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Effect of Pressure on Second-Generation PFB Combustion Plants

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EFFECT OF PRESSURE ON SECOND-GENERATION PRESSURIZED FLUIDIZED BED COMBUSTION PLANTS

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ABSTRACT

In the search for a more efficient, less costly, and more environmentally responsible method for generating electrical power from coal, research and development has turned to advanced pressurized fluidized bed combustion (PFBC) and coal gasification technologies. A logical extension of this work is the second-generation PFBC plant, which incorporates key components of each of these technologies. In this new type of plant, coal is devolatilized/carbonized before it is injected into the PFB combustor bed, and the low-Btu fuel gas produced by this process is burned in a gas turbine topping combustor. By integrating coal carbonization with PFB coal/char combustion, gas turbine inlet temperatures higher than 1149°C (2100°F) can be achieved. The carbonizer, PFB combustor, and particulate-capturing hot gas cleanup systems operate at 871°C (1600°F), permitting sulfur capture by lime-based sorbents and minimizing the release of coal contaminants to the gases.

This paper presents the performance and economics of this new type of plant and provides a brief overview of the pilot plant test programs being conducted to support its development.

INTRODUCTION

A new generation of coal-fired electricity generating plants is on the horizon—second-generation pressurized fluidized bed combustion (PFBC) plants. They offer the prospect of a 45-percent cycle efficiency and can meet present and future New Source Performance Standards (NSPS). Additional advantages of these plants are: ■ Lower capital costs ■ High reliability and availability ■ Shorter design and construction lead times ■ Modularity—all aimed at lowering the cost of electricity (COE) and minimizing the risk of surplus capacity. Foster Wheeler Development Corporation (FWDC) is leading a multicompany team working to make this new type of plant a commercial reality.

The team is currently in the second phase of a three-phase DOE-funded program to develop the technology for this new type

of plant—a plant with a COE at least 20 percent lower than the COE of a conventional pulverized-coal-fired plant with a stack gas scrubber and with 45 percent efficiency (based on the higher heating value of the coal). A conceptual design and an assessment of the R&D needs of a nominal 500-MWe plant were the products of Phase 1. Pilot plant construction has been completed in Phase 2, and FWDC is currently conducting tests at the John Blizard Research Center—Foster Wheeler's research location in Livingston, New Jersey—to determine how individual components perform when burning different coals in concert with varied sorbents.

Once Phase 2 has been completed, the plant will be operated in an integrated mode to determine how well the units "cooperate" and the overall effects of integration.

PLANT CONCEPT

The second-generation PFBC combined-cycle plant being developed by the FWDC team is shown in a simple process block diagram in Figure 1.

In operation, coal is fed to a pressurized carbonizer, where it is pyrolyzed/devolatilized at a low temperature, producing a low-Btu fuel gas and char. After the fuel gas passes through a cyclone and a ceramic barrier filter to remove gas-entrained particles, it is burned in a topping combustor to produce the energy to drive a gas turbine.

This gas turbine drives a generator and a compressor that feeds air to the carbonizer, to a circulating pressurized fluidized bed combustor (CPFBC), and to an external fluidized bed heat exchanger (FBHE). Char from the carbonizer is burned in the CPFBC with high excess air, heating the flue gas to 871°C (1600°F); vitiated air from the CPFBC supports combustion of the fuel gas in the topping combustor.

Surplus heat from the CPFBC is transferred to the FBHE by the recirculation of sorbent between the two units, which is controlled by cyclone separators and nonmechanical valves.

FIGURE 1 SIMPLIFIED PROCESS BLOCK DIAGRAM—SECOND-GENERATION PFB COMBUSTION PLANT

If the fuel gas produced in the carbonizer were not treated, it would contain hydrogen sulfide and sulfur-containing tar/light oil vapors. But lime-based sorbents injected into the carbonizer catalytically enhance tar cracking and capture sulfur in situ as calcium sulfide. The raw fuel gas is fired hot, eliminating fuel gas heat exchangers and chemical or sulfur-capturing bed cleanup systems. Such expensive, complex systems are an intrinsic part of the coal gasification combined-cycle plants now being developed. High-temperature filters capture the elutriated particles of char and calcium sulfide. The result is an almost particle-free fuel gas—one that meets NSPS. Along with the carbonizer bed drains, the captured material is collected in a central hopper and is injected into the CPFBC through a nitrogen-aerated nonmechanical valve. Once in the CPFBC, the calcium sulfide is transformed into sulfate by the excess air; it can then be safely disposed of with the normal CPFBC spent sorbent.

All cooling tube surface is in the FBHE, a move that virtually eliminates tube erosion because of the low FBHE fluidizing velocity [≤ 0.15 m/s ($\leq 1/2$ ft/s)]. Erosion and fouling of downstream equipment can be caused by the exhaust gases leaving the carbonizer and the CPFBC. These gases contain particles of char, sorbent, and fly ash. To prevent erosion and fouling, the gases are cleaned to < 20 ppm solids loading by a hot gas clean-up (HGPU) system before they enter the topping combustor and the gas turbine. Although the leading candidates for the final filtration stage are the ceramic cross-flow and ceramic candle filters, other devices such as ceramic bag filters and screenless granular-bed filters are possible alternatives.

The topping combustor consists of metallic-wall multiannular swirl burners (MASBs), which are already being developed (Garland, Pillsbury, and Vermes, 1986) and will be provided in two external combustion assemblies (topping combustors) on opposite sides of the gas turbine. Each MASB contains a series of swirlers that aerodynamically create fuel-rich, quick-quench, and fuel-lean zones to minimize NO_x formation during the topping combustion process. The swirlers also provide a thick layer of

air at the wall boundary to control the temperature of the metallic walls.

PLANT DESIGN, PERFORMANCE, AND ECONOMICS

Plant efficiency rises when the amount of coal energy transferred to the fuel gas in the carbonizer increases—without creating the need for a fuel-gas chemical cleanup system. Carbonizer performance characteristics are thus important to second-generation PFBC plants. Based on the limited carbonizer data available in the literature when FWDC began the project, 816°C (1500°F) appeared to be the low-temperature limit from the standpoint of sulfur-capture efficiency and potential fuel gas tar/oil vapor levels for bituminous coals.

To avoid substantial extrapolation of very limited data on carbonizer operation, the team chose that temperature for a baseline plant configuration, but they also investigated carbonizer operation at 871°C (1600°F) during a sensitivity study. Based on first-generation PFBC plant experience, 871°C (1600°F) was chosen for the CPFBC to eliminate the need for alkali getters while precluding gas turbine hot corrosion.

Operating as an integrated subsystem, the carbonizer, CPFBC, FBHE, and gas turbine form a modular building block to achieve plants with varied electrical outputs. Figure 2, a heat and material balance of a second-generation PFB combustion plant operating with an 871°C (1600°F) carbonizer, shows one module of a plant that utilizes two of each of these building blocks. The flow rates given are representative of the two-module plant, which produces 496 MWe of net power at 44.9 percent efficiency. The feedstocks for this plant (2.9 percent sulfur Pittsburgh No. 8 coal and Ohio Plum Run dolomite) are crushed to 12.7 mm (1/2 in.) $\times 0$, dried to less than 1 percent surface moisture, and injected into each carbonizer—coal at 66,215 kg/h (145,979 lb/h) and dolomite at 19,878 kg/h (43,823 lb/h)—by separate lock-hopper/pneumatic transport feed systems. Each carbonizer produces 141,694 kg/h (312,381 lb/h) low-Btu fuel gas with a 5.40 MJ (145 Btu/sft³) heating value and 50,865 kg (112,139 lb) of a char/coke/sorbent mixture. The mixture is burned in an 871°C (1600°F) CPFBC operating at approximately 220% excess air to produce 1,122,903 kg (2.476×10^6 lb) high-excess-air flue gas and an FBHE steam duty of 0.44 MJ (420×10^6 Btu/h).

The carbonizer fuel gas passes through cyclone separators and ceramic cross-flow filters and is burned in the topping combustor, heating the CPFBC flue gas to 1288°C (2350°F)—the ideal firing temperature for the carbonizer performance level shown in Figure 3.

Each gas turbine produces 114.1 MWe. The turbine exhaust gas is cooled by an HRSG from 599 to 138°C (1110 to 280°F) before it enters the stack. With the HRSG and FBHE of each module operating together, 16.5-MPa gage/ $538^\circ\text{C}/538^\circ\text{C}/8.5$ kPa Hg (2400 psig/ $1000^\circ\text{F}/1000^\circ\text{F}/2.5$ in. Hg) steam is produced. The total plant flow rate [$727,084$ kg/h (1.602×10^6 lb/h)] results in steam turbine electrical power generation at 283.7 MWe.

Coal ash and spent sorbent are removed at the FBHE and the CPFBC ceramic cross-flow filter vessels, depressured by restricted-pipe discharge systems (T. Knowlton, et al., 1986),

FIGURE 3 1.42 MPa (14 atm)/871°C (1600°F) CARBONIZER PERFORMANCE

and cooled by screw coolers to 149°C (300°F). The plant spent-bed material/bottom ash poses no toxicological or waste-disposal problems. After the char/coke/sorbent residue has been burned in the CPFBC at 871°C (1600°F), its composition is very much the same as the material leaving a first-generation PFBC system and less damaging to the environment than the residue from conventional pulverized-coal-fired plants.

Operating with a calcium-to-sulfur molar feed ratio of 1.75, the plant achieves 90-percent coal sulfur capture. Despite an overall plant excess-air level of 124 percent, the plant operates with an NO_x release that is less than half that allowed by NSPS because of staged combustion in both the CPFBC and topping combustor combined with the relatively low heating value of the carbonizer fuel gas. Particulate release, also well below the NSPS-mandated level, is the result of the high collection efficiency of the ceramic cross-flow filters. Their success eliminates the need for any particulate collection at the stack.

Overall plant performance is presented in Table 1, where both the 816 and 871°C (1500 and 1600°F) carbonizers are compared with a conventional pulverized-coal-fired plant with a scrubber.

Shown in plan and elevation views in Figures 4 and 5, second-generation plant components are small enough to be assembled in a shop and shipped by barge to many plant sites throughout the

United States. Once the vessels reach the docking area, they begin their overland trip to the plant site by crawler transporters. Figures 6 and 7 show units, designed by Foster Wheeler for a refinery in Venezuela, making such an overland trip.

The same plants compared for performance in Table 1 are compared for their economics in Table 2, which clearly shows the benefits of the second-generation plants. EPRI's *Technical Assessment Guide* (Electric Power Research Institute, 1986) was used to determine the economics of the three 30-year life plants in 1987 dollars, with first-year delivered coal and dolomite costs of \$1.70/GJ (\$1.79/10⁶ Btu) and \$0.0197/kg (\$17.9/ton) respectively. The values presented in the table are based on shipping the modular units by barge.

EFFECT OF REDUCED PRESSURE RATIO

Having determined the effect of carbonizer temperature on plant performance, an analysis was conducted to identify baseline plant sensitivity to gas turbine pressure level. A 1.0-MPa (10-atm) pressure was selected. The lower pressure has only a slight effect on the carbonizer performance level. Figure 8 is a heat and material balance for the new plant. The lower-pressure plant continues to operate with an 1149°C (2100°F) topping combustor temperature (the optimum firing temperature

TABLE 1
PLANT PERFORMANCE COMPARISONS

Description	Second-Generation PFBC Plant		Conventional PC-Fired Plant With Scrubber
	816°C (1500°F) Carbonizer	871°C (1600°F) Carbonizer	
Power Summary			
Net Capacity, MWe	452.8	496.3	500.9
Net Plant Efficiency, % (HHV)	43.6	44.9	35.9
Gross Power			
Gas Turbine, MWe	195.2	228.2	—
Steam Turbine, MWe	272.3	283.7	540.4
Turbine Parameters			
Gas Turbine Topping Combustor, °C (°F)	1149 (2100)	1288 (2350)	—
Main Steam Flow, kg/s (10 ³ lb/h)	193.9 (1538.6)	200.3 (1602.9)	499.9 (3967.9)
Consumables and Wastes			
Pittsburgh No. 8 Coal, kg/s (lb/h)*	35.8 (284,410)	38.2 (302,828)	53.8 (382,928)
HHV, MJ/kg (Btu/lb)*	30.02 (12,450)	30.02 (12,450)	30.02 (12,450)
Sulfur, wt%	2.89	2.89	2.89
Ash, wt%	9.94	9.94	9.94
Sorbent Flow, kg/s (lb/h)			
Dolomite	10.4 (82,315)	11.0 (87,645)	—
Limestone	—	—	5.5 (43,606)
Lime	—	—	0.3 (2,019)
Ash Production, kg/s (lb/h)			
Ash/Spent Sorbent	11.5 (91,144)	12.2 (97,073)	1.0 (7,612)
Fixed Sludge	—	—	8.9 (70,740)
*As received/before drying.

FIGURE 4 PLAN VIEW—CARBONIZER/CPFBC/FBHE MODULE

FIGURE 5 ELEVATION VIEW—CARBONIZER/CPFBC/FBHE MODULE

FIGURE 6 VESSELS ARRIVING BY SHIP

FIGURE 7 CRAWLER TRANSPORTING VESSEL TO SITE

TABLE 2

SUMMARY OF PLANT ECONOMIC COMPARISONS

Description	Second-Generation PFBC Plant		Conventional PC-Fired Plant With Scrubber
	816°C (1500°F) Carbonizer	871°C (1600°F) Carbonizer	
Unit Size, MWe net	452.8	496.3	500.0
Net Plant Efficiency, % (HHV)	43.6	44.9	35.9
Total Plant Cost, \$/kW	906.1	875.8	1192.6
Total Plant Investment, \$/kW	980.6	947.8	1307.7
Total Capital Requirement, \$/kW	1037.0	1002.1	1375.3
First Year Costs			
Total O&M, \$/kW·yr	38.0	35.6	45.6
Fixed O&M, \$/kW·yr	24.7	23.2	29.5
Variable O&M, mills/kWh	2.34	2.19	2.79
Consumables, mills/kWh	3.37	3.24	2.85
Fuel Cost, mills/kWh	14.0	13.6	16.8
Levelized O&M			
Fixed, \$/kW·yr	43.2	40.4	51.8
Variable O&M, \$/kW·yr	4.1	3.8	4.9
Consumables, mills/kWh	8.9	8.7	8.0
Fuel, mills/kWh	26.6	25.9	32.4
Levelized Carryover Charge, \$/kW·yr	179.6	173.4	237.9
Levelized Busbar Cost, mills/kWh (at 65% capacity factor)	75.7	72.9	93.2

is relatively insensitive to pressure in this range. The resultant efficiency is 0.12 percentage points higher than the baseline plant efficiency.

The PFBC island component arrangements are identical to those of the baseline plant, but physical dimensions differ because

of differences in flow rate and operating pressure. For instance, the carbonizer fuel gas volumetric flow rate is roughly 45 percent higher than the baseline plant, necessitating about a 20 percent increase in carbonizer I.D.s. The CPFBC flue gas volumetric flow rate is roughly 52 percent higher, necessitating

about a 23-percent increase in I.D.s. The carbonizer and CPFBC vessel heights remain similar to baseline plant values. Compared with the baseline plant, the FBHE duty is roughly 31 percent lower, requiring an 18-percent decrease in its heat-transfer surface area. Although the gas turbine output is 2.7 percent lower than in the baseline plant, the hot valving, piping, and blade path of the gas turbine are 25 to 30 percent larger because of the lower pressure. The gas turbine compressor contains fewer high-pressure stages because of the lower operating pressure of the cycle, and its discharge temperature is reduced to 311°C (591°F) [baseline plant value is 377°C (711°F)].

Because of the lower temperature involved, the heat exchanger incorporated in the baseline plant to cool a portion of the

compressor air for gas turbine blade cooling is eliminated. Since this heat exchanger was a source of hot air for coal drying in the baseline plant, the 1.0-MPa (10-atm) plant uses an oil-fired burner to reheat a portion of the HRSG exhaust gas. The steam turbine is essentially identical to the baseline unit, although the output is 3.9 percent lower.

The economics and performance of the 1.4- and 1.0-MPa (14- and 10-atm) plants are presented in Tables 3 and 4. Although the lower pressure raised the plant efficiency by 0.5 percentage points, the plant COE is 5 percent higher because of higher plant equipment costs. This is not surprising, since the lower pressure increases the gas volumetric flow rates; thus the diameters of the gas-carrying components

TABLE 3
PLANT PERFORMANCE COMPARISONS

Description	Second-Generation PFBC Plant	
	1.4 MPa (14 atm)/ 816°C (1500°F) Carbonizer	1.0 MPa (10 atm)/ 871°C (1600°F) Carbonizer
Power Summary		
Net Capacity, MWe	452.8	437.4
Net Plant Efficiency, % (HHV)	43.6	43.8
Gross Power		
Gas Turbine, MWe	195.2	189.9
Steam Turbine, MWe	272.3	261.8
Turbine Parameters		
Gas Turbine Topping Combustor, °C (°F)	1149 (2100)	1149 (2100)
Main Steam Flow, kg/s (10 ³ lb/h)	193.9 (1538.6)	186.4 (1479.2)
Consumables and Wastes		
Pittsburgh No. 8 Coal, kg/s (lb/h)*	35.8 (284,410)	34.5 (274,000)
HHV, MJ/kg (Btu/lb)*	30.02 (12,450)	30.02 (12,450)
Sulfur, wt%	2.89	2.89
Ash, wt%	9.94	9.94
Sorbent Flow, kg/s (lb/h)		
Dolomite	10.4 (82,315)	10.0 (79,302)
Limestone	—	—
Lime	—	—
Ash Production, kg/s (lb/h)		
Ash/Spent Sorbent	11.5 (91,144)	11.1 (87,810)
Fixed Sludge	—	—
Coal and Dolomite Drying—No. 2 Fuel Oil, m ³ /h (gal/h)	0.36 (94)	0.83 (216)
Water Consumption, 10 ³ m ³ /d (10 ³ gal/d)	21.1 (5575)	20.19 (5334)
*As received/before drying.		

TABLE 4
SUMMARY OF PLANT ECONOMIC COMPARISONS

Description	Second-Generation PFBC Plant	
	1.4 MPa (14 atm)/ 816°C (1500°F) Carbonizer	1.0 MPa (10 atm)/ 871°C (1600°F) Carbonizer
Unit Size, MWe net	452.8	437.4
Net Plant Efficiency, % (HHV)	43.6	43.8
Total Plant Cost, \$/kW	906.1	977.9
Total Plant Investment, \$/kW	980.6	1058.2
Total Capital Requirement, \$/kW	1037.0	1117.2
First Year Costs:		
Total O&M, \$/kW • yr	38.0	41.4
Fixed O&M, \$/kW • yr	24.7	26.9
Variable O&M, mills/kWh	2.34	2.54
Consumables, mills/kWh	3.37	3.62
Fuel Cost, mills/kWh	14.0	14.0
Levelized O&M:		
Fixed, \$/kW • yr	43.2	46.4
Variable O&M, \$/kW • yr	4.1	4.4
Consumables, mills/kWh	5.9	6.3
Fuel, mills/kWh	26.6	26.6
Levelized Carryover Charge, \$/kW • yr	179.6	193.3
Levelized Busbar Cost, mills/kWh	75.7	79.5

increase accordingly, along with refractory requirements, structures, piping length, and other supporting services to the components.

CONCLUSIONS

The proposed second-generation PFBC plant concept appears ideal for meeting the future power needs of the electric utility industry. When fired with high-sulfur bituminous coal, it can provide a COE at least 20 percent lower than that of conventional PC-fired plants with wet limestone flue gas desulfurization and an operating efficiency of 45 percent based on the lower heating value of the coal. Higher efficiencies and lower COEs may also

be possible. Emissions per megawatt of net power produced are considerably lower than those of PC-fired units, and components are amenable to shop assembly and barge shipment. In addition, it is modular; electric utilities can add power in smaller increments without sacrificing efficiency or economics.

PHASE 2 TESTING PROGRAM

The proposed plant is attractive from many standpoints—COE, efficiency, etc.; but it is not without risks. Pressurized carbonizer tests with in-situ tar cracking and sulfur capture must be performed. The gas streams and solid effluents from both the carbonizer and CPFBC must be characterized, their

FIGURE 9 10-IN. CARBONIZER TEST UNIT

compatibility with HGCU equipment currently under development must be demonstrated, and topping combustion tests must be run. In Phase 2 of our DOE program, the needs and uncertainties regarding this plant are being addressed via a series of laboratory-scale tests on these separate components.

The first part of the planned Phase 2 test program—carbonizer testing—began in November 1991 at FWDC's Research Center in Livingston, New Jersey. Eight test series were completed in the carbonizer test unit shown in Figure 9. Pittsburgh No. 8 and Illinois No. 6 bituminous coals and Eagle Butte subbituminous coal have been successfully tested along with dolomite and limestone sorbents. Results from these tests have been most encouraging, bettering our commercial plant predictions. Preliminary information from these tests revealed greater than 90-percent sulfur capture, only half the coal nitrogen released in the carbonizer converted to ammonia, no tars in the carbonizer gas, and heating values of the gas close to those predicted. The unit has been modified for CPFBC testing, which should be completed by the third quarter of 1993. Integrated carbonizer/CPFBC testing will be conducted by FWDC in 1994.

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