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(REPORTING PERIOD 01/01/97-03/31/97)

ON

SLAG CHARACTERIZATION AND REMOVAL USING PULSE DETONATION
TECHNOLOGY DURING COAL GASIFICATION

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ABSTRACT

This quarterly report has been written based on the research activities performed during the period 01/01/97 through 03/31/97. One paper Titled “Application of Detonation Wave for Removing Economizer Slag in Coal-Fired Utility Boilers” was presented in the College of Engineering and Architecture Symposium, Prairie View A&M University. A performance report was written based on the achievements during last year and presented at Energy Research and Development Technology Transfer Symposium, Historically Black Colleges and Universities (HBCU) Contractors Review Meeting, Baton Rouge, Louisiana (March 3, 1997).

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EXECUTIVE SUMMARY

A paper Titled “Application of Detonation Wave for Removing Economizer Slag in Coal-Fired Utility Boilers” was presented in E&A '97 symposium, College of Engineering and Architecture, Prairie View A&M University, TX , February 05, 1997. The paper is attached.

A progress report was written based on the achievements during last one year and presented at Energy Research and Development Technology Transfer Symposium, Historically Black Colleges and Universities (HBCU) Contractors Review Meeting, Baton Rouge, Louisiana (March 3, 1997). The abstract of the report is attached.

As reported in the previous quarterly reports, the test were performed with slags on tubes in axial positions. The test results showed that the detonation wave is capable of chipping off the slag from the tube if no other tube is in the front position. The results also showed that the detonation wave is less effective in removing slag from the back side of tube. But Computational Fluid Dynamic (CFD) study showed that the detonation wave is effective in removing the slag from both sides of tubes if they are arranged in a bundle. In the bundle, wave reflection and reverberation occurs which has the additional effects to remove the slag . In order to study the effects of wave reflection and reverberation, tests are planed to be performed with tube bundles. A multi-tube position fixture with tube arranged in a bundle was designed and fabricated.

The multi shot testing will be performed in the middle of July. We are in contact with the Aerospace Research Center at University of Texas, Arlington to use their Pulse Detonation Engine to perform the test.

We are in process to get more information about the feasibility study report submitted last quarterly. Dr. Louis Hunter of Lockheed Martin Co. provided the report and we are in contact with him. Once we get the information, we will write a report and send it to the document control center.

Application of Detonation Wave for Removing Economizer Slag in Coal-Fired Utility Boilers

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ABSTRACT

Boiler slagging and fouling as a result of inorganic impurities in combustion gases being deposited on heat transfer tubes have caused severe problems in coal-fired power plant operation. These problems are fuel, system design, and operating condition dependent. Pulse detonation technology for the purpose of removing slag and fouling deposits in coal-fired utility power plant boilers offers great potential. The detonation wave technique based on high impact velocity with sufficient energy and thermal shock on the slag deposited on gas contact surfaces offers a convenient, inexpensive, yet efficient and effective way to supplement existing slag removal methods. These detonation waves have been demonstrated experimentally to have exceptionally high shearing capability important to the task of removing slag and fouling deposits. The experimental results show that the single shot detonation wave is capable of removing the entire slag (types of slag deposited on economizer) even at a distance of 8 in. from the exit of a detonation engine tube. Wave strength and slag orientation also have different effects on the chipping off of the slag. This paper discusses about the results obtained in effectively removing the economizer slag.

INTRODUCTION

Historically, boiler slagging and fouling as a result of inorganic impurities in combustion gases being deposited on heat transfer tubes have caused severe problems in coal-fired power plant operation. These problems are fuel, system design, and operating condition dependent. Conventional ash removal methods include the use of in situ blowing or jet-type devices such as air or steam soot blowers and water lances. In soot blower and water lance cleaning devices being only partially successful in removing deposits, they also require considerable maintenance, and they reduce boiler efficiency when in use. Alternative technologies are therefore needed to more

efficiently and effectively remove ash deposits from heat transfer surfaces of utility boilers during full power plant operation. New methods are specially needed to remove deposits from the downstream side of heat transfer tube bundles in the convective pass sections. Pulse detonation waves offer potential solutions to many of the slag deposit problems by providing simple, inexpensive, yet efficient and effective ways to supplement existing ash removal methods, without expensive plant shut down. The three main areas in which work has been performed during the past one year are in slag characterization studies, pulse detonation technology studies, and single pulse testing on slag removal. Considerable achievement have been accomplished in each of the three areas during the past year.

SLAG CHARACTERIZATION

The slag characterization studies were performed by MTI and provided to Prairie View A&M University (PVAMU). MTI provided background information on fuel properties, ash deposition, ash formation, and ash removal based on Coal Analysis, Deposit Analysis, and Deposit Phase and Compositional Analysis. Deposit Analysis includes Deposit descriptions, Morphological Analysis and Porosity Calculations, and Scanning Electron Microscopy of polished cross-section of sample. In addition, MTI provided slags from basin electric deposits and northern states power deposits for testing. The basin electric deposits have a medium-to-low porosity, low crystallinity, and are sulfate based. The sulfation process fills pores and increase density. This set of deposits represent a wide range of deposits found in the convective pass of a utility boiler firing a high calcium subbituminous coal. These subbituminous coals are being used extensively in the U.S. for power generation. The northern states power deposits were characterized to determine some of the chemical and physical properties that effect the strength of the deposit as well as the resistance to removal. The deposits range in porosity (area percent epoxy) from 44.4% for the weakest to 29.4% for the strongest. The lower critical porosity value for slag removal from full scale utility boilers by a soot blower is about 25% porosity. The deposits are primarily sulfate based with varying levels of sulfation. The microstructure indicated coating on the particles that are likely contributing to the strength development. These chemical and physical properties of the deposits influence the ability of conventional soot blowers to remove the deposits.

SLAG FORMATION AND REMOVAL

During combustion or gasification the inorganic materials are transformed into ash species that are in the form of gases, liquids and solids. The submicron size of particles form as a result of condensation of flame volatalized species upon gas cooling. Flame volatalized species may also condense on the surface of larger particles or deposits. The larger particles are sometimes referred to as residual ash, which is largely derived from mineral grains. Ash deposit formation is related to coal quality (chemical and physical characteristics of the inorganic material), system operating conditions, and system design and consists of both slag deposits and fouling deposits. Slag deposits are those that form in the radiant section of the boiler. Fouling deposits are characteristic of those found in the convective pass of the boiler. The chemical and physical characteristics of utility boiler deposits vary widely. Slag deposits typically contain more liquid phase components

causing more assimilation and reaction of the ash particles. Fouling deposits consists of two primary types, i.e., high temperature silicate deposits and low temperature sulfate-based deposits. These deposits types form under very different temperatures and form very different ash materials. At low temperatures, sulfates dominate, while at higher temperatures, silicates are more prone to cause deposits. In high-temperature fouling, the bonding of particles is due to silicate liquid phases and in low-temperature fouling, the bonding is a result of formation of sulfates. Condensed sulfur species, principally in the form of CaSO_4 are stable and form the matrix or bonding material in the low-temperature deposits. High temperature fouling occurs in regions of the utility boiler where temperatures exceed the stability of the sulfate-bearing phases. Deposits in the convective pass of utility boilers collect on both upstream and downstream side of tubes. The particles collected on the downstream side of the tube area are a result of small particles that are caught in the circulation eddies and impinge upon the downstream side of the tubes.

The primary factors that influence the ability to be removed are the strength of the deposit and the adhesive bond between the ash deposit and the heat transfer surface. The removal of the deposit involves breaking the deposit matrix and/or breaking the bond between the deposit and heat transfer surface. Methods typically used to remove deposits include load reduction and on-line cleaning. Load reduction results in cooling of the deposit and heat transfer surface because of a differential in the thermal expansion coefficients between the deposit and heat transfer surface. On-line ash deposit cleaning devices are called sootblowers. The blowing medium is either high pressure steam or compressed air. The blowing medium is directed at the deposit through a nozzle. The impacting fluid causes the deposit to crack and eroded away. The design of the blowers vary depending upon the location in the boiler. For extremely difficult to remove deposits water-jet sootblowers have been used. These work well to remove large accumulations of deposits in the furnace. The impact of water is much greater than that of air or steam so it is effective in removing deposits. Unfortunately, removing deposits formed on the downstream side of the tube is not possible using conventional sootblowing techniques.

PULSE DETONATION TECHNOLOGY

Pulse detonation technology studies were performed by both PVAMU and Lockheed Martin Co. under subcontract from PVAMU. Pulse detonation technology for the purpose of removing fouling ash deposits in heat exchangers was evaluated by running Lockheed supplied an algebraic Pulse simulation CFD code using 2-D time dependent methods to determine the effect of a detonation wave passing through a 3-tube heat exchanger. Pressure, pressure gradients, temperature and velocities were recorded as a function of time. Wave reverberations were noted on the back side of the heat exchanger lead tube. Conventional methods clean the front side of the tubes, but have great difficulty on the back side. The CFD results show a thorough scrubbing of the cylinders on all sides. The CFD results also showed that the number more tubes in front of detonation waves the better are the result in terms of reverberation activity. The study also showed large negative velocities impinging on the back side of the lead tube as a result of fixtures being placed over and under the tube bank and the wave interaction between the tubes. These single shot detonation wave studies indicate peak pressures of several hundred atmospheres which

act over a very short period of time and which fall off very rapidly. Pressure gradients move around the tubes and large velocities alternate with pressure which scrub all surfaces circumferentially to remove the ash. Wave strength is an important variable for slag deposit removal applications. A full strength detonation wave is referred to as a Chapman-Jouget (C-J) wave. Its velocity is approximately 2200 meters per second and its maximum pressure jump approximately 20 times that of unburned reactants.

SINGLE PULSE TESTING

Test chamber facility

A pulse detonation facility specially designed to study detonation waves at the University of Texas at Arlington has been utilized to remove slags using single shot detonation waves. The main components of the pulse detonation facility are the test chamber, the injection system, the ignition system and the instrumentation. To hold the slag samples at the exit of detonation tube, two different types of fixture (mounting) was designed and fabricated at Prairie View A&M University. The injection system was upgraded for repetitive use. A control circuit was also designed and built to sense the injection of fuel and oxidizer, provide a short time delay, fire the ignition source, recharge the ignition capacitor bank and provide a synchronized signal to the data acquisition system if required or desired. The overall schematic of UTA detonation engine including the fixture is given in Figure 1.

Test Chamber

The test chamber consists of steel tubes of varying length connected end to end in different combinations but with the same cross sectional area. The three different segment lengths are 7.62 cm (3 in.) , 15.24 cm (6 in.) and 30.48 cm (12 in.). Each section has an inner diameter of 7.62 cm (3 in.) and an outer diameter of 13.97 cm (5.5 in.). A 1.905 cm (0.75 in.) thick flange is welded to each end of the test sections. Each section of the chamber has provisions for mounting pressure transducers, thermocouples, thin film gauges and heat flux gauges every 7.62 cm (3 in.). The ignition plug is mounted in a 7.62 cm (3 in.) section and can be inserted any where along the length of the tube between other sections. One end of the chamber is sealed with a plate. The fuel and oxidizer is injected through this plate. The various sections of the chamber are flanged and bolted together at each joint. The open end of the chamber is bolted to a thrust stand to hold the chamber in place.

Injection System

The fuels and oxidizers are injected through an passage on the end plate which closes one end of the tube. The opposite end is open for the exhaust of the detonation wave and combustion product. The rotary injection valves are connected together by pulleys and timing belt, turned by a variable speed electric motor, controlled remotely from the control room for frequency control. A magnetic pickup is located nearby to sense the closure of the valves and initiate the ignition process.

Ignition Process

The tests are started by igniting the fuel and oxidizer mixture in the chamber. This is done by an arc plug developed specially for this program. The arc plug is mounted in a 7.62 cm (3 in.) section of the test chamber which allows placement at nearly any location along the length of the test chamber. The arc welder ionizes a path through the gas between the two electrodes of the arc plug. This reduces the resistance of the gas. When the gas path is ionized sufficiently, the discharge capacitors discharge through the path in the form of a high current arc. A higher amount of energy can be dissipated into the mixture in this way by using a normal spark plug.

Instrumentation

The instrumentation used to obtain the experimental data are the seven pressure transducers. The instrumentation sensors are mounted in the side wall at 7.62 cm (3 in.) increments with the capability for all types of sensors to be mounted at the same axial locations. The pressure transducers are PCB model 111A24 dynamic pressure transducers with a full scale range of 6.89 MPa (1000 psi), rise time of 1 microsecond, and a time constant of 100 seconds. The pressure transducers are connected to a DSP Technology data acquisition system which has the capability of 100 kHz sampling rate, 12 bits of accuracy, and 48 channels, each with its own amplifier and analog to digital converter to allow for simultaneous sampling for all channels.

Fixture

Two types of fixture were used to hold the slag sample attached on solid steel tube at the exit of detonation tube. One has four axial positions and the other has three triangular positions. High strength Aluminium plate is used to fabricate the fixtures. Aluminium plate, 0.75 in. thick, has been used for the flange bases and Aluminium plate, 0.50 in. thick for slag sample rod holder plates. The flange bases (top and bottom) are bolted through the test chamber flange with four 0.75 UNC bolts. The slag sample rod holder plates (top and bottom) are bolted through the flange bases (top and bottom) with eight equally spaced (1/4)-20-2A bolts. In the axial positions slag holder plates (top and bottom), there are four through holes in the top plate and four step holes in the bottom plate. The step holes in the bottom plate facilitate to properly hold in position the slag sample rods. In addition, the slag sample tube can be bolted through the bottom plate step holes with (1/4)-20-2A bolts. Similar hole arrangements have been done in the triangular positions plate. Schematic of slag holder plates are shown in Figure 2 and 3.

TEST PARAMETERS

Input conditions

Fifty eight experiments were performed with single shot detonation wave at the Aerospace Research center at University of Texas at Arlington. The effects of axial distance, and slag orientations are discussed below.

Input parameters for the experiments were as follows:

Wave pattern: Weak detonation and C-J detonation

Types of slag: MTI 96-54, MTI 96-55, MTI 96-56

Types of fixture: (a) 4 axial positions
(b) 1 triangular configuration

Slag orientation: Front, back and side mounting.

Slag types

Three different types of Northern States Power Solid Slag Deposits were used. They are as follows:

- 1) MTI 96-54 is an air-heater inlet deposit which is softer than others.
- 2) MTI 96-55 is a reheater deposit which is very tough like a rock.
- 3) MTI 96-56 is an economizer deposit which is softer than MTI 96-55 but harder than 96-54.

Wave pattern

Two detonation wave patterns were used for the experiments. Weak detonation waves were generated by using hydrogen as the fuel and C-J detonation waves were generated using propane as the fuel.

Sample location

Two different arrangements were used to study the effect of detonation wave on the position of the sample with respect to the exit of the detonation tube. In axial arrangement sample could be attached at four different locations, 2 in., 4 in., 6 in. and 8 in. from the detonation tube exit as shown in Figure 2. Figure 3 shows the second arrangement in which the samples are attached at the apex or corners of a unilateral triangular arrangements at 1.3 in. apart from each other with the first tube at 2 in. from the exit of the detonation tube.

Slag orientation

At each position with respect to the exit of the detonation tube the samples were attached such that the slags are at three positions with respect to the to the direction of the propagation waves. These positions are front of the tube, side of the tube and back of the tube. Figure 4 shows the schematic of slag orientation.

Sample preparation and Experimental procedure

Each sample consists of a solid stainless steel bar, .635 in. dia. and 6.5 in. long. Solid slags were cut into pieces with approximate dimension of 1 in. X .5 in. X 1 in. . Each piece is attached to a bar with the help of epoxy resin J-B weld. Use of this epoxy assures that the bonding between the slag and the solid surface is stronger than the bonding within the slags. Each sample is then placed in desired location and orientation with the help of the two fixtures attached with the exit of detonation tube (see Figure 1).

RESULTS AND DISCUSSION

Effects of axial location

The results from the experiments show that the weak detonation wave is capable of chipping off soft slag (MTI 96-54) samples attached at the front of the steel rod even at a distance of 8 in. from the exit of the detonation tube. The wave is unconstrained. Though there are flanges at the top and bottom, the wave is allowed to expand on the sides. The wave chipped off almost the whole slag at 2 in. position and almost 90% at 8 in. location. Observations at 4 in. and 6 in. locations also showed complete removal. Another observation noted is that the chipped off samples are broken into several pieces. The number of pieces increases as the sample moves closer to the exit of the detonation tube. Figure 5 shows pictures of the sample before and after the test, with the slag attached at the front, at a location of 2 in. from the exit of the detonation tube. Figure 6 shows for location 8 in. from the exit with other conditions remaining same.

Effects of slag orientation:

With weak detonation wave and soft slag (MTI 96-54) attached on the side of the steel rod, the experiments show that the shearing off of the entire slag takes place without any breaking. Figure 7 shows pictures of the sample before and after the test at a distance 2 in. from the exit of the detonation tube. Figure 8 shows for location 8 in. from the exit with other conditions remaining same. Thus the wave is found to shear off the entire slag, even at 8 in. from the exit of detonation tube, if the slag is attached to the side of the rod.

Similar tests were performed with slag attached to the back of the tube. Results at 2 in. and 6 in. positions also show almost complete removal of slag, even if they were attached to the back but the number of broken pieces of slag are less than the slag attached in front position of the rod. This result support the result from the CFD analysis that the wave scrub all surfaces circumferentially to remove the ash deposits.

CONCLUSIONS

Several conclusions can be drawn from the results obtained during the first year research activities with single shot detonation waves. They are as follows:

- Softer slag samples can be removed more easily.
- Sample with forward attachment breaks into several small pieces.
- Side facing slag shear off without breaking.
- Closer the slag is to the exit of the detonation tube, the better are their removals.
- Stronger waves can remove slag more effectively.
- In effective removal if the slag is not directly on the path of the wave, i.e., if there is no wave reflection.

REFERENCES

Huque, Ziaul and others, 1995, “ Slag Characterization and Removal Using Pulse Detonation Technology for Coal Gasification”. Technical proposal submitted to PETC.

Steven A. Bension, 1996, “ Slag Characterization Study”. Quarterly Report submitted to PVAMU.

Characterization and Removal of Slag Deposits Using Pulse Detonation Technology for Coal Gasification

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ABSTRACT

Pulse detonation technology for the purpose of removing slag and fouling deposits in coal-fired utility power plant boilers offers great potential. The detonation wave technique based on high impact velocity with sufficient energy and thermal shock on the slag deposited on gas contact surfaces offers a convenient, inexpensive, yet efficient and effective way to supplement existing slag removal methods. These detonation waves have been demonstrated experimentally to have exceptionally high shearing capability important to the task of removing slag and fouling deposits. The experimental results prove that the single shot detonation wave technique is efficient and reliable in comparison with various conventional cleaning methods. Wave strength and slag orientation also have different effects on the chipping off of the slag. The three main areas in which work has been performed during the past one year are in slag characterization studies, pulse detonation technology studies, and single pulse testing on slag removal. Considerable achievement have been accomplished in each of the three cases. This abstract discusses about the results obtained in effectively removing the slag with single shot detonation wave up to a distance of 8 in. from the exit of detonation tube.

Historically, boiler slagging and fouling as a result of inorganic impurities in combustion gases being deposited on heat transfer tubes have caused severe problems in coal-fired power plant operation. These problems are fuel, system design, and operating condition dependent. The problems are severely noticed in cases of boilers fired with coal of low calorific value and high content of mineral constituents, especially those that tend to accumulate on heat transfer solid surfaces. Conventional ash and fouling deposit removal methods include the use of in situ blowing or jet-type devices such as air or steam sootblowers and water lances. In sootblower and water lance cleaning devices being only partially successful in removing deposits, they also require considerable maintenance, and they reduce boiler efficiency when in use. Alternative technologies are therefore needed to more efficiently and effectively remove ash deposits from heat transfer surfaces of utility boilers during full power plant operation. New methods are specially needed to remove deposits from the downstream side of heat transfer tube bundles in the convective pass sections. Pulse detonation wave technique, based on the action of mechanical and thermal shock on material, deposited on heat transfer surfaces, offers potential solutions to many of the slag deposit problems by providing simple, inexpensive, yet efficient and effective ways to supplement existing ash removal methods, without expensive plant shut down. The three main areas in which work has been performed are in slag characterization studies, pulse detonation technology studies, and single pulse testing on slag removal. This detonation wave technique has been applied to remove the slag deposits, deposited on economizer, reheater, and air-heater and has been found to be effective and successful with some marginal differences depending on type of slags and wave patterns. The best results have been achieved with soft slag and strong detonation wave at a closer distance from the exit of detonation tube.

The slag characterization studies were performed based on the background information on fuel properties, ash deposition, ash formation, and ash removal based on Coal Analysis, Deposit Analysis, and Deposit Phase and Compositional Analysis. Deposit Analysis includes Deposit descriptions, Morphological Analysis and Porosity Calculations, and Scanning Electron Microscopy of Polished cross-section of sample. Slags from Basin Electric Deposits and Northern States Power Deposits were studied. The Basin Electric Deposits have a medium-to-low porosity, low crystallinity, and are sulfate based. The sulfation process fills pores and increase density. This set of deposits represent a wide range of deposits found in the convective pass of a utility boiler firing a high calcium subbituminous coal. These subbituminous coals are being used extensively in the U.S. for power generation. The Northern States Power Deposits were characterized to determine some of the chemical and physical properties that effect the strength of the deposit as well as the resistance to removal. The deposits range in porosity (area percent epoxy) from 44.4% for the weakest to 29.4% for the strongest. The lower critical porosity value for slag removal from full scale utility boilers by a soot blower is about 25% porosity. The deposits are primarily sulfate based with varying levels of sulfation. The microstructure indicated coating on the particles that are likely contributing to the strength development. These chemical and physical properties of the deposits influence the ability of conventional sootblowers to remove the deposits.

Pulse detonation technology for the purpose of removing fouling ash deposits in heat exchangers was evaluated by running Lockheed supplied CFD code using 2-D time dependent methods to determine the effect of a detonation wave passing through a 3-tube heat exchanger. Pressure, pressure gradients, temperature and velocities were recorded as a function of time. Wave reverberations were noted on the back side of the heat exchanger lead tube. Conventional methods clean the front side of the tubes, but have great difficulty on the back side. The CFD results show a through scrubbing of the cylinders on all sides. The CFD results also show that the more tubes in front of detonation waves the better result in terms of reverberation activity. The study also shows large negative velocities impinging on the back side of the lead tube as a result of fixtures being placed over and under the tube bank and the wave interaction between the tubes. These single shot detonation wave studies indicate peak pressures of several hundred atmospheres which act over a very short period of time and which fall off very rapidly. Pressure gradients move around the tubes and large velocities alternate with pressure which scrub all surfaces circumferentially to remove the ash.

Fifty eight experiments were performed with single shot detonation wave. The experimental results can be analyzed based on the effect of axial distance, orientation of the slag samples, slag types, and wave patterns.

Several conclusions can be drawn from the results obtained during the first year research activities with single shot detonation waves. They are as follows:

Softer slag samples can be removed more easily.

Sample with forward attachment breaks into several small pieces.

Side facing slag shear off without breaking.

Closer the slag is to the exit of the detonation tube, the better are their removals.

Stronger waves can remove slag more effectively.

In effective removal if the slag is not directly on the path of the wave, i.e., if there is no wave reflection.

Figure 1: Test chamber Schematic

Figure 2: Schematic of 4 axial positions fixture

Figure 3: Schematic of triangular positions fixture

Figure 3: Schematic of triangular positions fixture

Figure 4: Schematic of slag orientation with steel tube

Figure 5: Slag with front attachment before and after the test at a distance of 2 in. from the exit of detonation tube.

Figure 6: Slag with front attachment before and after the test at a distance of 8 in. from the exit of detonation tube.

Figure 7: Slag with side attachment before and after the test at a distance of 2 in. from the exit of detonation tube.

Figure 8: Slag with side attachment before and after the test at a distance of 8 in. from the exit of detonation tube.