DOE/MC/31261-95/C0448

Conf-950522--3

Four Rivers Second-Generation Pressurized Circulating Fluidized-Bed Combustion Project

Authors:

E. P. Holley
J. J. Lewnard
G. von Wedel
K. W. Richardson
H. T. Morehead

Contractor:

Environmental and Energy Systems
Air Products and Chemicals, Inc.
7201 Hamilton Boulevard
Allentown, PA 18195-1501

Contract Number:

DE-FC21-94MC31261

Conference Title:

13th International FBC Conference

Conference Location:

Orlando, Florida

Conference Dates:

May 7-10, 1995

Conference Sponsor:

American Society of Mechanical Engineers (ASME)

DISCLAIMER

DISCLAIMER

Four Rivers Second Generation Pressurized Circulating Fluidized Bed Combustion Project

E.P. Holley, J.J. Lewnard
Air Products and Chemicals, Inc.

G. von Wedel
LLB Lurgi Lentjes Babcock Energietechnik GmbH

K.W. Richardson
Foster Wheeler Energy Corp.

H.T. Morehead
Westinghouse Electric Corp.

ABSTRACT

Air Products has been selected in the DOE Clean Coal Technology Round V program to build, own, and operate the first commercial power plant using second generation Pressurized Circulating Fluidized Bed (PCFB) combustion technology. The Four Rivers Energy Project (Four Rivers) will produce approximately 70 MW electricity, and will produce up to 400,000 lb/hr steam, or an equivalent gross capacity of 95 MWe. The unit will be used to repower an Air Products chemicals manufacturing facility in Calvert City, Kentucky.

INTRODUCTION

The second generation Pressurized Circulating Fluidized Bed (PCFB) combustion process has been in active development for the past six years. An initial DOE-sponsored study by Foster Wheeler identified significant economic and environmental advantages (1) for the process. Recent pilot testing by Foster Wheeler and Westinghouse (WEC) has focused on the development of the process critical components (2). These tests provided the design basis for a 3 MWth integrated pilot plant currently in start-up at Foster Wheeler's Livingston facility, and for the 7 MWe (equivalent capacity) Wilsonville Power Systems Development Facility (3). Independently, LLB Lurgi Lentjes Babcock Energietechnik (LLB) has run a 15 MWth PCFB combustor with hot gas filtration for several years (4). These development efforts led Air Products to join with Foster Wheeler, LLB and WEC to successfully propose the Four Rivers Project at Air Products' chemicals manufacturing facility in Calvert City, KY under the Clean Coal Technology Round V Program.

Efficient, environmentally acceptable, and economic advanced processes such as second generation PCFB combustion will ensure that coal continues to play a major role in power generation. Advanced second generation PCFB power cycles can achieve 45% (HHV) thermal efficiency, and future cycles are anticipated to approach 50% (5). The high efficiency is derived from a combined cycle operation in which 45% of the electric power is generated in the gas turbine, with the balance from the steam cycle. The inherent higher plant efficiency provides a number of environmental advantages. For example, coal consumption is 25% lower per unit power output than a pulverized coal or ACFB plant. Consequently, there will be lower emissions of CO_2 and other pollutants. In addition, 95% sulfur capture can be attained with a Ca/S molar ratio less than 2.0. This exceeds the 90-93% sulfur removal criterion in New Source Performance Standards (NSPS) with BACT review. NOx emissions are estimated at 0.3 lb/MMBtu, which are half those required by NSPS. In LLB's pilot plant tests particulate emissions have consistently measured below 3 ppm (0.003 lb/MMBtu), which is an order of magnitude lower than NSPS.

This excellent environmental performance comes with a competitive price. The second generation PCFB process, as fully commercialized, will have a life cycle cost-of-electricity 20% below the cost of conventional coal technologies (1). The savings are due to higher thermal efficiency; lower capital, operating, and maintenance costs; and shorter construction times.

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 it will play an important role at the turn of the century for power generation. This paper will introduce the second generation PCFB process for the Four Rivers project, discuss the critical technology components, provide an update on the current status of the project, review the project team scope, and present the project schedule.

PROCESS DESCRIPTION

The Four Rivers project is a cogeneration facility, producing an annual average of approximately 70 MWe to the grid and 310,000 lb/hr of 190 psia/420°F process steam to Air Products' adjacent chemical manufacturing facility. The gas and steam turbines generate 38 MWe and 34 MWe, respectively. At its annual average operating condition, the feed rates are 36.5 ton/hr western Kentucky high-sulfur bituminous coal and 7.5 ton/hr local limestone. The steam load will vary from 250,000 lb/hr in summer to 400,000 lb/hr in winter. If all of the steam were expanded through the steam turbine, the plant would generate about 95 MWe gross. A flowsheet of the process is shown in Figure 1.

In the second generation PCFB 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 gasifier, the coal slurry undergoes partial combustion to produce a low-Btu fuel gas and char. Limestone is added to capture sulfur and enhance gasification reactions. 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, additional coal slurry, and limestone are burned in the PCFB combustor. The PCFB combustor generates steam in its waterwalls and an INTREX™ integrated 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 external 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.

CRITICAL TECHNOLOGY COMPONENTS

The following is a description of the critical technology components, which are the key elements of the second generation PCFB process. Demonstration of these components at the commercial scale is a primary goal for the Four Rivers project.

Carbonizer

The distinguishing feature between first and second generation PCFB processes is a fired gas turbine. Increasing the gas turbine inlet temperature is the key to higher efficiency. The carbonizer generates the fuel gas which is fired in the topping combustor to increase the gas turbine inlet temperature.

The carbonizer is a vertical, pressurized spouted bed reactor which is refractory-lined. It is approximately 46 ft. high and has a conical bottom. 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.

Coal slurry is fed through radial nozzles and sorbent is gravity fed with nitrogen assist to the lower zone of the vessel. The carbonizer operates at 250 psia/ 1700°F to produce 135,000 lb/hr of approximately 130 Btu/scf fuel gas. Limestone captures sulfur as CaS and catalyzes cracking of oil and tar species which could foul the ceramic filter. 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 bed drains in the char transfer hopper. The particulate and the char are fed to the PCFB combustor through an "N" valve.

PCFB Combustor

The PCFB combustor provides 460,000 lb/hr of 1515 psia/950°F steam. In addition, it heats over 800,000 lb/hr of vitiated air to 1600°F 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, "J" valve, INTREX ™ integrated heat exchanger, and ash stripper/coolers, which are all housed in a 110-ft high x 28-ft diameter pressure vessel. It operates at 225 psia/1600°F with varying amounts of excess air, depending on the export steam load.

The combustor has a very small footprint because PCFB combustion generates a very intensive heat output per unit cross-section area. The steam-cooled cyclone has a 2-inch layer of refractory, which facilitates rapid start-up, and reduces weight and structural support requirements. The INTREX™ integrated heat exchanger has three bubbling fluidized bed cells in which solids are distributed through serpentine superheat or steam generating coils.

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 it 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 furnace through multiple openings in the front wall at two elevations. A portion of the secondary air is pre-heated in the ash stripper-coolers. The staged combustion minimizes NOx formation.

Carbonizer char is discharged from the "N" valve into the lower combustor through an opening on the centerline of the combustor front wall. Coal slurry is injected into the lower combustor through two air-atomized nozzles positioned on either side of the char feed opening. Sorbent is gravity fed with air assist through two openings in the front wall near the fuel feed points. Ash is removed through two 100% stripper/coolers located on the side walls of the combustor. The coolers have two sections divided by a refractory brick wall. Ash is cooled to 500°F and discharged through a rotary valve.

High Temperature Gas Cleaning Systems (HTGC)

The HTGC is essential for operating the second generation PCFB 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 1600°F to 1975°F for Four Rivers and as high as 2350°F for future facilities. These high temperatures require that almost all particulate and trace species such as alkalis be removed to prevent erosion, corrosion, and formation of deposits in the topping combustor or gas turbine.

Separate HTGC trains are used for the carbonizer fuel gas and PCFB combustor vitiated air. Each HTGC consists of three cleaning stages in series: a cyclone separator, a ceramic filter, and a fixed-bed alkali removal unit. The carbonizer has a stand-alone cyclone of conventional design. The PCFB cyclone is integral to the PCFB combustor and is located within the pressure vessel.

Carbonizer Candle Filter

Westinghouse will provide two 100% ceramic filter assemblies for the carbonizer fuel gas. The carbonizer train cleans 135,400 lb/hr of 230 psia/1400°F fuel gas containing char and sorbent. The ceramic filter is a 44-ft high x 10-ft diameter refractory-lined pressure vessel containing the gas inlet shroud, tubesheet, three vertical filter clusters, and a bottom conical section which acts as a dust hopper.

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 are supported from the high alloy tubesheet and cleaned by a dedicated pulse nozzle. Each cluster has 128 candle filter elements distributed among three plenums vertically arranged in the vessel. The 384 candle design is similar to the candle system installed at the Tidd facility. Westinghouse has developed the design in over 4,600 hours of operating time under both reducing and oxidizing conditions in various facilities.

PCFB Candle Filter

LLB will provide three 50% ceramic filter assemblies for the PCFB combustor vitiated air. Two units will be kept on-line to clean 815,000 lb/hr of 216 psia/1600°F vitiated air containing fly ash. 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 30-ft high x 14-ft diameter refractory-lined pressure vessel with a 17-ft long conical bottom. The LLB design does not have a tubesheet; instead, each of the three levels containing 600 candles has a dedicated manifold comprised of horizontal header tubes and vertical gas collection pipes. Candles are bottom supported instead of the more conventional hanging arrangement.

LLB's design is based on over 3000 hr of operating experience gained at their 15 MWth pilot unit.

Alkali Removal Units

Thermodynamic models indicate that alkali control may be required to protect the gas turbine from erosive alkali sulfate deposits. Westing-house has developed designs for vertical, downflow beds packed with 1/8" x 1/4" emathlite pellets in a carbon steel, refractory-lined pressure vessel. The beds will be designed for 8000 hours operation. The waste emathlite will be inert, with very low leachability, and can be disposed in a landfill. A single unit will be used to remove approximately 10 ppmv alkali vapor from the carbonizer fuel gas. The PCFB combustor train will require two 50% parallel vessels to remove 0.1 ppmv alkali due to the higher gas flow rate. Future pilot plant tests will determine if the units are required.

Topping Combustor

The topping combustor is supplied by Westinghouse, and is integral to their 251B12 turbine. Its purpose is to increase the inlet temperature to the gas turbine above the 1600°F operating temperature of the PCFB combustor. The low-Btu fuel gas from the carbonizer is burned with vitiated air from the PCFB combustor to generate 213 psia/1975°F gas to the turbine in a steady and controlled manner. There are two critical elements in the topping combustor: the Multi-Annular Swirl Burners (MASB), and the hot valve control system.

Multi-Annular Swirl Burners (MASB)

Combustion of the low-Btu 1400°F fuel gas with 1400°F vitiated air occurs in a ring of eight 18-inch diameter MASBs located in a topping combustor which is external to the combustion turbine. The need to cool the combustor walls with 1400°F air presents a significant challenge. In addition, the fuel gas will contain approximately 0.2 wt% NH_3 from the reduction of nitrogen-containing compounds in the coal. The mixing and residence time/temperature distribution in the MASB is critical to minimize NH_3 conversion to NOx. In addition, thermal NOx must also be minimized. These constraints preclude the use of conventional combustor designs.

The MASB is a rich-quench-lean combustor based on the design by Beer (6), with extensive modifications by Westinghouse. It satisfies the demanding requirements by introducing all 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. Fuel-bound NOx formation is suppressed by the combustion staging that results from sequencing the air inlets. A high recirculation rate at the inlet provides flame stability. Initial tests on the 18-inch prototype have exceeded expectations for NOx emissions.

Hot Control Valve System

Because the heating value for carbonizer fuel gas is approximately 130 Btu/scf, its volumetric flow rate is an order of magnitude greater than natural gas. Its high flow rate and 1400°F temperature present challenges for selection of valves to regulate and shut off flow. Unlike a conventional gas turbine, valves are required on the PCFB vitiated air stream for overspeed protection. Merely shutting off the fuel gas system is not sufficient for overspeed protection. The large inventory of hot pressurized air in the PCFB systems and piping contains a considerable amount of thermal energy that must be controlled to prevent the turbine from excessive overspeed. Development of large, high temperature, high pressure valves with quick response for safe shutdown is a challenge that will be addressed in this project.

CURRENT PROJECT STATUS

Since being selected by DOE in May 1993, Air Products and its partners have provided DOE with documentation for DOE's Fact-Finding investigation. DOE then conducted a Reasonableness Review of the Air Products' Proposal and the updated documentation. Negotiations on a Cooperative Agreement were undertaken in late 1993. Air Products signed the Cooperative Agreement in March, 1994. The Cooperative Agreement passed through Congress, and was finalized in July 1994.

Air Product has completed an Environmental Information Volume (EIV) as part of the DOE's NEPA process. After receiving DOE's response to the draft EIV, a final version was submitted in May, 1994. The DOE is reviewing the EIV, and will soon announce whether an Environmental Assessment (EA) or an Environmental Impact Statement (EIS) will be required for the project. The environmental review process is expected to conclude in late 1995.

The Four Rivers team is working closely with the DOE to define the pilot plant activities necessary for detailed engineering and environmental permits. Foster Wheeler Development Corporation has completed modifications to their Livingston pilot plant to allow it to operate in a fully integrated mode. An LLB-designed candle filter system will be installed on the PCFB flue gas stream after the unit is shaken down. Westinghouse will provide the candle filter for the carbonizer at the pilot plant, as well as assume responsibility for alkali test measurements. The Livingston pilot operations are anticipated to require six months. In addition, Westinghouse will be running further tests on the 18-inch MASB combustor at the University of Tennessee Space Institute during mid 1995. These pilot plant activities will be a major project focus for 1995.

PROJECT TEAM SCOPE

The project team consists of Air Products, Foster Wheeler, Westinghouse, and LLB. As the Four Rivers team leader, Air Products will provide overall project management, procurement, construction management, and operation services. Air Products will also provide all required non-DOE funding for the project. Following the design and construction phases, Air Products will operate the plant for 30 months to demonstrate the technology and to develop a database. The plant will then be operated commercially to provide electric power and steam to Air Products' chemicals manufacturing facility.

Foster Wheeler's effort will be led by Foster Wheeler Energy Corporation, whose scope includes the design, fabrication, and erection of the boiler island. The boiler island includes the carbonizer, PCFB combustor, Westinghouse carbonizer filter and alkali removal units, and LLB combustor filter. Foster Wheeler Development Corporation will provide pilot plant tests to support the design. Foster Wheeler USA Corporation will provide the engineering design for the overall plant.

Westinghouse will supply the carbonizer filter and alkali removal units, as well as the design and fabrication of the topping combustor and a modified 251B12 gas turbine.

LLB will provide the PCFB combustor filter, coal slurry feed system and ash removal system. In addition, they will provide engineering services to incorporate their pilot-scale PCFB combustor experience into the Four Rivers design.

DOE will monitor the project activities, give technical advise, assess progress by periodically reviewing the project performance with the other team members, and will participate in the decision making process at major project milestones.

References

1. Robertson, A., et al, Second Generation PCFB Combustion Plant - Conceptual Design and Optimization Phase 1 - Task 1 Report, FWC/FWDC/TR-89/11, prepared for US DOE (1989)
2. Robertson, A., Garland, R. V., Pillsbury, P., and Bonk, D. L., Carbonizer, CPFBC, and Topping Combustor Testing for Second Generation PFB Combustion Plants, Proc. 11th Intl. Conf. Fluidized Bed Comb., San Diego (1993)
3. McClung, J. D., Advanced PCFB Commercialization Update, Proc. American Power Conf., Chicago (1993)
4. Dehn, G., Meier, H., Mollenhoff, H., Rehrwinkel, H., and von Wedel, G., 15 MWth PCFB Operating Experience with DBE Pilot Plant and Outlook on Future Development, Proc. 11th Intl. Conf. Fluidized Bed Comb., San Diego (1993)
5. Rubow, L. N., Horazak, D. A., Hyre, M. R., and Buchanan, T. L., PFBC Concepts Analysis for Improved Cycle Efficiency and Cost, U.S. DOE Contract DE-AC01-88FE61657 Task 2 (1992)
7. Beer, J. M., U.S. Patent 4,845,940 and British Patent 45652/65