Current Status of Development and Testing of a Novel Coal Preheating Technology for NO_x Reduction from Pulverized Coal-Fired Boilers

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ABSTRACT

The Gas Technology Institute (GTI) is developing the PC PREHEAT technology, a NO_x reduction process for pulverized coal-fired boilers, under a Cooperative Agreement with the U.S. DOE. Development targets include NO_x reduction below 0.15 lb/MMBtu and 55% cost reduction compared to SCR. GTI's proven METHANE de-NOX reburn technology is combined with a pulverized coal-preheating approach developed by the All-Russian Thermal Engineering Institute (VTI). GTI and VTI are joined in the project by Riley Power Inc. (RPI), a subsidiary of Babcock Power Inc. Results of PRB coal firing tests with a 3-million Btu/h PREHEAT burner prototype in RPI's Pilot Scale Combustion Facility (PSCF) in Worcester, MA demonstrated NO_x emissions below 100 vppm (dry basis, corrected to 3% O_2) at 2% stack O_2 and CO in the range of 35-112 vppm. Three additional U.S. coals will be tested. Pilot testing will be followed by design, construction, and testing of a 100-million Btu/h commercial prototype PC PREHEAT system.

INTRODUCTION

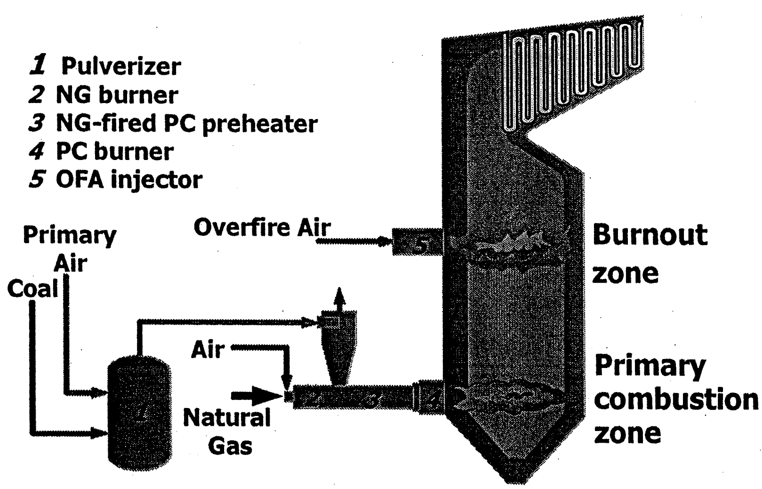
Over half of the electric power generated in the U.S. is produced by coal combustion, and more than 80% of these units utilize pulverized coal (PC) combustion technology. Conventional measures for NO_x reduction in PC combustion processes rely on combustion and post-combustion modifications. In general, combustion modification technologies try to reduce the formation of NO_x precursors while destroying already-formed NO_x. This approach usually involves combustion staging and slow mixing to redistribute combustion and create a fuel-rich environment. These measures reduce oxygen levels in the NO_x formation zone and burn the fuel at lower peak flame temperatures. A variety of NO_x reduction technologies are in use today, including Low-NO_x Burners (LNB's), flue gas recirculation (FGR), air staging, and natural gas or other fuel reburning. Selective Non-Catalytic Reduction (SNCR) and Selective Catalytic Reduction (SCR) are post-combustion techniques. NO_x reduction effectiveness from these technologies varies from 30 to 60% and up to 90-93% for SCR.

Typically, pre-NSPS wall-fired PC boilers produce NO_x emissions in the range of 0.7 - 1.3 lb/million Btu. Low-NO_x burner systems, using combinations of fuel staging within the burner and air staging by introduction of overfire air in the boiler, can drop the NO_x emissions by 50-60%. This approach alone is not sufficient to meet the desired 0.15 lb/million Btu NO_x standard with a range of coals and boiler loads. Furthermore, the heavy reliance on overfire air can lead to increased slagging and corrosion in the furnace, particularly with higher-sulfur coals, when LNB's are operated at substoichiometric conditions to reduce fuel-derived NO_x in the flame. Therefore, it is desirable to minimize the need for overfire air by maximizing NO_x reduction in the burner.

CONCEPT DESCRIPTION

The PC PREHEAT combustion system for conventional or low-NO_x PC burners uses gas-fired coal preheating to destroy NO_x precursors and prevent NO_x formation. In this process, a concentrated pulverized coal stream enters the PREHEAT chamber where flue gas from natural gas combustion is used to rapidly heat the coal up to about 1500°F prior to complete coal combustion in the PC burner. Secondary fuel consumption for preheating in commercial-scale burners is estimated to be 3 to 5% of the boiler heat input. This thermal pretreatment releases coal volatiles, including fuel-bound nitrogen compounds into an oxygen-deficient atmosphere that converts the coal-derived nitrogen compounds to molecular N_2 rather than NO. This allows the system to achieve very low NO_x levels–down to 0.15 lb/million Btu or below–without the need for post-combustion flue gas cleanup technology. A schematic of the PREHEAT combustion system is shown in Figure 1.

Figure 1: PC PREHEAT NO_x Reduction Concept for PC Boilers



The PC PREHEAT system will provide more flexibility in burner operation, particularly with LNB's, to achieve minimum NO_x production while maintaining acceptable carbon burnout. In an integrated system with overfire air, the fully staged combustion process lowers NO_x emissions in three ways:

- Natural gas-fired coal preheating releases and reduces NO_x precursors before they have a chance to react with oxygen to form NO or NO_2;
- NO_x formation is limited in the PC flame via combustion staging in the burner;
- NO_x formation in the coal combustion products in the furnace is reduced by use of low excess air, followed with overfire air to complete burnout at lower temperature [1, 2, 3].

VTI'S BENCH SCALE AND FIELD TEST RESULTS

Pulverized coal preheating has been investigated extensively by VTI with a variety of Russian utility coals.[4, 5, 6] Basic combustion research, lab-scale testing, and field-testing using the natural gas preheated PC burner were done at VTI in Moscow beginning in 1980. Five Russian coals were investigated with preheat temperatures up to 1508°F. Following promising laboratory studies, coal preheating for fuel NO_x reduction was scaled up and field-tested in a number of facilities:

- 1982-83: A single burner tested at a 3.8-million Btu/h (1.12 MW_{th}) demonstration facility achieved NO_x reduction of 60 % with improved flame stability and carbon burnout.
- 1983-84: A single 205-million Btu/h (60 MW_{th}) prototype burner was installed and tested through 1991at a 300-MW double boiler. NO_x reduction was limited to 42% due to a pulsation problem with the microflame burners used.
- 1994: All 12 burners of an opposed-fired furnace were installed with preheating at a 420 t/h wet-bottom furnace. NO_x reduction of 67% was achieved with natural gas usage of only 2.5-3.0% of the total heat release.

As a result of this work, GTI entered into an agreement with VTI to cooperate in further evaluation, development, demonstration and commercialization of the PC PREHEAT system for all types of coal.

DEVELOPMENT OF PC PREHEAT TECHNOLOGY FOR U.S. COALS

In a development project sponsored by the U.S. DOE's National Energy Technology Laboratory (NETL), GRI, and GTI's Sustaining Membership Program (SMP), the PC PREHEAT concept is being developed and tested for commercial application with U.S. utility coals and PC firing methods. GTI has teamed with VTI and Riley Power Inc. (RPI) for the project.

The overall objective of the project is the development and validation of the PC PREHEAT concept to reduce NO_x emissions to 0.15 lb/million Btu or less on U.S. utility PC boilers. This NO_x reduction should be achieved without loss of boiler efficiency or operating stability, and at more than 25% lower levelized cost than state-of-the-art SCR technology. A further objective is to make the technology ready for full-scale commercial deployment in order to meet market demand for NO_x reduction technologies resulting from the EPA's NO_x SIP call.

Initial project efforts focused on comparison of Russian and U.S. utility coal properties and PC firing practices in order to evaluate the potential for, and guide the development of, applications of the PC PREHEAT technology in the U.S utility market. Based on the results of these studies, a 3-million Btu/h pilot-scale PC PREHEAT system was designed, fabricated and installed at RPI's Pilot-Scale Combustion Facility (PSCF) in Worcester, MA. [6] Computational Fluid

Dynamics (CFD) modeling was used extensively in the pilot system design for both the gas combustor and PC burner. Pilot testing will be conducted with up to four U.S. coals and data from this testing will be used to validate the initial PREHEAT system model. Pilot testing will be followed by design, construction and testing of a 100-million Btu/h commercial prototype PC PREHEAT system in RPI's 29 MW_{th} Coal Burner Test Facility (CBTF). A CFD model of the CBTF furnace will be developed and validated during the commercial prototype testing. The pilot-validated PREHEAT system model will be used to guide the scaleup of the system. When validated through CBTF testing, the combined PREHEAT and furnace models will form a valuable design tool for future commercial installations.

Pilot Test Unit Installation at RPI

Fabrication, installation and initial testing of the pilot-scale PC PREHEAT system equipment were completed in the fall of 2001. Key components of the PCP unit are illustrated in Figures 2 through 4.

Figure 2. PC Feeder above PREHEAT combustion chamber

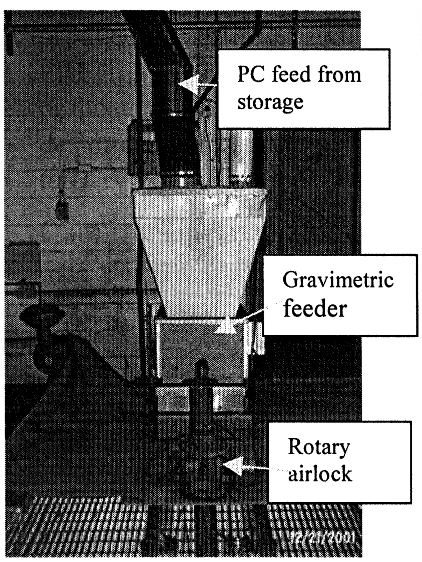


Figure 3. Gas-fired PREHEAT combustion chamber

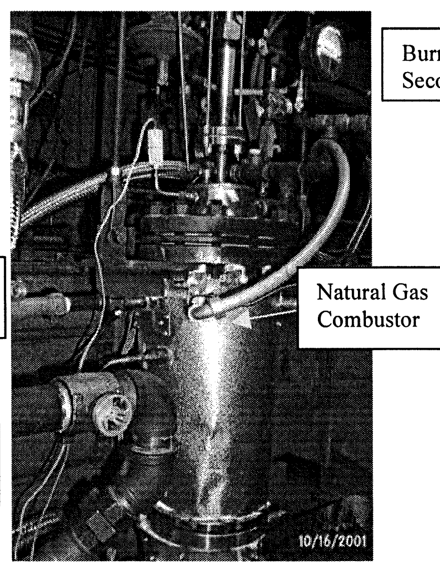
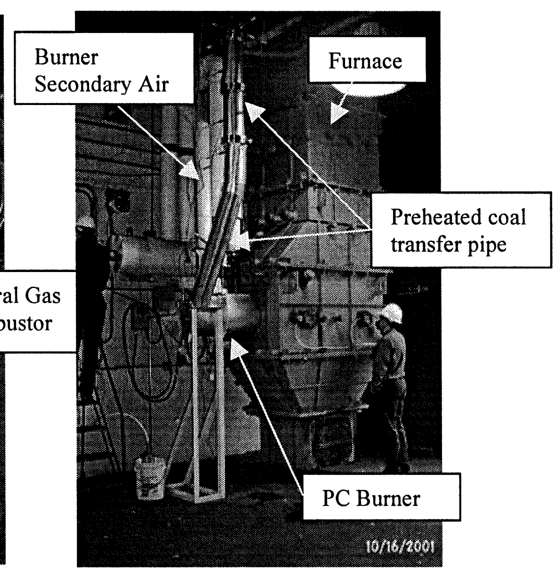


Figure 4. 3-million Btu/h PC burner and test furnace



Briefly, the PC PREHEAT pilot system regulates pulverized coal flow with a gravimetric feeder, which drops the coal through a rotary airlock into the natural gas-fired PREHEAT combustor. The combustor produces hot combustion gases, which combine with the pulverized coal to produce a mixture of coal char and pyrolysis products at the desired test temperature. Two PREHEAT pipe sections after the combustor provide additional residence time for the coal at the preheated conditions. The hot char and pyrolysis products then enter the PC burner, which is designed for operation over a broad range of flow distributions between primary, secondary and tertiary burner combustion air streams.

During testing, real time operating data are collected at 1-second intervals and recorded by the personal computer-based data acquisition system (DAS). The concentrations of CO, CO_2, O_2, THC and NO/NO_x in the PC PREHEAT unit exhaust and the furnace exit are continuously monitored by on-line gas analyzers, including a Rosemount Analytical Model 880A infrared CO analyzer, a Rosemount Analytical Model 880A infrared CO_2 analyzer, a Rosemount Model 400 flame ionization total hydrocarbons (THC) analyzer, a Rosemount Analytical Model 755R paramagnetic O_2 analyzer, and a ThermoElectron Model 14A chemiluminescence NO_x analyzer.

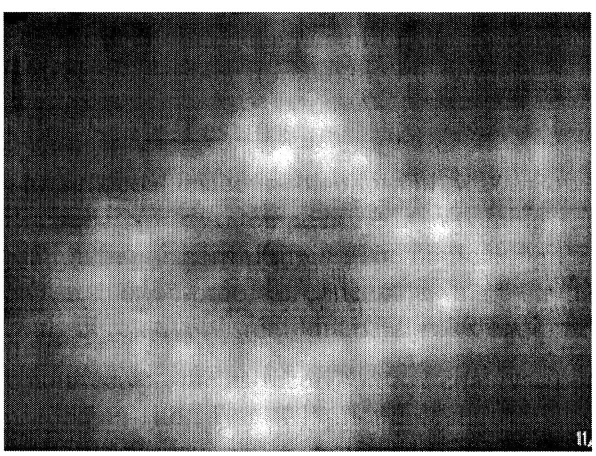
The PREHEAT gas combustor wall temperature is monitored by thermocouples installed on both the outer walls and inside of the combustion chamber. Temperature of the gas/air mixture is monitored in the gas/air plenum entering the combustor nozzles. Temperature are monitored downstream of the combustor by thermocouples installed in the PREHEAT pipe sections between the combustor and the PC burner.

Pilot-Scale Testing

The first coal tested in the pilot unit was a Powder River Basin (PRB) coal out of the Rochelle/North Antelope mine in Wyoming. This coal was obtained from the Hennepin Power Station in northern Illinois. The non-caking PRB coal was selected for initial testing to facilitate NO_x reduction proof-of-concept testing by avoiding plugging anticipated when firing caking coals in relatively small diameter pilot equipment with high heat losses.

Upon receipt, the as-received PRB coal was placed in a 20-ton storage silo and pulverized as needed on-site. The PCP pilot unit start-up procedure requires heat up of the test furnace and PC PREHEAT system prior to introduction of coal. Heat from natural gas combustion in the gas combustor raises temperatures in the PREHEAT sections while furnace components are heated via insertion of a 1-million Btu/h gas-fired igniter placed in the test furnace chamber. Initial tests of the PCP pilot unit demonstrated stable PC flow rates up to 250 lb/hr. At PC flow rates above 150 lb/hr, the furnace gas igniter is shut down and retracted from the chamber leaving only the coal flame. A picture of the coal flame (with furnace igniter retracted) produced from the original pilot PC Burner design is shown in Figure 5.

Figure 5. Short, intense flame produced by the original pilot PC burner design



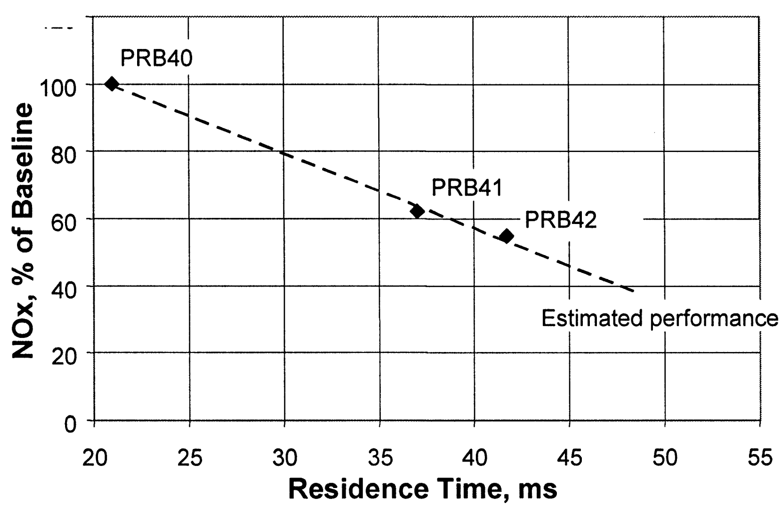
The initial test objective was to confirm the NO_x reduction effectiveness of the PC PREHEAT system as implemented in the pilot unit. With a high-volatile coal such as PRB, VTI experience indicated that a preheat temperature of 1300 °F would be required. Early pilot tests were unable to achieve this preheat temperature, however. High-pressure drops were observed in the gas combustor air and natural gas piping, causing a reduction in flow capacity. This problem was fixed by changing the piping on both the air and gas supply systems. This allowed the pilot-scale system to achieve preheat temperatures in the range of 1100° to 1400 °F in accordance with VTI guidelines.

Extensive testing was conducted with the original PC PREHEAT pilot system. During the initial testing period, approximately 5,000 pounds of the PRB coal was processed. Test data covering over 50 different operating periods were collected for analysis. After initial problems with providing stable coal feed to the PREHEAT gas combustor were resolved, the pilot unit operated well. In addition to GTI and RPI personnel, two staff members from VTI traveled from Moscow and actively participated in testing from end of November through mid December 2001.

Analysis of the initial test data confirmed that the PC PREHEAT system has a significant effect on final NO_x formation in the coal burner and that the mechanism by which this is effected is not directly controlled by the final equilibrium preheat temperature, but rather by the residence time of the coal in the high temperature region within the gas-fired PREHEAT combustor. Modifications to the pilot system gas-fired combustor were determined to be necessary in order to test the full potential of the process for NO_x reduction.

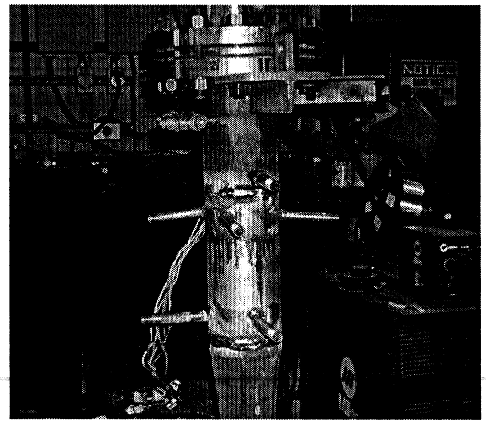
Pilot results from three test runs with PRB coal are given in Figure 6. Operating parameters for these three tests such as furnace exit oxygen, coal flow, combustor firing rate, combustor stoichiometry and preheat exit temperature were very similar. The main difference between these tests was the small amount of conveying gas flow used to transport coal to the PREHEAT combustor, which, at constant gas combustor firing conditions, can be varied to control the residence time of the coal in the high temperature portion of the gas combustor. In the plot shown below, the PRB40 transport gas flow was roughly double that of tests PRB41 and PRB42, which had significantly higher NO_x reduction due to increased residence time of coal in the high temperature zone of the gas combustor.

Figure 6. NO_x Reduction VS. Coal Residence Time in Combustor



A second significant determination from this initial testing was that the PC burner design utilized was not optimally constructed for low-NO_x combustion of the preheated char and pyrolysis products generated in the PREHEAT combustor. The burner produced a short, hot, intense flame (Figure 5) rather than the longer, cooler staged-combustion flame necessary to achieve low NO_x emissions. It was determined that to function properly with preheated coal, the burner design must consider the high proportion of gaseous fuel components present and the fact that the char is already heated to about 1200°F before entering the burner, requiring a more distributed flame with internal staging as in, for example, GTI's gas-fired forced internal recirculation (FIR) low-NO_x burner designs.

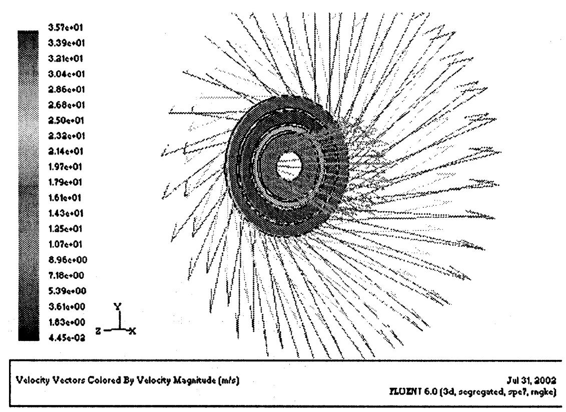
Figure 7. Modified gas-fired combustor for pilot-scale testing



A CFD modeling study for a modified PC PREHEAT gas combustor was completed using flow conditions from the pilot-scale tests with a computational mesh generated for the modified combustor. Completed modifications to the pilot-scale combustor are shown in Figure 7. In the new gas combustor, the average residence time of coal particles in the high temperature chamber is approximately double that of the original design.

CFD modeling was also used to develop a modified PC burner around design concepts normally employed in GTI's natural gas-fired low-NO_x burners. Computational meshes were developed for both the original and modified burner designs in order to compare their flame characteristics and optimize the modified design for preheated coal. Modeling of velocity vectors in the original PC burner design is presented in Figure 8, which shows the original three tangential air inlets with swirl. The predicted flame shape agrees very well with that observed with the original burner (Figure 5). The flame is very short, with a very limited fuel-rich zone indicative of a poorly staged flame.

Figure 8. Velocity vectors for the original PC burner design



Figures 9 and 10 compare the reducing regions produced in the original and modified pilot PC burners, respectively. In the modified burner, a much longer "reducing zone" is produced, allowing NO_x precursors to be destroyed and more heat to be removed from the flame before final burnout. This comparison indicates that the modified burner design approach is much more suitable for the highly reactive preheated fuel produced by the PC PREHEAT process. Another comparison of the original and modified burner design is shown in Figures 11 and 12, which look at fuel particle path lines from the burner in the pilot furnace. Again, a short, intense mixing region is shown immediately in front of the burner with the original design and very little recirculation of particles predicted in the upper and lower furnace. Figure 10, however, shows a significantly longer mixing profile with much more recirculation of particles in both the lower and upper furnace. The result is a longer, more staged flame and a significantly more reducing atmosphere in the lower furnace, both of which contribute to much lower NO_x production.

Figure 9. Vertical cross section of volatile matter in the original PC burner flame

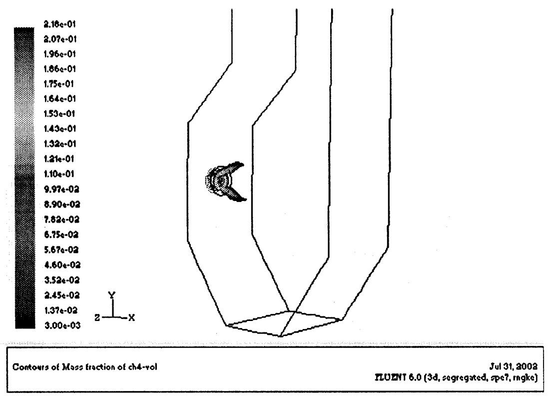


Figure 10. Vertical cross-section of volatile matter in the modified PC burner flame, indicating increased flame length

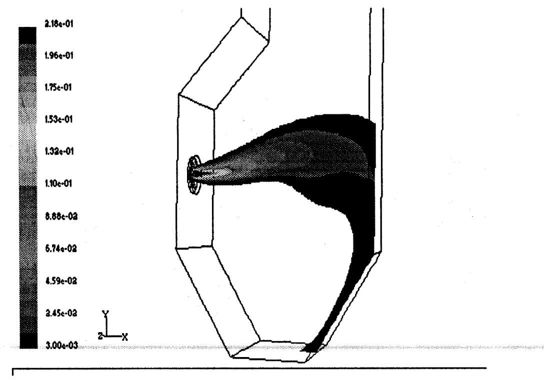


Figure 11. Fuel particle path lines with the original PC burner design

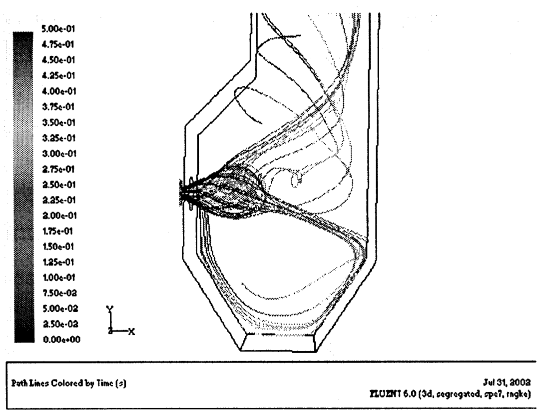
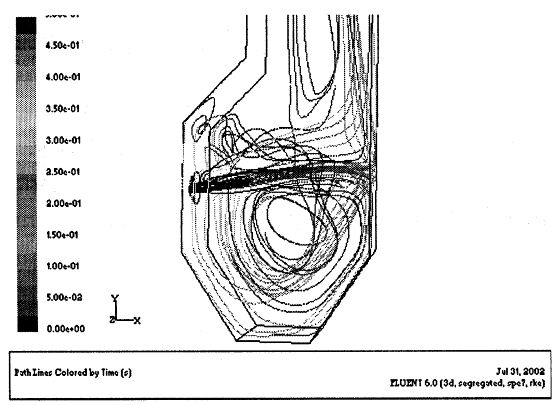


Figure 12. Fuel particle path lines with the modified PC burner design



The pilot test system was reactivated with the modified PREHEAT gas combustor and a series of shakedown tests was completed for gas-only operation. A series of twelve PRB coal-fired tests were then completed using the modified gas combustor and the original PC Burner design. Significant improvement in the previously attained NO_x emissions was achieved with the modified gas combustor. NO_x at the furnace exit was reduced to as low as 150 ppm with only 36 ppm CO (all gas data is reported on a dry basis, corrected to 3% O_2).
Observation of the PC burner flame during these tests confirmed that modification of the coal burner was still necessary to achieve the full NO_x reduction potential of the PC PREHEAT approach. For this reason, redesign of the PC burner was continued in collaboration with RPI design engineers. The design approach considered both NO_x performance and fabrication cost and complexity. Two modified PC burner designs were developed using different approaches for burner air distribution-air channels and air nozzles. The modified PC burners also incorporated a new coal injector design. This design was based on RPI's Combustion Controlled

Venturi (CCV™) burner coal nozzle technology[7]. The modified PC burner included a low swirl coal spreader and a flame stabilizer ring. These design modifications together with changes to the secondary and tertiary air channel design helped to produce an attached fuel-rich flame core. Fabrication and testing of the air channel version of the modified PC burner was then completed and a total of 38 firing tests were conducted with the modified system using PRB coal.

During these tests, NO_x reduction was improved to levels below 100 vppm at 2% stack O_2 and CO ranging from 35-112 vppm without any furnace air staging. The coal flame from the modified PC burner was observed to be extremely stable and uniform and filled the combustion chamber. Figure 13 shows another view toward the burner along the centerline of the flame before the burner modifications. Figure 14 shows the same view with the modified PC burner. Figure 15 shows a side view of the modified burner flame. As predicted in the modeling studies reported earlier, the longer, less intense flame produced by the modified burner significantly reduced NO_x production.

Figure 13. Intense, high NO_x flame before burner modification, rear furnace window view

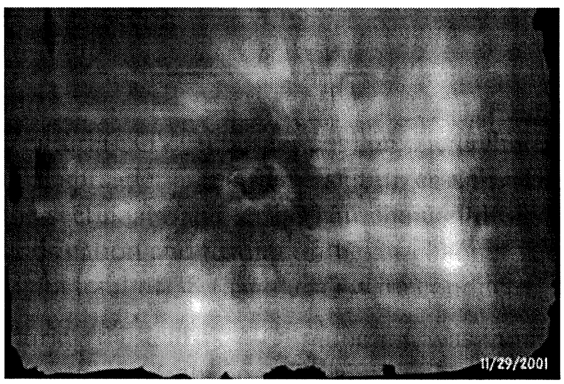


Figure 14. More uniform, low-NO_x flame with modified burner, rear furnace window view

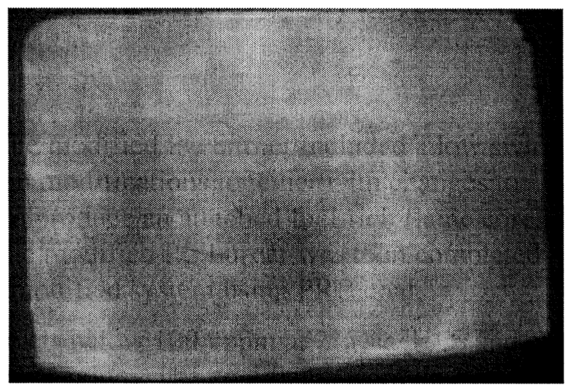
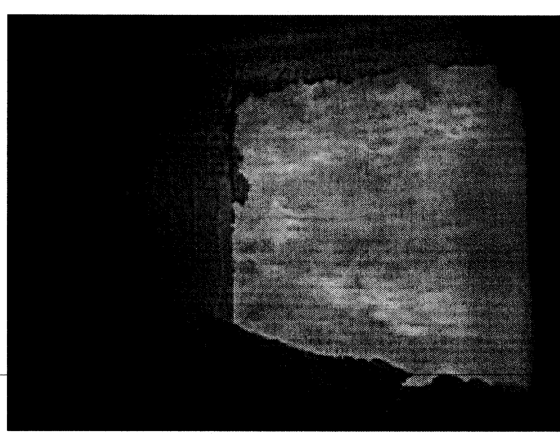


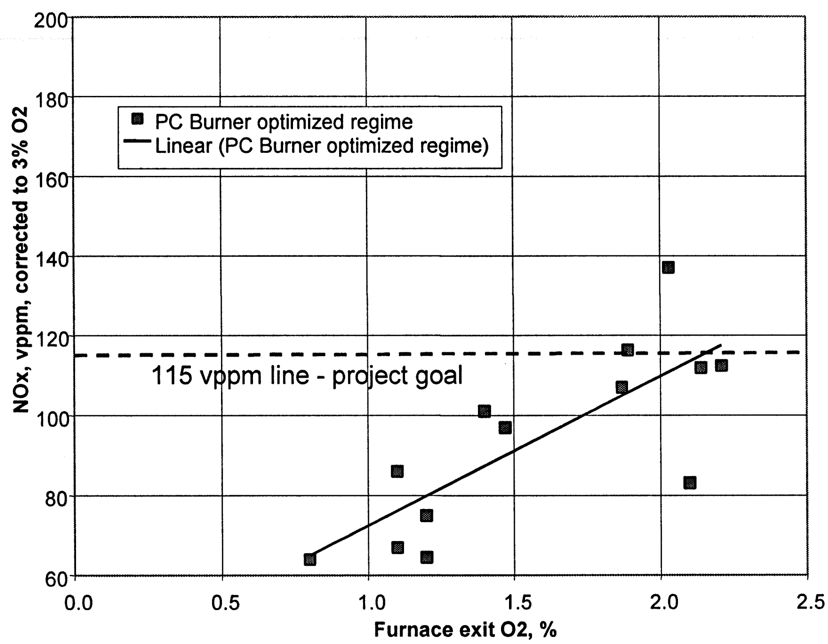
Figure 15. Modified burner, flame roots are more uniform



The balance of the original inventory of PRB coal was consumed during the first nine tests, and it was therefore decided to conduct several tests with bituminous Central Appalachian coal to evaluate operation of the PC PREHEAT system with caking coal. As anticipated, operation of the pilot unit with caking bituminous coal resulted in incidences of plugging in the system, the severity of which depended on the gas combustor operating conditions. Sufficient testing was completed to allow preliminary analysis of the plug formation and operating parameters used, which indicated several approaches to eliminate plugging in future tests, including further changes to the PREHEAT chamber geometry and operating conditions.

It was decided to complete parametric testing of both of the modified burner designs with PRB coal prior to any additional tests with bituminous coals. Accordingly, additional PRB coal was obtained and PRB testing continued in order to fully characterize the PC PREHEAT system operation with respect to the gas combustor and PC burner operating variables. Testing included varying air to the gas combustor, varying the gas combustor firing rate and varying air distribution to the PC burner. Test results presented in Figure 16 show NO_x emissions versus furnace-exit O_2 for optimized air channel burner operating conditions relative to the project goal of 0.15 lb NO_x per MMBtu. This data will be used in development of the design for a 100 MM Btu/h prototype PC PREHEAT burner for testing in the next phase of the project.

Figure 16. Optimized PC burner operation during Oct- Dec. 2002 testing.



PRB testing has now been completed with the air channel version of the modified PC burner. Final testing included evaluating the effects of reducing natural gas usage in the gas combustor to the range of 8-10 % of the total thermal input to the system. In prior testing, gas usage ranged from 12-15 %. Gas usage in a commercial-scale system is expected to be on the order of 3-5%. The pilot unit includes a relatively long transfer pipe between the gas combustor and PC burner in order to be able to vary the residence time of preheated coal and pyrolysis products at the equilibrium preheat temperature before they enter the burner. The larger surface to volume ratio of the pilot-scale equipment also contributes to higher heat losses. The best results achieved at the reduced gas usage were a NO_x level of 116 ppm or 0.15 lb NO_x/MMBtu with furnace exit O_2 at 1.9 % and CO at about 106 ppm.

A second "hybrid" version of the PC burner design has been developed using air nozzles rather than air channels. This design more closely resembles GTI's gas-fired low NO_x burner designs. Testing of this burner is currently underway and is expected to provide further insight on which burner design approach results in the best performance with the hot mixture of solid and gaseous fuels produced by the PREHEAT combustor. Performance of both burners will be compared with respect to flame stability, turndown, NO_x reduction, burnout, and gas usage requirements in the combustor. One of the two burner designs will then be selected for further development and testing with caking coals. Planning is currently underway for scale-up of the PREHEAT system design to a 100-million Btu/h commercial prototype PC PREHEAT system for testing in RPI's 29 MW_{th} Coal Burner Test Facility (CBTF).

SUMMARY

GTI, VTI and RPI are cooperating in a project to develop and validate a new pulverized coal combustion system to reduce utility PC boiler NO_x emissions to 0.15 lb per million Btu or less without post-combustion flue gas cleaning. Work has been completed on the design, installation, shakedown and initial PRB coal testing of a 3-million Btu/h pilot system at RPI's Pilot-Scale Combustion Facility (PSCF) in Worcester, MA. Based on these results, necessary modifications to the gas-fired PREHEAT combustor and PC burner were defined and CFD modeling was used to develop and verify revised design approaches for both the PREHEAT gas combustor and PC burner.

A series of successful tests of the new combustor with PRB coal using the original PC burner were completed. NO_x at the furnace exit was reduced significantly with the modified gas combustor, to as low as 150 ppm with only 36 ppm CO. Concurrent with testing, GTI and RPI collaborated on development of two modified designs for the PC burner optimized to fire preheated char and pyrolysis products from the Preheat gas combustor.

The air channel version of the modified PC burner design was fabricated and installed in the pilot test facility. Testing of the modified pilot system (modified gas combustor and modified PC burner) included 38 tests with PRB coal. NO_x reduction was further improved to levels below 100 ppmv with CO in the range of 35-112 ppmv without any furnace air staging. Gas usage in the pilot system has been reduced to about 8-10 % of total thermal input to the PC burner. Gas usage for commercial-scale systems is expected to be in the range of 3-5 % of thermal input as elimination of preheated coal transfer pipe and the smaller surface to volume ratios of the larger-scale equipment will significantly reduce heat losses.

A second version of the PC burner employing air nozzles in place of channels has been fabricated and installed in the pilot unit and is currently undergoing testing. Based on this testing, the preferred PC burner design will be selected and tested with caking bituminous coals. Pilot testing will be followed by design, construction and testing of a 100-million Btu/h commercial prototype PC PREHEAT system in RPI's 29 MW_{th} Coal Burner Test Facility (CBTF).

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