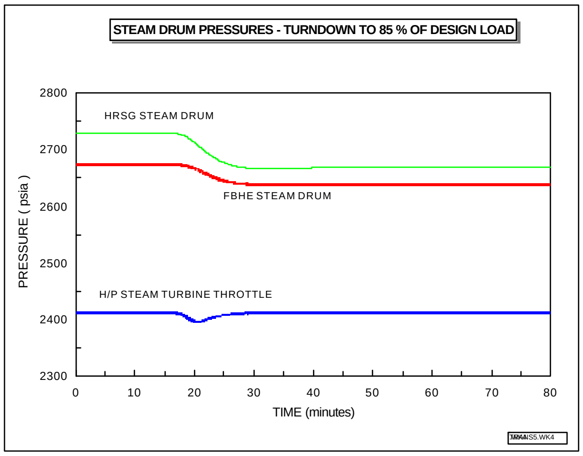

Figure 7 - Selected Steam-Side Process Pressures for Turn Down to 85 Percent of Design Load

Plant turndown as presented in Figures 3 through 7 utilizes the so called "steam-turbine-following" control approach. This controller approach is configured such that plant load changes are initiated by the topping cycle. In the plant model presented here, carbonizer coal flow is modulated to decrease gas turbine output through increased/decreased fuel gas flow. The control scheme is such that the steam turbine "follows" the gas turbine to the new load point. The lag between gas turbine turndown and steam turbine turndown in Figure 3 illustrates this concept of "following". However, plant economics and dispatch considerations may dictate alternative turndown strategies. One possible alternative is discussed below.

Figure 8 shows a turndown to 80 percent of load achieved entirely through steam turbine turndown. This approach is available with "maximum-power-output" plants but may not be available for "maximum-efficiency" APFBC plants which may not utilize coal feed to the PFBC. Total gross plant power is cut from 465 MWe to 375 MWe by turning down the steam turbine from 300 MWe to 210 MWe. Gas turbine power output remains at or near design load levels.

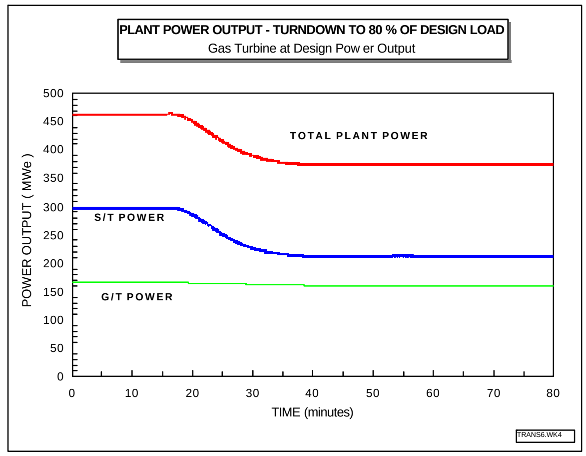

Figure 8 - Plant Power Output for a Turn Down to 80 Percent of Design Load with Gas Turbine Output at Design Level

Figure 9 shows the carbonizer and PFBC coal flow (left ordinate) along with FBHE steam drum riser duty (right ordinate) for the transient illustrated in Figure 8. Notice that carbonizer coal flow remains at design load conditions and that PFBC coal flow decreases to approximately 50 percent of the design load flow. The affect of decreased PFBC thermal input is reflected in the FBHE steam drum riser duty decrease. Decreased riser duty leads to decreased drum steaming and less steam turbine power output with little or no affect to gas turbine power output.

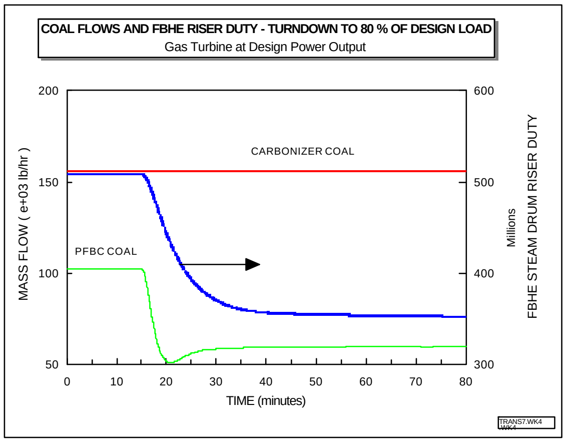

Figure 9 - Coal Flows and FBHE Riser Duty for a Turn Down to 80 Percent of Design Load with Gas Turbine Output at Design Level

Plant turndown rates can be affected by secondary control considerations. As an example of this, lets consider carbonizer temperature control approach on gas turbine turndown rate. Figure 10 shows a plot of carbonizer temperature, carbonizer air flow, and gas turbine power output. In this case, carbonizer air flow is a strict function of carbonizer coal feed. Gas turbine power output decreases from a design load of 165 MWe to 153 MWe in approximately 15 minutes. Air flow follows coal flow (not shown) to the new steady-state condition. Carbonizer temperature drops off from the design point of 1,700 °F to 1,690 °F before slowly recovering to 1,700 °F.

Figure 11 shows the same transient except that carbonizer air flow is a function of carbonizer coal flow with a trim on carbonizer temperature. Carbonizer temperature is maintained nearly constant at the design point of 1,700 °F, however, gas turbine turndown is more sluggish; requiring approximately 20 minutes to reach a new steady-state point.

Figure 12 shows the same transient except that carbonizer air flow is a strict function of carbonizer temperature. While carbonizer temperature is maintained nearly constant, the gas turbine requires over 35 minutes to reach a new steady-state point. The rate at which the gas turbine turns down is hindered by the increased time required to settle carbonizer air flow to a new steady-state condition. This analysis shows that gas turbine turndown rates, and hence plant turndown rates, may be benefited by less restrictive carbonizer temperature control.

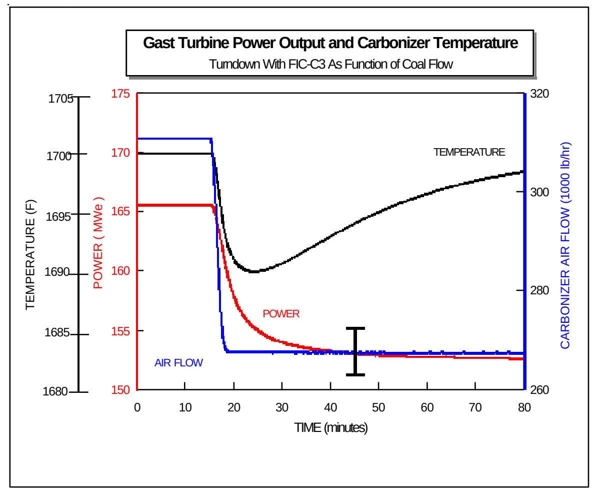

Figure 10 - Gas Turbine Output, Carbonizer Air Flow and Temperature for Turndown with Carbonizer Air Flow a Function of Carbonizer Coal Flow

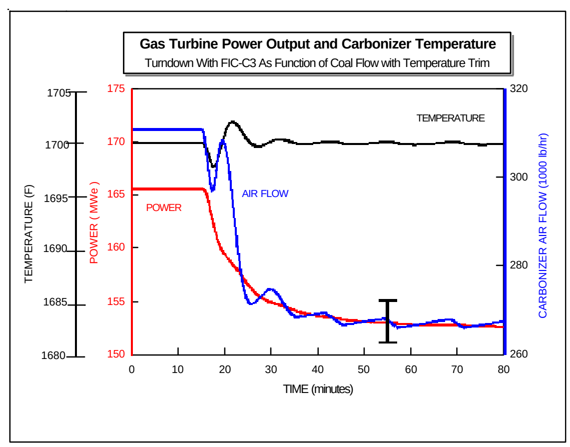

Figure 11 - Gas Turbine Output, Carbonizer Air Flow and Temperature for Turndown with Carbonizer Air Flow a Function of Carbonizer Coal Flow with Temperature Trim

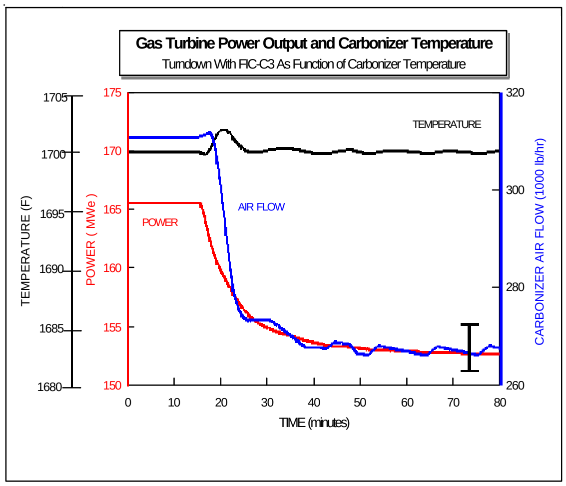

Figure 12 - Gas Turbine Output, Carbonizer Air Flow and Temperature for Turndown with Carbonizer Air Flow a Function of Carbonizer Temperature

Conclusions

A dynamic model of a commercial-scale APFBC power plant has been developed. The model accounts for the basic hydrodynamics, thermodynamics, process chemistry, control, and instrumentation of the power plant. The model has shown to be robust and has been used to evaluate plant turndown and to investigate alternative turndown scenarios. The model is a useful tool that will be utilized by DOE FETC personnel to investigate and evaluate power systems at the Wilsonville facility and other power system RD&D endeavors.

Future Activities

The U.S. DOE's FETC personnel will use the models and results generated in the effort described here as a starting point for a dynamic model of an demonstration-scale Advanced PFBC power plant concept. This work may be extended by DOE personnel for use in a Clean Coal Technology application.

Contract Information

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Acknowledgments

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