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Pressurized Circulating Fluidized-Bed Combustion for Power Generation

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ABSTRACT

Second-generation Pressurized Circulating Fluidized Bed Combustion (PCFBC) is the culmination of years of effort in the development of a new generation of power plants which can operate on lower-quality fuels with substantially improved efficiencies, meet environmental requirements, and provide a lower cost of electricity. Air Products was selected in the DOE Clean Coal Technology Round V program to build, own, and operate the first commercial power plant using second-generation PCFBC technology, to be located at an Air Products chemicals manufacturing facility in Calvert City, Kentucky. This paper describes the second-generation PCFBC concept and its critical technology components.

INTRODUCTION

Air Products, Foster Wheeler, Westinghouse, and Lurgi-Lentjes-Babcock (LLB) have formed a project team for the Calvert City Clean Coal Technology project known as the Four Rivers Energy Modernization Project (1). As an independent power producer, Air Products considers PCFB technology to be strategic for its cogeneration business. The partnership recognizes its advantages for repowering and feels that it will play an important role after the turn of the century for power generation. This paper will introduce the second generation PCFB process, review the anticipated power generation efficiency for this process, and review the critical technology components which require demonstration.

Second-generation PFBC systems are an outgrowth of fluidized bed combustion research which began in the late 1950's in the U.K. (4) and of fluidized bed gasification technology which stretches back to the Winkler gasification process of the 1920's (7). Although the early work used atmospheric-pressure bubbling fluidized beds, and the first pressurized fluidized bed power plant demonstration in the US -- American Electric Power's (AEP) TIDD plant -- was also a bubbling bed design, circulating fluidized bed combustors are proving more advantageous for larger scale applications. Plant efficiency, costs, and environmental performance favor the circulating mode (2) for the combustor.

Atmospheric-pressure circulating fluidized bed combustion, described in another paper at this session, has become established as a clean coal technology for steam and power generation, and it is now being scaled up to the 250-MW range. Operational experience has shown that CFB technology is capable of meeting the operability, reliability, and emissions requirements needed to be competitive in the utility industry (5). The addition of limestone directly to the circulating bed allows as much as 95% retention of the coal sulfur as calcium sulfate (5, 6), and the combination of relatively low maximum combustion temperature, uniform temperature conditions, and inherent air staging of CFBCs leads to low NOx emissions -- sometimes < 100 ppmv without back-end controls, and ~20 ppmv with SNCR (6).

However, as is also the case for conventional pulverized-coal-fired power plants, the efficiency of atmospheric-pressure systems is limited by the upper temperature for steam-power cycles of ~1000 °F (540 °C). In order to avoid exergy losses and improve power generation efficiency, it is necessary to raise the upper process temperature by moving to plants in which the steam cycle is topped by a gas turbine cycle (2). Coal may be used directly in a gas turbine cycle if the coal is combusted under pressure, but the maximum practical combustion temperature in a pressurized fluidized bed system is still limited to the 1580 - 1650 °F (860 - 900 °C) range by considerations such as sulfur capture in the bed, alkali emissions, and the operation of the necessary hot gas particulate removal systems (2, 4). These considerations have led to the development of the second-generation process by Foster Wheeler (3, 13, 14).

DESCRIPTION OF THE SECOND GENERATION PROCESS

The second-generation process differs from a first-generation process in that, in the second-generation process, all or part of the feed coal is sent to a pressurized "carbonizer" upstream of the combustor. The carbonizer produces a fuel gas which is used to raise the temperature of the vitiated air leaving the fluidized bed combustor. This allows much higher gas turbine inlet temperatures without affecting sulfur capture. The carbonizer does not need to operate under severe gasification conditions, nor is the loss of carbon in elutriated fines of major concern, since the unreacted carbon in the char is burned in the combustor. Carbon conversions of <70% are acceptable, and the carbonizer can operate at temperatures much lower than typical coal gasifiers (12).

In the second generation process, air is withdrawn from the gas turbine's compressor for the carbonizer and PCFB combustor. In the carbonizer, an air-blown pressurized fluidized bed, the coal feed is partially combusted to produce a low-Btu fuel gas and char. Limestone is added to capture sulfur, enhance gasification reactions and retard agglomeration of caking coals. Solids are removed from the fuel gas in a cyclone and ceramic filter. Trace alkali components are removed in a packed bed adsorber. Char from the carbonizer, plus additional coal and limestone if needed, are burned in the PCFB combustor. The PCFB combustor generates steam in its water walls and an INTREX™ integrated fluid bed heat exchanger. Flue gas from the PCFB combustor is also cleaned by a cyclone, ceramic filter, and alkali removal train.

The fuel gas from the carbonizer is burned with cleaned, hot pressurized air from the PCFB combustor in the gas turbine topping combustor. This stream is expanded in the gas turbine to drive a generator and the turbine's air compressor. The turbine exhaust raises additional steam in the heat recovery steam generator (HRSG). Steam raised in the PCFB combustor and HRSG drives the steam turbine generator.

POWER GENERATION EFFICIENCY

The Four Rivers projects is a cogeneration facility, producing an annual average of approximately 72 MW of electricity (including parasitic power) and 310,000 lb/hr (141,000 kg/hr) of 190 psia/420 °F (1.3 MPa/215 °C) process steam to Air Products' adjacent chemical manufacturing facility. The gas and steam turbines generate 39 MWe and 33 MWe respectively. At these conditions, the feed rates are 33.5 ton/hr (30,500 kg/hr) (dry basis) western Kentucky high-sulfur bituminous coal (864 MMBtu/hr [912 GJ/hr], HHV) and 7.5 tons/hr (6800 kg/hr) local limestone. If all of the steam were expanded through the steam turbine, the plant would generate about 97 MWe gross (91 MWe net), for a net equivalent efficiency of approximately 36% on a higher heating value basis.

An initial DOE-sponsored study by Foster Wheeler identified significant economic and environmental advantages for advantages for the second generation process (3). A 1993 DOE study (4) compared efficiencies of the second generation, utility-scale process against a conventional pulverized coal boiler with a scrubber, first generation PCFB, and IGCC. The results, summarized in Table 1, show a significant advantage for the second generation PCFB process:

Table 1. Net Plant HHV Efficiency (4)

2nd Gen. PCFB	PC w/ scrubber	1st Gen. PCFB	IGCC
43.6	36.6	40.8	42.3

The equivalent power generation efficiency for the Four Rivers cycle, as stated above, is ~36%, on a higher heating value basis (9), which is comparable to today's pulverized-coal-fired power plants with flue gas desulfurization. This contrasts with the target of 43.6% or higher (1, 3, 4) for a second-generation PCFBC utility power generation facility. The changes which can be anticipated in order to reach the target include:

- The Four Rivers design is intended to produce a large amount of intermediate-pressure process steam. To achieve this, coal is fed directly to the combustor -- which generates most of the steam -- as well as to the carbonizer. For a power-only plant, it is better to feed coal to the carbonizer only, while the combustor uses only the char from the carbonizer. This switches the power-generation ratio away from the steam cycle toward the more efficient gas turbine.

- The Four Rivers plant uses a conservative gas turbine inlet temperature, well within today's turbine availability, of 1975 °F (1080 °C). The future utility plant will use a turbine inlet temperature of at least 2100 °F (1150 °C) or higher (3, 4).

- A utility-scale plant will use a higher-pressure steam cycle, with reheat. For example, Ref. 3 proposes a conventional single reheat, 2400 psig/1000 °F/1000 °F (16.6 MPa/540 °C/540 °C) cycle, in contrast to the Four Rivers values of 1515 psig/950 °F (10.5 MPa/510 °C) without reheat (9).

Increasing the gas turbine combustor outlet temperature to 2350 °F (1290 °C) raises the power generation efficiency to 45% (HHV), and future cycles are anticipated to approach 50% (8).

CRITICAL TECHNOLOGY COMPONENTS

The following is a description of the critical technology components which are the key elements of the second generation PCFB process.

Carbonizer

The carbonizer is a vertical, pressurized, refractory-lined, jetting fluidized bed reactor. At the Four Rivers scale, it is approximately 46 ft. high. The lower 25 ft. of the carbonizer has an 8-ft. inner diameter, while the upper 21 ft. of the vessel expands to 10.5 ft. inner diameter. The bottom is conical with a central air jet. Coal and sorbent will be fed to the lower section of the vessel. Coal will probably be fed directly into the central air jet, although side feed ports are an alternative. The carbonizer will operate at 250 psia/1700 °F to produce 135,000 lb/hr of approximately 130 Btu/SCF fuel gas (HHV basis). Limestone captures sulfur as CaS and catalyzes cracking of oil and tar species which could foul the ceramic filter. The limestone also serves to dilute the coal feed and inhibit agglomeration of caking coals (11). Fuel gas, with entrained char and sorbent, exits at the top of the vessel. A cyclone and ceramic filter removes the particulate, which is combined with material from the bed drains and fed to the PCFB combustor.

PCFB Combustor

At the Four Rivers scale, the PCFB combustor provides ~350 MMBtu/hr for steam generation. Combined with heat from the HRSG, this allows the generation of ~460,000 lb/hr of 1515 psia/950 °F steam. In addition, it heats over 800,000 lb/hr of vitiated air for the topping combustor. Finally, it consumes char from the carbonizer and converts CaS to innocuous $CaSO_4$.

The PCFB combustor is comprised of a membrane wall combustion chamber, cyclone, INTREX™ integrated heat exchanger, and ash stripper coolers, all of which may be housed in a single 110-ft. high x 28-ft. diameter pressure vessel. (Multiple pressure vessels could be used if they prove to be more economical.) The combustor operates at 230 psia/1600 °F, with ~8.5 vol % O2 (wet basis) in the exit vitiated air.

The combustor has a very small footprint because PCFB combustion generates a very intensive heat output per unit cross-section area. The cyclone will be steam-cooled with a 2" layer of refractory. The INTREX™ integrated heat exchanger has multiple bubbling fluidized bed cells in which steam can be generated and/or superheated.

Air enters through the bottom head of the pressure vessel to pressurize the vessel. Primary air flows through an annular opening in the pressure vessel and into the externally mounted startup burner. From the burner if flows into the bottom of the water-cooled air plenum. It then passes through a water-cooled air distributor which has directional air nozzles. Secondary air is injected into the combustor through multiple openings in the front wall at two elevations. Some of the secondary air is preheated in the ash stripper-coolers and in the INTREX™ integrated heat exchanger. The staged combustion minimizes NOx formation.

Carbonizer char, and additional coal and sorbent as required, will be introduced into the lower portion of the combustor. Ash is removed thorough two 100% stripper/coolers located on the side walls of the combustor. The ash is cooled to 500 °F and discharged through rotary valves.

High Temperature Gas Cleaning Systems

High temperature gas cleaning is essential for the second generation PCFBC technology. As discussed above, the difference between first and second generation PCFB processes is the fired gas turbine, which raises the turbine inlet temperature from 1400 °F to 1975 °F for Four Rivers and to 2100 °F or higher for future facilities. These high temperatures require that almost all the particulates, and some trace species such as alkalis, be removed to prevent erosion, corrosion, and formation of deposits in the topping combustor or gas turbine. Separate hot gas cleaning trains must be used for the carbonizer fuel gas and the PCFBC vitiated air. Each train consists of a cyclone separator, a ceramic filter, and a fixed-bed alkali removal unit in series. The carbonizer has a stand-alone cyclone of conventional design. The PCFB cyclone is integral to the PCFB combustor. A recent study by Bechtel for EPRI (15) has shown that reducing the fuel gas and flue gas temperatures would improve the expected operating reliability of the filters and possibly eliminate the need for separate alkali removal with minimal effects on the plant heat rate.

At Four Rivers, Westinghouse will provide two 100% ceramic filter assemblies for the carbonizer fuel gas. The fuel gas will be cooled to 1400 °F or less ahead of the filters. Each filter is a 44-ft. high x 10-ft. diameter refractory-lined pressure vessel containing the gas inlet shroud, tube sheet, three vertical filter clusters, and bottom conical dust hopper section. The system is designed to handle particulate loading from 2,000 to 30,000 ppmw and a ratio of char to sorbent from 1:1 to 25:1. The design face velocity is 7 ft/min for the ceramic filter elements. Each of the three vertical cluster assemblies is supported from the high alloy tube sheet and cleaned by a dedicated back-pulse nozzle. Each cluster has 128 candle filter elements. The 384-candle design is similar to the candle filter system installed at the AEP TIDD facility mentioned above.

At Four Rivers, LLB will provide three 50% ceramic filter assemblies for the vitiated air. Two units will be kept on-line to clean ~800,000 lb/hr of 220 psia/1600 F vitiated air containing fly ash. (The vitiated air may be cooled to 1400 °F, using the bypass air, if necessary for filter operation.) The design inlet dust loading is 20,000 ppmw, and a conservative face velocity of 5 ft/min has been used for the design basis. Each filter vessel has 1800 candle elements in a 65-ft. high x 14-ft. diameter refractory-lined pressure vessel with a 17-ft. long conical bottom. The LLB design does not have a tube sheet; instead, each of the three levels containing 600 candles has a dedicated manifold comprised of horizontal header tubes and vertical gas collection pipes; the candles are bottom-supported.

Topping Combustor

The topping combustor for Four Rivers will be supplied by Westinghouse and will be used with the Westinghouse 251B12 turbine. The low-Btu fuel gas from the carbonizer is burned with the vitiated air to generate 216 psia/1975 °F gas to the turbine in a steady and controlled manner. At the entrance to the topping combustor, both the fuel gas and the vitiated air may be at 1400 °F, which presents a significant challenge for burner design. The burner must minimize NOx formation, both from thermal NOx and from the combustion of the approximately 0.2 wt% NH_3 expected in the coal-derived fuel gas. To meet these challenges, Westinghouse has developed a Multi-Annular Swirl Burner (MASB) based on a design by Beer (10), with extensive testing and modification by Westinghouse. The MASB satisfies the demanding cooling requirements by introducing all of the combustion air through annuli which have substantial radial thickness. Cooling air is created at the leading edge from each of the concentric inlet sections. NOx formation is suppressed by the combustion staging, including an initial fuel-rich zone having sufficient residence time to convert NH_3 to N_2. A high recirculation rate at the inlet provides flame stability.

CONCLUSION

The second generation Pressurized Circulating Fluidized Bed Combustion process has been in active development since the mid-1980's. Demonstration of this technology at an industrial commercial scale will lead to a new, clean, efficient, and cost-effective coal-based power generation technology for the 21st century.

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