DEVELOPMENT OF AN ACOUSTICALLY ENHANCED CYCLONE COLLECTOR FOR PFBC

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ABSTRACT

Acoustically enhanced cyclone collectors offer the potential of achieving environmental particulate control standards under pressurized fluidized bed combustion (PFBC) conditions without the need for post turbine particulate control. The objective of this research program is to extend acoustic agglomeration technology from the laboratory scale up to the sub-pilot scale. The effects of high intensity sound on the agglomeration of fly ash particles are being investigated in a simulated PFBC effluent stream. The test facility consists of a variable residence time acoustic agglomeration chamber with a vitiating air preheat combustor, an ash injection system utilizing an auger feeder, a natural gas fired pulse combustor sound source, and a two-stage high temperature, high pressure cyclone. Fly ash for these tests has been obtained from the TVA (Tennessee Valley Authority) Shawnee Station circulating fluidized bed combustor (CFBC), as well as the Nucla CFBC, and Tidd PFBC. Acoustic agglomeration tests are underway.

The acoustically enhanced cyclone collector is being evaluated with two distinct goals in mind: 1) determine the effects of the major operating parameters on acoustic agglomeration efficiency, and 2) optimize the agglomeration system performance for maximum particulate removal efficiency. The data obtained during these tests will provide direct information on the effects of sound intensity and frequency, particle residence time, ash loading, and pressure on the enhancement of cyclone collection efficiency with acoustic agglomeration. These data, in conjunction with results from an acoustic agglomeration computer model will be used to evaluate the economic and engineering feasibility of an acoustically enhanced cyclone collector for a full scale pressurized fluidized bed combustor.

OBJECTIVES

The overall program objective is to demonstrate, on the sub-pilot-scale, the effectiveness of an acoustically enhanced cyclone collector under high temperature, high pressure conditions found in coal-fired pressurized fluidized bed combustion combined cycle power generating systems. The data obtained will be used to design an acoustically enhanced cyclone gas cleanup system which can meet the New Source Performance Standards (NSPS) particulate control level with capital and operating costs significantly lower than currently available with conventional cyclones and post turbine particulate control.

BACKGROUND

In coal-fired PFBC combined-cycle power generation systems, gas turbines are used to recover energy from the high temperature gases exiting the PFBC. Before the gases enter the turbine, most of the fly ash from the coal must be removed by a hot gas cleanup device in order to protect the turbine components from erosion, corrosion, and deposition of the ash. Conventional, high efficiency cyclone systems are thought to be capable of removing a sufficient quantity of ash to protect the turbine hardware; however, these systems are not capable of meeting the stringent environmental particulate emissions regulations. A hot gas cleanup system that meets both turbine protection and environmental emissions requirements without post-turbine cleanup devices should have improved overall system economics compared to a system with conventional cyclones prior to the gas turbine and a baghouse or electrostatic precipitator after the turbine.

Acoustic agglomeration can increase the cyclone collection efficiency by increasing the average particle size of the ash. In this concept, the ash-laden effluent stream from the PFBC is passed through a high intensity sound field prior to entering the cyclone train. The high intensity sound causes the smallest particles to oscillate with the sound waves, while the largest particles travel with the bulk gas flow, unaffected by the sound. Due to the increased motion of the smallest particles, the number of collisions between the small and large ash particles increases. When the ash
particles come into close contact, they agglomerate, being held together by molecular forces, as stated in Rawlins (1991). The design and operational simplicity of acoustic agglomeration prior to a conventional cyclone train offers significant economic advantage over other hot gas cleanup methods.

A major goal of this program is to establish whether a full-scale agglomerating cyclone system can meet NSPS particulate emission standards and still provide a 15% reduction in the fixed and operating costs of the cleanup system relative to conventional hardware (conventional cyclones coupled with post-turbine control).

**PROJECT DESCRIPTION**

The project duration has been extended from its original two-year study, to five years. The program is divided into three phases covering the test facility design, experimental testing, and commercial assessment.

**Phase I**

The initial phase of the program consisted of a detailed design of the subpilot-scale acoustic agglomeration test facility and the preparation of an experimental plan. Due to the high costs and unavailability of operating PFBC's and the need to accurately control the input flow parameters, the test facility has been based upon a simulated PFBC effluent stream in which fluidized bed fly ash is injected into a high temperature, high pressure vitiated air stream. High intensity sound is produced within the agglomeration chamber with a natural gas fired pulse combustor.

**Phase II**

The second phase covers the fabrication and installation of the test hardware and the execution of the acoustic agglomeration tests, including system characterizations test with various pulse combustors supplied by MTCI (Manufacturing and Technology Conversion International, Inc.). The testing includes detailed parametric tests to identify the dependence of critical operating variables on the agglomeration efficiency, and duration test to assess the durability of the system. Comparisons of the experimental data with computer predictions of acoustic agglomeration will also be made.

**Phase III**

The final phase will provide a commercial assessment of the system. An engineering and cost analysis of a full-scale design for an acoustically enhanced cyclone collection system, integrated with a PFBC combined-cycle system, will be performed.

**TEST FACILITY DESIGN**

The acoustic agglomeration test facility consists of a vertical, refractory lined agglomeration chamber which has a maximum residence time of approximately 3 seconds. High pressure air (9 bars) is preheated to approximately 900°C with a natural gas combustor and fly ash is injected into the air stream to simulate PFBC operating conditions. Natural gas fired pulse combustors are used to generate high intensity sound at selected frequencies to enhance acoustic agglomeration of the fine, fly ash particulate. A two-stage high temperature, high pressure cyclone system is used to separate the ash particles from the bulk air flow. A heat exchanger and a sintered metal filter are used to cool the air and remove particulate for local environmental control. Samples of the fly ash particulate are removed from the gas stream in three areas: near the exit of the agglomeration chamber, between the two cyclones, and after the final cyclone. These samples are analyzed for particle size distribution and mass loading within the gas stream to determine the effects of the high intensity sound and other operating parameters on the agglomeration of the fly ash.

**Pulse Combustor**

A pulse combustor, supplied by MTCI, typically consists of a flow diode, a combustion chamber, and a resonance tube, or tailpipe. Fuel and air enter the combustion chamber where a glow plug ignites the mixture. As the gas expands, the flow diode permits preferential exiting flow in the direction of the resonance tube with significant momentum as explained in Mansour (1991). A vacuum is created in the combustion chamber due to the inertia of the gases in the tailpipe. This inertia permits only a small fraction of exhaust gases to return to the combustion chamber; the balance of the exhaust exits the resonance tube. Since chamber pressure is below inlet pressure, air and fuel are drawn into the chamber where auto ignition takes place. Again, the flow diode constrains reverse flow, and the cycle repeats. Once the first cycle is initiated, operation is self-sustaining.

The rapid pressure oscillations in the combustion chamber generate an intense oscillating flow field which travel the length of the agglomeration chamber. Pulse combustors experience very high mass transfer and heat transfer rates within the combustion zone. While these combustors tend to have very high heat release rates (typically 10 times those of conventional burners), the vigorous mass transfer and high heat transfer within the combustion region result in a more uniform temperature. Therefore, peak temperatures attained are much lower than in the case of conventional systems. This results in a significant reduction in the formation of nitrogen oxides. The high heat release rates also result in a smaller combustor size for a given firing rate, and a reduction in the residence time required.

**High Frequency Agglomeration**

A flow diagram of the acoustic agglomeration test facility for high frequency agglomeration is shown in Figure 1. In this arrangement, air enters the system through the preheat combustor at the bottom of the agglomeration chamber. The bulk flow of the air is in an upward direction. Ash is injected near the bottom of the chamber, and the particle sample is withdrawn from the top of the chamber. The pulse combustor sound source is located at the top of the agglomeration chamber firing downward. This produces a counter-current flow between the ash particulate flow direction and the sound propagation direction. With this configuration, the combined fuel and air flow rate of the high frequency combustors is approximately 15-30% of the total gas flow into the system.

**Low Frequency Agglomeration**

With the low frequency pulse combustors, the total air and gas flow rate drawn through the pulse combustor increases relative to
So...-Type
Ash Feeder Acoustic
ApplOMerthen
Gimbel
Ptdse Combustor.
Swnd Seurat
Panicalale
Gas
Pate:Mate
Sample
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Ash Collection
FIGURE 1. HIGH FREQUENCY AGGLOMERATION SCHEMATIC

the bulk flow through the agglomeration chamber. To minimize the variation in air flow between the agglomeration chamber and the cyclones, the test facility was modified as shown in Figure 2. The preheat combustor was moved to the top of the agglomeration chamber and a refractory-lined duct was installed between the bottom of the chamber and the inlet to the first stage cyclone. During testing, it was found to be unnecessary to use the preheat combustor for generating the heat required for PFBC conditions, as the low frequency pulse combustor provided sufficient heat due to the increased mass flow. The ash is injected near the top of the chamber and the particulate sample withdrawn near the bottom. The bulk flow of the gas is downward, with the co-current flow between the injected ash and the sound waves. The remainder of the test facility is unchanged.

FIGURE 2. LOW FREQUENCY AGGLOMERATION SCHEMATIC

FACILITY CHARACTERIZATION
The facility shakedown and characterization tests have been completed. Several facility modifications were required to complete these shakedown tests.

Ash Feed System
The original ash feed system planned for this program was a rotary disc feeder. Problems with this feeder in feeding the fine fly ash were experienced due to an insufficient angle of inclination within the ash hopper and the narrow groove width on the rotary disc. An existing auger-type feeder, shown in Figure 3, was used in place of the disc feeder. This auger feeder proved successful in feeding the fly ash stably over the range of ash feed rates necessary for the planned acoustic agglomeration tests.

FIGURE 3. AUGER-TYPE ASH FEED SYSTEM

Particulate Sampling
Fly ash particulate is removed from the flowing gas stream, through three water cooled sample probes located within the agglomeration chamber, between the two cyclones, and after the final cyclone. After the ash sample is removed from the gas stream, it is collected in either an Andersen Cyclade™, shown in Figure 4, or a Balston Filter. The Cyclade consists of 6 small cyclones in series followed by a backup filter and is used to segregate the ash into discrete size classes. The Balston Filter is used to determine only the mass loading within the gas stream. Figure 5 shows the sampling canisters in which the Cyclade or filters are installed.

Excessive cooling of the particle laden gas sample occurred during operation of the sample probes such that water condensed along the walls of the transfer tubing between the water cooled...
sample probe and the pressurized canister holding the Cyclade and Balston Filters. This caused the ash to form a paste along the tubing walls, preventing it to flow into the filter. Electrical heaters were added to maintain the temperature of the sample above the dew point.

**Ash Collection**
The ash hoppers below the high temperature cyclones, shown in Figure 6, were originally designed as water cooled vessels with knife gate valves at the top and bottom of the hopper. The water cooling caused water to condense within the hopper and an insufficient angle of inclination on the hopper allowed bridging to occur above the knife gate valves, thus preventing the hoppers from emptying completely when the gate valves were opened. These hoppers have been redesigned with non-water cooled walls and a steep angle of inclination at the exit. The top knife gate valves have also been removed to simplify the system. These valves will be reinstalled prior to the system durability testing.

**Pulse Combustor Operation**
Three high frequency pulse combustor sound sources have been fabricated and tested by MTCI. The nominal 1000 Hz, 2000 Hz, and 3000 Hz pulse combustor have been tested with the acoustic agglomeration test facility. Modifications to the fuel/air injectors were made by MTCI to provide easier ignition and eliminate the potential of the flame to propagate back into the injector.

The 1000 Hz pulse combustor has been capable of producing sound pressure levels (SPL) (integrated from 0-20,000 Hz) as high as 165 dB at approximately 1170 Hz. The sound pressure level of
the fundamental frequency was approximately 6-10 dB lower than the integrated value. One of the planned test variables for the agglomeration tests was to vary the SPL over a range of 145 to 165 dB. The stable operating envelope of the pulse combustor does not allow this wide of a range in SPL output. Reducing the fuel input to the combustor by half only reduced the SPL within the agglomeration chamber by approximately 6 dB. Therefore, sound intensity will not be used as an independent variable on the acoustic agglomeration tests.

The SPL has been measured to be nearly constant down the length of the agglomeration chamber with only a 2 to 5 dB attenuation during the initial characterization tests. The 2000 and 3000 Hz T-bumers have not achieved high intensity pulsations in this test facility. New fuel injectors have been fabricated to use with these combustors.

MTCI has also fabricated, tested, and delivered two low frequency (150 Hz and 550 Hz) pulse combustors. System characterization tests have been completed with the 150 Hz combustor. Ash feeding tests are underway. A third pulse combustor will be fabricated by MTCI and tested in the agglomeration facility. The specified frequency of this combustor will be based upon prior test results. Currently, a <100 Hz combustor is projected.

ACOUSTIC AGGLOMERATION TEST PLAN

The acoustically enhanced cyclone collector is being evaluated with two distinct goals in mind: 1) determine the effects of the major operating parameters on acoustic agglomeration efficiency, and 2) optimize the agglomeration system performance for maximum particulate removal efficiency. During the tests, ash samples are collected from the bulk gas stream at the exit of the agglomeration chamber, between the two cyclones, and also from the discharge pipe of the final cyclone. The main dependent variables of interest are the mass mean particle size and size distribution of the ash before and after the agglomeration process, and the cyclone collection efficiency of the unagglomerated and agglomerated particulate streams.

Seven independent variables have been identified for the parametric testing. These are: 1) frequency of the sound generator, 2) ash residence time within the agglomeration chamber, 3) ash loading in the bulk gas stream, 4) operating system pressure, 5) agglomeration chamber temperature, 6) particle size distribution of the fly ash, and 7) ash type. The testing is performed using a statistical experimental design approach. First, a two-level fractional factorial design is used to obtain basic information about each independent test variable. Next, a three-level response surface design is used to determine optimum operation conditions.

RESULTS

The high frequency agglomeration tests (1000-3000 Hz) have been performed with ash feeding at the 1000 Hz level. System characterization and injector optimization tests have been completed with the 2000 Hz and 3000 Hz combustors. Based upon testing under a separate, outside DOE contract, a shift in technical direction to low frequency work resulted and low frequency hardware modifications were incorporated. Preliminary observations during these tests indicated that a higher incidence of agglomeration occurred at low frequency, approximately 100-200 Hz, opposed to high frequency. System evaluations have been completed with ash injection tests underway.

High Frequency Test Results

Pulse combustor testing began with the 1000 Hz Schmidt tube type combustor. The single burner from MTCI is shown in Figure 7. Once this sound source had been characterized, the 2000 Hz and 3000 Hz T-bumers were tested. The 3000 Hz generator is shown in Figure 8. Measuring the sound intensity with four microphones, shows that it does not drop off significantly down the length of the agglomeration chamber. Typical sound pressure level data is shown in Figure 9 for microphones 1-4 for the (a) 1000 Hz combustor and (b) 3000 Hz combustor. Microphones are numbered 1-4 beginning at the entrance of the agglomeration chamber. The 1000 Hz Schmidt tube achieved the goal of 160 dB in the agglomeration chamber. Both the 2000 and 3000 Hz combustors were unable to achieve sufficient acoustic intensity. The noise in the frequency spectra below approximately 300 Hz is due to flow and combustion noise produced by the preheat combustor of the agglomeration chamber (note, the preheat combustor was not fired during which sound pressure level data for the T-bumers was taken).
Pulse combustor performance is not influenced significantly by firing rate or pressure over the operating ranges tested in this facility. Increasing and decreasing both parameters has had no significant effect on the pulsations. With the existing facility, there is no control over the sound intensity of the pulse combustors. The frequency can be altered by changing pulse combustors.

Several agglomeration tests have been performed during which ash is injected into the 3 second residence time port. One successful comparison sample was taken in which ash samples were collected both with and without sound. The particle size distributions for the samples collected from Tests 47, 48, and 49, and measured with the Andersen Cyclade at the exit of the agglomeration chamber, are presented in Figure 10. The mass fraction of ash less than approximately 10 microns was 7.2% in Test 47, when the pulse combustor was tuned in. This mass fraction increased to 12.2% and 10.9% respectively in the two "no sound" tests. This signifies that in an active sound field, the percentage of small particles is decreased through agglomeration, resulting in larger particles which are more likely to be cleaned by conventional means. Further testing is required to determine

FIGURE 9. TYPICAL SOUND PRESSURE LEVEL DATA FOR (A) 1000 Hz, AND (B) 3000 Hz PULSE COMBUSTORS

FIGURE 10. PARTICLE SIZE DISTRIBUTION DATA FROM TESTS 47, 48, AND 49
whether the reduction in the small micron mass fraction with the operating, acoustic sound source is truly significant.

**Low Frequency Test Results**

Once all modifications were completed, testing began with the nominal 150 Hz pulse combustor. Changes that were made include the addition of piping to redirect the gas flow from an upward path to a downward course. Heavy insulation was also installed on the piping because heat loss was too great between the first and second sampling probes. Also, the ash feed system was moved to the top of the rig and the first sample probe was reinstalled at the bottom of the agglomeration chamber.

MTCI's low frequency pulse combustor is shown in Figure 11. Very high sound pressure levels were achieved with this combustor. Highs of 181 dB were easily and consistently obtained at a frequency of approximately 170 Hz. The overall fundamental frequency ranged from 169-173 dB for microphone 1 when high peaks were achieved. Figure 12 displays the sound pressure level versus frequency curves for Test 79. Although microphones 2 and 4 were not operating properly, little attenuation is seen down the length of the agglomeration chamber, as was observed with the high frequency pulse combustors. Ash feeding tests are in progress in the low frequency mode.

**FUTURE WORK**

Plans to test a <100 Hz, ultra-low frequency pulse combustor are underway. Comparisons between the test data and predictions made by an acoustic agglomeration computer model will be performed when testing is completed. The Phase III Commercial Assessment will be started prior to completion of all experimental testing in order to provide sufficient time to complete the assessment.

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**REFERENCES**
