CONF-9506162--42

DOE/MC/21023-96/C0549

Development of a Topping Combustor for Advanced Concept Pressurized Fluidized-Bed Combustion Systems

Authors:

William F. Domeracki
Thomas E. Dowdy
Dennis Bachovchin

Contractor:

Westinghouse Electric Corporation
4400 Alafaya Trail
Orlando, Florida 32826-2399

Contract Number:

DE-AC21-86MC21023

Conference Title:

Advanced Coal-Fired Power Systems '95 Review Meeting

Conference Location:

Morgantown, West Virginia

Conference Dates:

June 27-29, 1995

Conference Sponsor:

U.S. Department of Energy, Morgantown Energy Technology Center (METC)

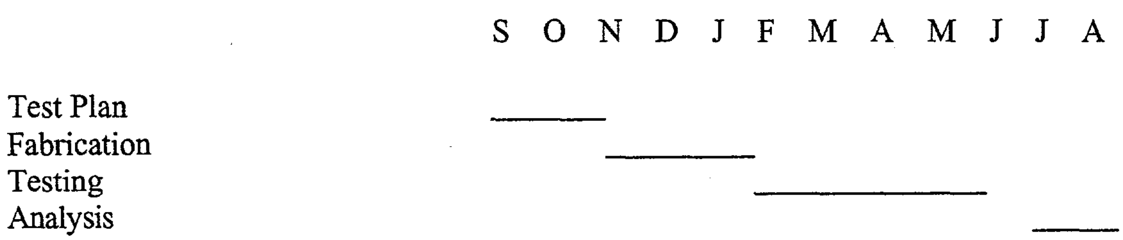
DISCLAIMER

5.3 Development of a Topping Combustor for Advanced Concept Pressurized Fluidized-Bed Combustion Systems

CONTRACT INFORMATION

Contract Number	DE-AC21-86MC21023
Contractor	Westinghouse Electric Corporation 4400 Alafaya Trail Orlando, Florida 32826-2399 (407) 281-3387 (telephone TED) (407) 281-5014 (FAX)
Other Funding Sources	Cost Shared by Westinghouse, Foster-Wheeler, and Other Major Subcontractors
Contractor Project Manager	William F. Domeracki
Principal Investigators	Thomas E. Dowdy Dennis Bachovchin
DOE Project Manager	Donald L. Bonk
Period of Performance	January 5, 1987 to December 31, 1994
Schedule and Milestones	No activity planned FY95

FY1994 Program Schedule



OBJECTIVE

A project team consisting of Foster Wheeler Development Corporation, Westinghouse Electric Corporation, Gilbert/Commonwealth and the Institute of Gas Technology, are developing a Second Generation Pressurized Fluidized Bed System. Foster Wheeler is developing a carbonizer (a partial gasifier) and a pressurized fluidized bed combustor. Both these units operate at a nominal 1600°F (870°C) for optimal sulfur capture. Since this temperature is well below the current combustion turbine combustor outlet operating temperature of 2350°F (1290°C), to reach commercialization, a topping combustor and hot gas cleanup (HGCU) equipment must be developed.

Westinghouse's efforts are focused on the development of the high temperature gas cleanup equipment and the topping combustor. This paper concentrates on the design and test of the topping combustor, which must use a low heating value syngas from the carbonizer at approximately 1600°F and 150 to 210 psi. The syngas entering the topping combustor has been previously cleaned of particulates and alkali by the hot gas cleanup (HGCU) system. It also contains significant fuel bound nitrogen present as ammonia and other compounds. The fuel-bound nitrogen is significant because it will selectively convert to NOx if the fuel is burned under the highly oxidizing conditions of standard combustion turbine combustors.

The fuel must be burned with the vitiated air produced by the pressurized fluidized bed combustor (PFBC). The vitiated air has been cleaned of particulates and alkali by the HGCU system, and has also been partially depleted in oxygen. The 1600°F (870°C) vitiated air must also be used to cool the combustor as much as possible, though a small amount of compressor discharge air at a lower temperature 700°F may be used.

The application requirements indicate that a rich-quench-lean (RQL) combustor is necessary and the multi-annular swirl burner (MASB) was selected for further development. This paper provides an update on the development and testing of this MASB combustor. Additionally, Westinghouse has been conducting computational fluid dynamic (CFD) and chemical kinetic studies to assist in the design and to help optimize the operation of the combustor. Results of these models are presented and compared to the test results.

BACKGROUND

Cycle Description

In a second generation PFB combined cycle, coal is fed to a pyrolyzer/carbonizer unit that operates at 1600°F to produce a low heating value fuel gas and combustible char. The char is burned in the PFB, and the 1600°F product gases, after filtration, are piped back to the combustion turbine as illustrated in Figures 1 and 2.

Before entering the gas turbine, the 1600°F (870°C) gas, still rich in oxygen, is raised to 2100°F (1150°C) or higher by burning the filtered, pyrolyzer-produced low heating value fuel gas in a topping combustion system. Since turbine inlet temperature is at least 500°F (260°C) higher than the PFB air temperature, plant efficiency is 5- to 7-percentage points higher than similar first generation PFB plants.

The Combustion Turbine

The use of a Circulating Pressurized Fluidized Bed Combustor (CPFBC) as the primary combustion system for a combustion turbine requires transporting compressor air to the CPFBC and vitiated air/fuel gas back to the turbine. In addition, the topping combustion system must be located in the returning vitiated airflow path. The conventional fuel system and turbine center section require major changes for the applications.

The combustion zone of the Westinghouse 501 combustion turbines currently in production cannot contain a topping combustion system within the main structural pressure shell. Although the pressure casing can be enlarged both radially and longitudinally to accommodate the topping combustor system, the integrity and rigidity of the

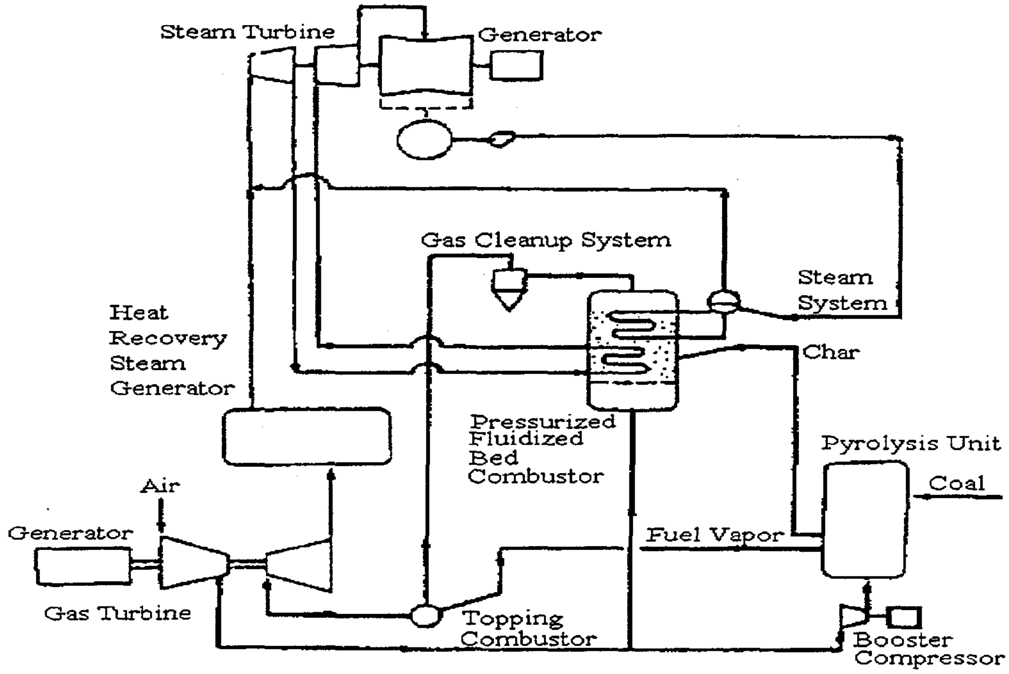


Figure 1. Schematic Representation of a Second Generation PFB Combined Cycle

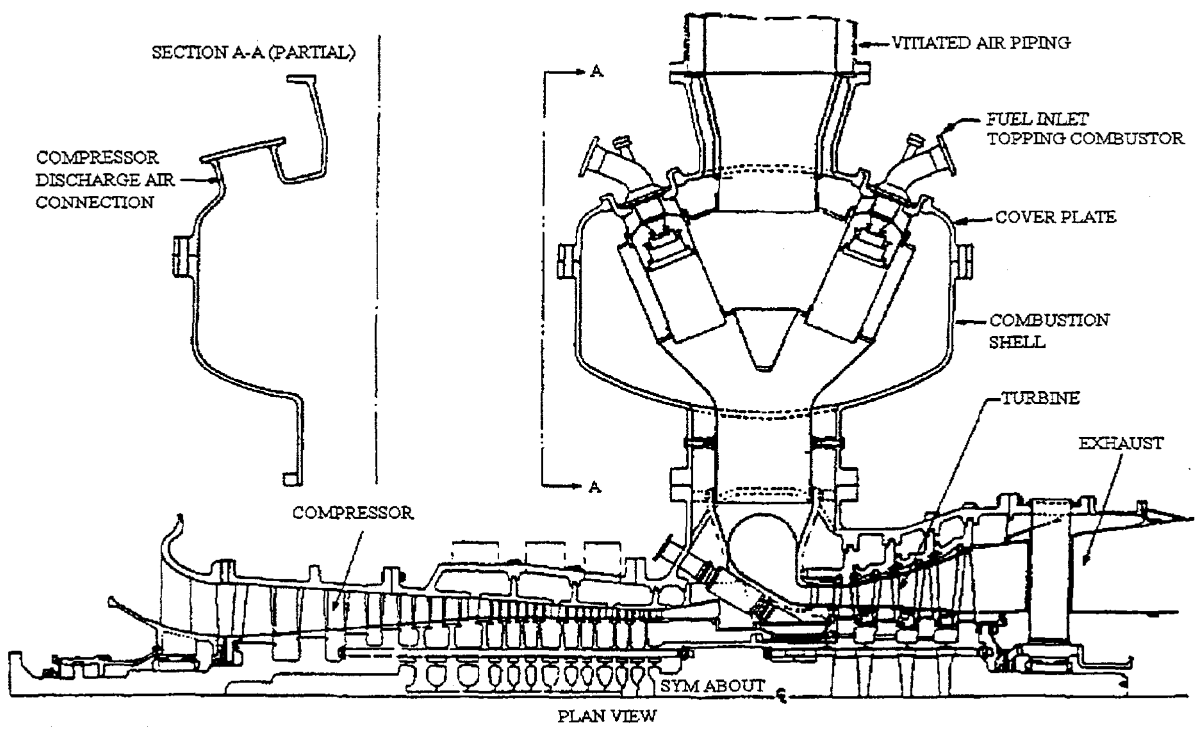


Figure 2. Combustion Turbine Conceptual Design

main shell would be significantly affected, possibly impacting rotor dynamics and precluding shipping the unit assembled.

One alternative configuration, which uses two topping combustor assemblies, on the side of the unit, is shown in Figure 2. The vitiated air from the CPFBC enters each of the internal plenum chambers in which the topping combustors are mounted. Fuel gas enters the assembly via the fuel nozzles at the head end of the combustor. Combustion occurs, and the products of combustion are ducted into the main shell for distribution to the first-stage turbine vanes.

Compressor discharge air leaves the main shell, flowing around the annular duct into adjacent combustion shells. The air flows around the vitiated air plenums and leaves each combustion assembly via nozzles and is ducted to the CPFBC and carbonizer. (See Figure 2.)

Combustor Design

Because the air entering the combustor is at 1600°F rather than the 700°F usual for gas turbines, the conventional type of combustor is not suitable. Both emissions and wall cooling problems preclude the use of the conventional design. Therefore, a combustor that will meet the requirements of utilizing the higher temperature air for both wall cooling and combustion is required.

In selecting a combustor design that will withstand the conditions expected in the topping application, the effective utilization of the 1600°F air mentioned above could satisfy the wall cooling challenge by maintaining a cooling air layer of substantial thickness. The creation of thick layers of cooling air at the leading edge of each inlet section is easily achieved if the combustor is made up of concentric annular passages. In addition to wall cooling considerations, the burner must inhibit the formation of NOx from syngas that contains fuel-bound nitrogen, have high combustion efficiency, produce an acceptable exhaust temperature pattern, exhibit good stability, and be able to light off at cold plant conditions. The Multi-Annular Swirl Burner (MASB), was chosen as the candidate to meet these requirements.

The MASB as shown in Figure 3 is designed to operate in a staged combustion mode to inhibit the formation of NOx. The details of the NOx-inhibiting process were described in a previous paper (Garland and Pillsbury, 1990). Figure 4 shows the half-scale 14" MASB.

Test Facility

The topping combustor tests are being conducted at the University of Tennessee Space Institute (UTSI), Tullahoma, Tennessee in the DOE Coal, Oil, or Gas-Fired Flow Facility (CFFF). This facility was designed to accommodate a variety of coal-, oil-, or gas-fired energy conversion equipment.

UTSI modified the existing facility to accommodate the topping combustor and provided all necessary ancillary systems required to conduct the test and obtain data for evaluation. Modifications included the installation of the syngas fuel system with heater, which delivers fuel from tube trailers to the combustor at 1200°F, establishing required pressure, and perform fuel blending. The fuel gas is a six component mixture of N_2, H_2, CH_4, CO, H_2O and NH_3, that simulates the heating value and flammability limits of carbonizer gas.

Test Rig

The Westinghouse advanced combustor test rig was adapted for use at the UTSI test site. Figure 5 is a longitudinal view of the rig as configured for use in the topping combustor tests.

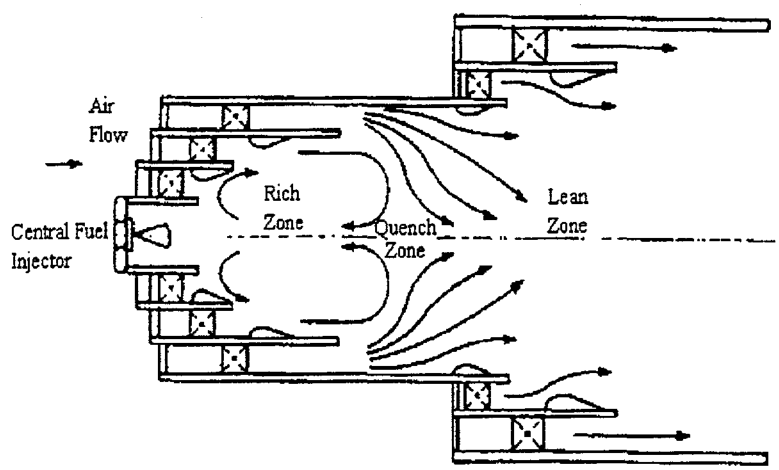


Figure 3. Conceptual Arrangement of the Multi-Annular Swirl Burner Based on J. M. Beér's Patent Design (1989)

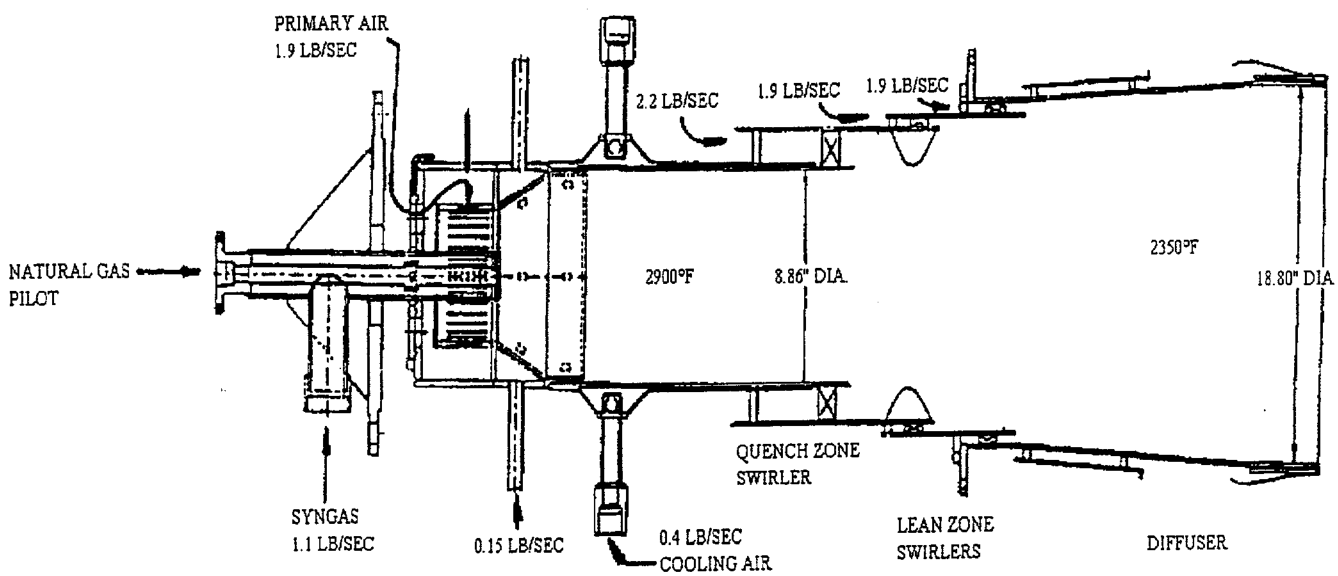


Figure 4. Recent 14" MASB Design

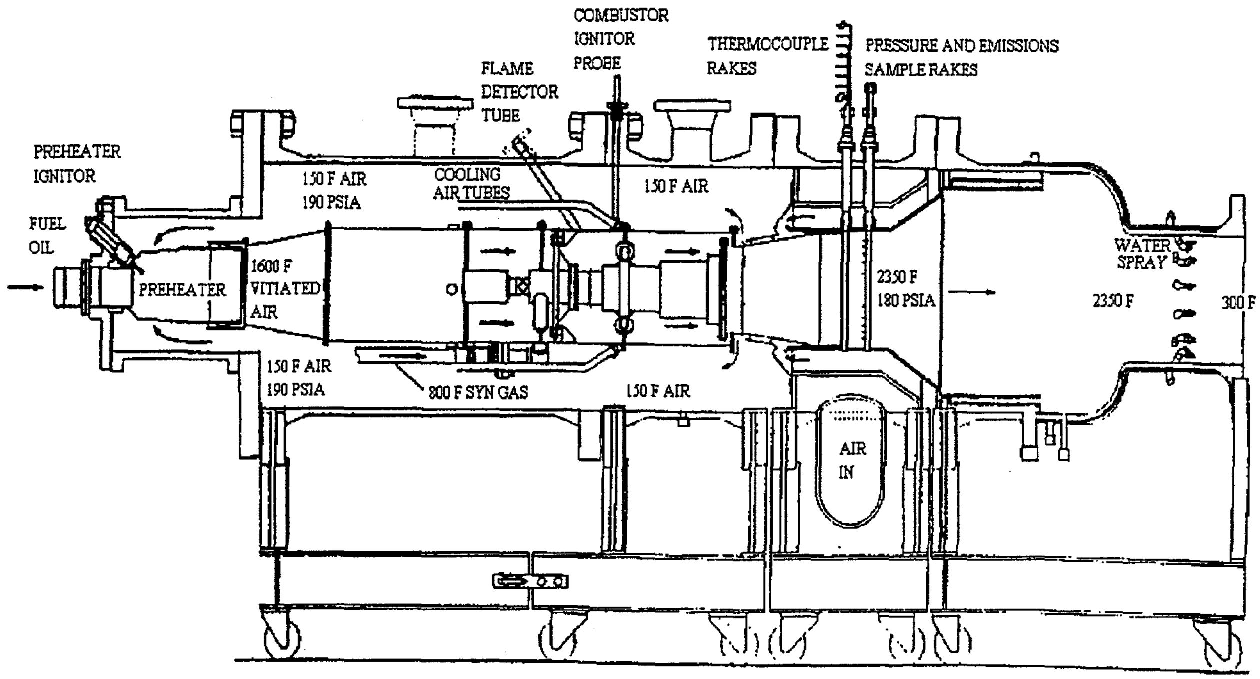


Figure 5. Topping Combustion and Test Rig Configuration

To simulate actual operating conditions, several modifications and auxiliary systems were required. These items provided: the supply of hot vitiated air; the supply of hot, synthesized fuel gas and/or natural gas and/or fuel oil; and, the ability to dope the fuel with ammonia when firing syngas. The ammonia allowed investigating the effects of fuel bound nitrogen on emissions.

The test facility at UTSI is capable of delivering 20 lb/s of air at 200 psia and 120°F. To raise this air to the required 1600°F temperature, a distillate oil-fired combustor, referred to as the preheater or the preburner, is placed upstream of the MASB. Directly heating the air through combustion partially depletes the oxygen in the air while adding carbon dioxide, water vapor and NOx. The vitiated air, still high in oxygen content, produced by the preheater simulates the PFB exhaust gases and makes the test conditions more realistic. The high oxygen content is important as it relates to obtaining high plant efficiency. (Garland and Robertson, 1988.)

Note on Figure 5 that the MASB is held within a series of flanged containment cylinders. In this way, the entering 120°F air comes forward to the preheater, where it burns the distillate oil, and is raised to 1600°F.

Instrumentation and Control

Approximately 200 temperature measurements, over 50 pressure measurements, and measurements relating to flow and emissions were taken during testing.

PROJECT DESCRIPTION

The MASB has the desired characteristics for a topping combustor for this application. Three syngas tests and one fuel oil/natural gas test were conducted in 1990-1991 with 12" and 14" diameter MASB's at UTSI. These tests have confirmed that the MASB can be successfully cooled with 1600°F vitiated air (supplemented with a small amount (5 to 10% of total air flow) of additional cooling air at the hottest locations). The 12" combustor demonstrated that good temperature patterns could be obtained at 2100°F firing temperature, and the 14" test showed that a uniform 2350°F combustor outlet temperature could be obtained without overheating the materials of construction.

Emissions from the 12" and 14" MASB tests have shown low CO, and no soot or unburned hydrocarbons have been detected. In a "conventional" oil or natural gas fired combustion turbine combustor, Westinghouse would predict that as much as 85% of the fuel-bound nitrogen would be selectively converted to NOx. The 1990-1991 tests with the 12" and 14" MASB's have shown 20% to 30% conversion of the NH_3 added to the syngas to simulate fuel bound nitrogen to NOx. This is obviously a significant improvement over conventional combustors, but further improvements on the NH_3 conversion appear possible.

Recent MASB Design Development

The MASB has been designed as a combustor specifically for low-Btu, coal-derived fuel gases containing significant fuel bound nitrogen, primarily in the form of NH_3. Standard Dry Low-NOx combustors have focused on minimization of thermal NOx generation. The MASB must minimize thermal NOx and also must convert NH_3 to molecular nitrogen.

The MASB approach is to:

- employ a high-residence-time, fuel-rich zone at an optimized temperature such that NH_3 is converted to N_2 rather than to NOx.
- establish strong swirl and strong recirculation in the rich zone for flame stabilization, and to ensure that the entire rich zone is used for this purpose.
- achieve a rapid quench to fuel lean conditions to minimize the formation of thermal NOx after the rich zone.

Westinghouse together with UTSI have completed significant computer models of the system, both with computational fluid dynamic (CFD) codes and with chemical kinetics codes. Output from this analysis has been factored into the latest designs of the MASB, particularly with respect to the primary (fuel-rich) zone. CFD modeling of the redesigned configuration shown in Figure 4 shows that this new design will have significant recirculation in the primary zone.

A half scale cold flow model with similar Reynolds number and velocity profiles as the hot 18" MASB was tested to verify the flow characteristics required and expected. Axial and radial velocity measurements were made across the diameter of the unit at each of seven axial positions.

Figure 6 is a map of the resulting axial velocities. A strong donut-shaped recirculation region was confirmed in the wake of the bluff body end of the fuel swirler. This extends about one third of the way down the rich zone cylinder. Additionally, there is an absolute boundary (location C to C2) between the rich and quench zones through which no reverse flow occurs, thereby guaranteeing the existence of fuel rich combustion. Swirl was very strong (100 to 200 ft/sec tangential velocity), especially near the wall, for good stabilization, and wall cooling.

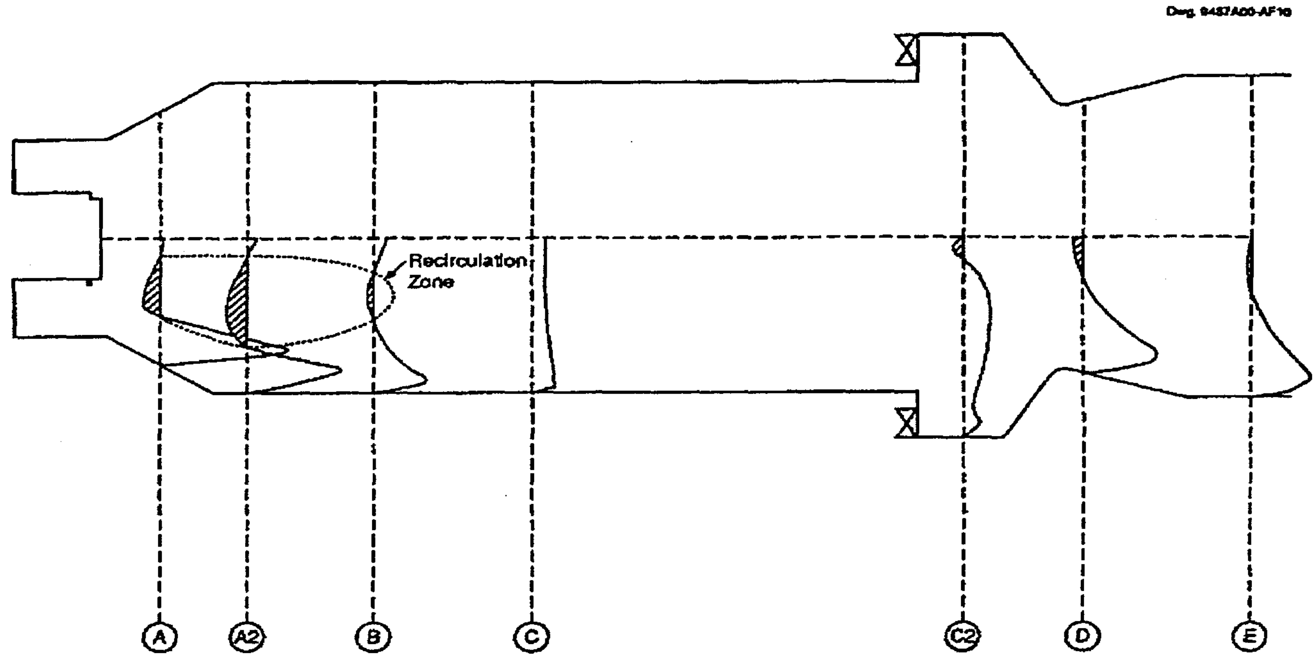


Figure 6. Cold Flow Model Axial Velocities

RESULTS

These results verified CFD modeling efforts and confirmed that no additional design changes were needed prior to full size MASB testing.

Westinghouse has performed chemical kinetic studies under conditions as close as possible to those planned for the next series of tests. Basically, the equivalent of 5 milliseconds of backmixing followed by 40 miliseconds of plug flow could yield NOx levels below 20 ppm when corrected to 15% O_2. The CFD model and the cold flow work indicate that significant recirculation (backmixing) should occur with the redesigned fuel-rich zone.

Recently, significant MASB design improvements have been made with the objective of improving the flame pattern in the combustor, and thereby achieving improved low NOx performance. The effectiveness of these improvements is to be demonstrated in a two stage test.

The first test was conducted in June 1993 with the 14" configuration shown in Figure 4. These tests confirmed that the redesigned fuel nozzle achieved the rich zone environment control, flame stability and oxidant distribution required. The redesigned rich zone also improved upon the fuel bound nitrogen to NOx conversion rates. Results of the tests showed a conversion rate of only 9% to 10% at the 0.27% ammonia levels, surpassing our goal of 10% to 12% conversion. The detailed results of these tests were reported in a previous paper (Domeracki et al. 1994).

In the next stage, a full-scale 18" MASB was tested. Lessons learned in the 14" MASB tests were incorporated into a full-scale 18" MASB. In addition, the 18" design will have a greater rich zone residence time for improvement of low-NOx performance, higher pressure drop downstream swirlers, and on-line oxidant flow control.

Full Scale 18" MASB Test Results

During the summer of 1994, the 18" MASB was successfully tested, meeting all of the following objectives:

1. Demonstrate successful scale up to full commercial size single basket design.
2. Optimize rich zone performance for lower (12% target) conversion of fuel nitrogen (as NH3) to NOx, by increasing residence time and tighter and control of equivalence ratio in the 1.2 to 1.4 range.
3. Demonstrate effectiveness and durability of mechanical design improvements, particularly as related to the quench flow deflector, swirlers, ignitor, and cooling designs.
4. Operate on-line adjustable control of the variable orifice mechanism for rich zone fuel/air ratio control.
5. Operate firing with syngas in vitiated air, and with natural gas in vitiated air.

Explore affects of variable operating parameters: fuel NH3 content, rich zone temperature, part load, vitiated air temperature, vitiated air oxygen level.

Remaining future test objectives include demonstration of operation firing natural gas in compressor (700ºF) air, and on-line fuel switching.

Natural gas firing in vitiated air was successfully demonstrated over a range of operating conditions. A stable flame was easily achieved, with no ignitor firing required. The burner proved mechanically durable, with no metal distress and wall (Haynes 230) temperatures maintained at less than 1500ºF at all conditions. Generally, the rich zone was operated at higher temperatures and lower equivalence ratio than planned, because of difficulties in operating the fuel/air ratio control mechanism (caused by pre-test preburner excessive discharge temperature). MASB exhaust temperature rakes revealed the flame to be somewhat stretched out.

The emission results in terms of NOx and CO are summarized in Table 1. Note that the burner functions as a very low NOx combustor for natural gas when the rich zone is operated rich, and then NOx results are not excessive even when operated lean. The MASB completely burns out CO in vitiated air at the levels expected in actual PFBC plant operation.

Table 1. Natural Gas Test Results - Emissions

Conditions:

- Vitiated air oxygen level: 12 to 18 vol% (dry)
- Vitiated air temperature: 1575 to 1700°F
- Background NOx in vitiated air: 26 to 200 ppm (dry, unnormalized)
- Pressure: 7.3 and 10 atm
- Calculated rich zone temperature: 2300 to 3460°F

Nox (dry, normalized to 15% O2):

7.3 atm results (rich zone equivalence ratio 1.05 to 1.3)

- 2 ppm MASB-generated NOx @ 12.2 vol% 02 in vitiated air
- 5 to15 ppm MASB-generated Nox @ 14.7 vol% 02 in vitiated air
- 50 to 75% reduction compared to earlier 14-inch MASB testing

10 atm results (rich zone equivalence ratio 0.85 to 1.05)

- 46 to 74 ppm MASB-generated NOx

CO (dry)

- 0 to 20 ppm exit CO when vitiated air CO < 100 ppm CO
- CO reduced by 50 to 75% when vitiated air CO > 150 ppm

Following natural gas testing, the two identified issues were solved by minor hardware modifications. 1) The fuel/air ratio control mechanism was rebuilt with more forgiving tolerances to differential thermal expansion. 2) Several backwall holes were drilled to admit a fraction of the primary air without swirl, thereby reducing flame stretch.

Note that rich zone temperatures are calculated using flow distributions and assuming uniformity without backflow from subsequent zones, and so are approximations ONLY.

Syngas testing was then successfully executed. Again a stable flame was easily achieved and controlled, without the need for ignitor firing. Apart from one thin weld crack, without test performance consequence, there was no burner damage. The fuel/air ratio control functioned properly. Rich zone equivalence ratio was controlled in the proper range. There was no flame stretch apparent.

Emissions results for the syngas tests are shown in Table 2. The MASB has now been demonstrated to generate negligible NOx additional to the PFBC background levels. This is a result of engineering the rich zone to achieve needed residence time and good recirculation. Figure 7 shows theoretical curves of NOx generation, as well as data for the 14" MASB and the current 18" MASB. Note in Figure 7 and in Table 2 that "MASB-generated NOx" is defined as the difference between the measured exit NOx, and the expected NOx exit level if 100% of the vitiated air NOx survived and no additional NOx were generated. The theoretical curves in Figure 7 were calculated using the Chemkin model with a Westinghouse data base, with the "no recirculation" line being plug flow, and the "good recirculation" line being 5 msec well mixed plus balance of residence time plug flow. (There is scatter because of the wide range of other variables in the actual testing.) The progress made is clear.

Table 2. Syngas Test Results - Emissions

Conditions:

- Vitiated air oxygen level: 10 to 17 vol% (dry)
- Vitiated air temperature: 1400 to 1630°F
- Background NOx in vitiated air: 20 to 130 ppm (dry, unnormalized)
- Pressure: 7.3 atm
- NH3 in syngas: 0 to 0.41 vol% 0.17 for most set points
- Calculated rich zone temperature: 2650 to 3160°F
- Calculated rich zone equivalence ratio: 0.9 to 1.5, 1.2 to 1.4 for most set points

Nox (dry, normalized to 15% O2):

- 8.3 ppm MASB-generated Nox, averaged over entire test matrix
- 5.8% conversion of NH3 to Nox, averaged over entire test matrix
- Insensitive to NH3 leve
- Low sensitivity torich zone equivalence ratio or temperature
- 50% reduction from 14" MASB results

CO (dry)

- CO reduced by 50% (Vitiated air CO always > 150 ppm)

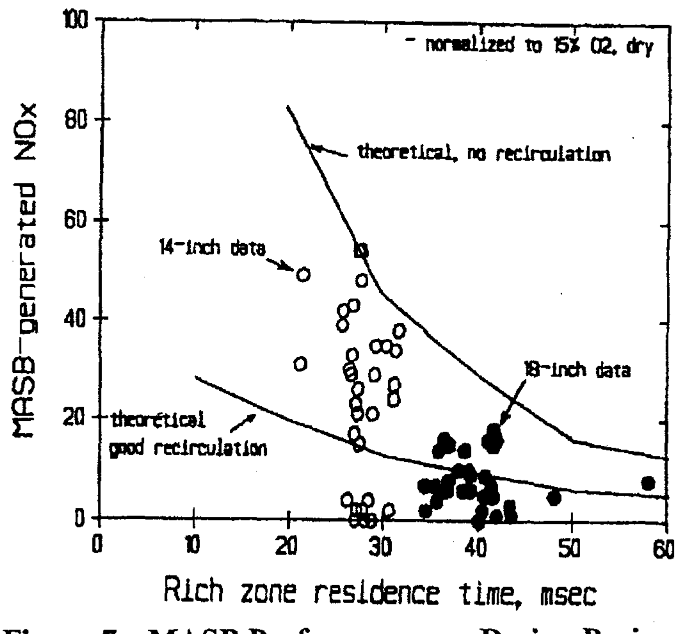


Figure 7. MASB Performance vs. Design Basis

FUTURE WORK

The MASB design described in this paper will be used at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama which is a DOE/Industry cost-shared facility operated by Southern Company Services.

This facility is designed to provide long-term hot gas cleanup and process testing for an advanced design Pressurized Fluidized Bed Combustion (PFBC) and Gasification system. It incorporates carbonization with a circulating fluidized bed and topping combustion developed at Foster Wheeler. The nominal 7-MW plant is being designed by Foster Wheeler and is scheduled to be in operation in 1996.

Figure 8 shows the topping combustor assembly for the PSDF. Each of the carbon steel spools is a pressure vessel. A concentric stainless steel cylinder inside each piece serves as the high temperature boundary. A layer of insulation fills the void between the concentric cylinders. The exhaust diffuser is a double-wall steel piece designed to accommodate cooling water for this region of the MASB. The inner liner of this piece is a Hastelloy alloy. The topping combustor itself is an Inconel or Hastelloy-type alloy with a diameter of about 18 in., which is commercial scale. Multiple combustors will be used in a utility-size plant incorporating Westinghouse 501 or 251 combustion turbines.

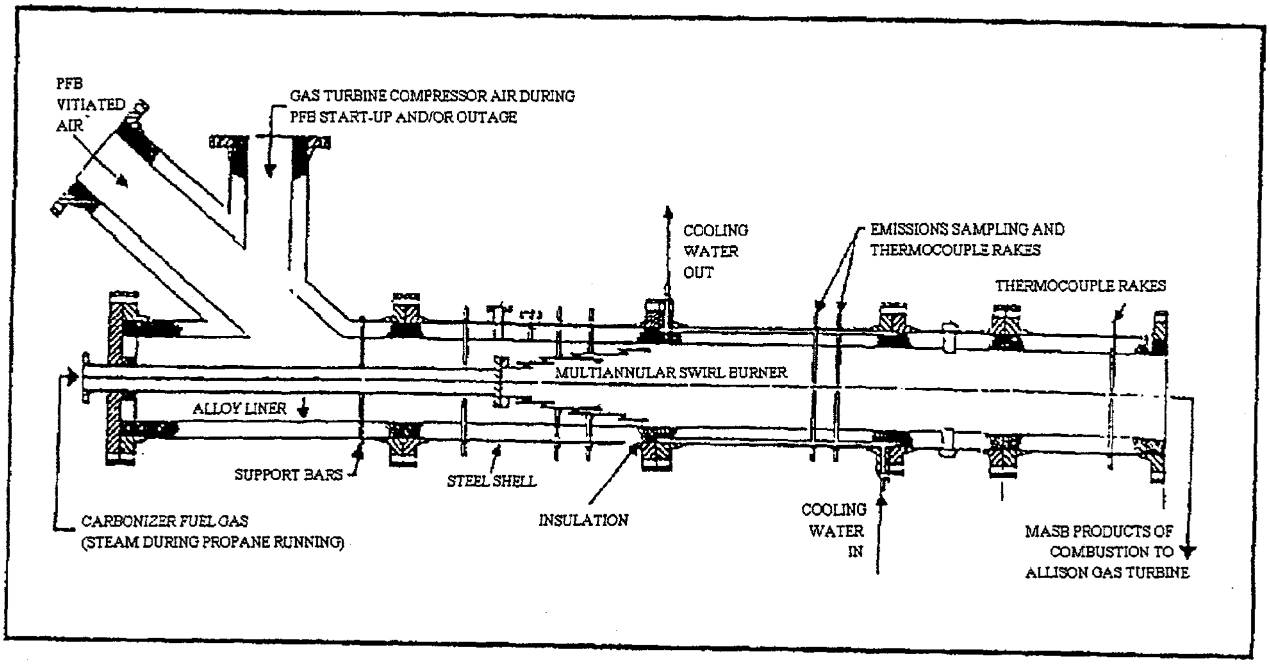


Figure 8. Topping Combustion Assembly

About 76,000 lb/h vitiated air enters the combustor at 1.03 MPa-a/760°C (150 psia/ 1400°F). About 1.46 kg/s (11,600 lb/h) carbonizer fuel gas, at about 1650°F, is burned in the MASB, producing an exhaust gas temperature of 2350°F--the optimum firing temperature for a utility-size plant. In a commercial plant, the 2350°F gas from the MASB is fed at full temperature to the gas turbine expander. For Wilsonville, the gas will be cooled to about

1975°F with compressor bypass air since the combustion turbine is limited to this temperature level. This advanced CPFBC facility at Wilsonville Alabama was described in detail by J. D. McClung et al. 1994.

In addition to the Wilsonville facility mentioned above, the MASB configuration will be applied at Air Products and Chemicals Four Rivers Energy Modernization Project (FREMP). This application will be the first commercial power plant using second generation pressurized fluidized bed (CPFBC) combustion technology. Air Products has been selected in the DOE Clean Coal Technology Round V to build, own and operate this combined cycle facility which will produce 66 MWe, export up to 400,000 lb/hr of steam, and be located at their chemical manufacturing facility in Calvert City, KY. The gas turbine will be a Westinghouse model 251B12 that will be modified to accommodate full air extraction and an external topping combustor with a cluster of MASB's as shown in Figure 2. This project was described in detail by J. J. Lewnard et al 1993.

REFERENCES

Robertson, A., Garland, R., Newby, R., Patel, J., and Rubow, L., 1988, "Second-Generation PFB Combustion Plant Performance and Economics," EPRI Seminar on Fluidized Bed Combustion Technology for Utility Applications.

Garland, R., Pillsbury, P., 1990, "Status of Topping Combustor Development for Second Generation Fluidized Bed Combined Cycles," ASME paper 90-GT-30.

Domeracki, W. F., Dowdy, T. E., Bachovchin, D. M., 1994, "Topping Combustor Development for Second-Generation Pressurized Fluidized Bed Combined Cycles", Proceedings of the ASME, IGTI 1994 Gas Turbine Conference.

McClung, J. D., Quandt, M. T., Frochlich, R. D., 1994, "The Advanced CPFBC Facility at Wilsonville, AL, USA". Proceedings of the First International Conference on Combined Cycle Power Generation, Calcutta, India, 1994.

Lewnard, J. J., et al., 1993, "Commercialization of Second Generation Pressurized Circulating Fluid Bed Combustion Process". Proceedings of the Power Gen Americas Conference, Dallas, TX, 1993.