EXPERIMENTAL INVESTIGATION OF SLAG REMOVAL USING PULSE DETONATION WAVE TECHNIQUE

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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. Conventional slag removal methods including soot blowers and water lance cleaning devices are being only partially successful in removing deposits specially from the downstream side of heat transfer tube bundles in the convective pass sections. They also require considerable maintenance and reduce boiler efficiency when in use. The detonation wave technique, based on high pressure and velocity impact with sufficient energy and thermal shock on the slag deposited on gas contact surfaces, offers a potentially convenient, inexpensive, yet efficient and effective way to supplement existing on-line slag removal method. A slight increase in the boiler efficiency, due to more effective ash/deposit removal and corresponding reduction in plant maintenance downtime and increased heat transfer efficiency, will save millions of dollars in operational costs. Reductions in toxic emissions will also be accomplished due to reduction in coal usage resulting clean and healthy environment.

The present paper reports experimental results on the study of slag removal using single pulse detonation waves. The experiments were carried out at the University of Texas at Arlington Detonation Testing Laboratory. Three different types of slag (obtained from Northern States Power) deposited on economizer, reheater and air-heater were used. The slag were placed at several positions up to a distance of 20 cm from the exit of the detonation tube.

INTRODUCTION

Historically, boiler slagging and fouling as a result of inorganic impurities in combustion gasses being deposited on heat transfer tubes have caused severe problems in coal-fired power plant operation. These problems are fuel, system design, and operating conditions dependent. Ash in conventional power system is known to be a major problem that results in the loss of millions of dollars annually as a result of decrease in efficiency, unscheduled outages, equipment failures, and cleaning requirements. The ash deposition problems persist in both the radiant high temperature environment in the main boiler, where iron-rich phases and/or silicate-based slagging dominates, and in the lower temperature convective pass areas, where both silicate-based and sulfate-based fouling dominate on the superheater, reheater, and economizer tube bundles as shown in Figure 1. These 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 soot blowers and water lances. Soot blower and water lance cleaning devices are 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 alternative methods are especially needed to remove deposits from the

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DOE/HBCU/OMI Annual Symposium, Miami, Fl, March 16-18, 1999

downstream side of heat transfer tube bundles in the convective pass sections. Pulse detonation combustion technology, based on the action of mechanical and thermal shock on materials deposited on heat transfer surfaces, offers potential solutions to many of the slag/fouling deposit problems by providing simple, inexpensive, yet efficient and effective ways to supplement existing ash removal methods, without expensive plant shut down.

SLAG FORMATION AND REMOVAL

The effects of ash and slag deposits on the performance of conventional utility boilers depend upon the inorganic composition of the fuel, boiler design, and the operating conditions of the boiler. The literature on ash-related issues is immense. Overviews of ash-related and compilations of work by many investigators can be found by referring to the work of Couch [1], Williamson and Wigley [2], Benson and others [3], Benson [4], Bryers and Vorres [5], and Raask [6,7]. Current methods to assess and predict ash deposition in utility boilers have been reviewed by Benson and others [8].

During combustion or gasification of coal 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. The size of the intermediate ash species in the flue gas stream, boiler design, gas velocity, and temperature determine how the ash particles are transported to heat transfer surfaces. The ash species are transported to the heat transfer surfaces by several mechanisms based on their size and state. Submicron particles are transported to the surfaces by diffusion and thermophoresis. Larger particles are transported to the surface by internal impacting. Ultimately one has to understand both the size and chemistry of the particles entrained in the bulk gas flow through the boiler in order to understand how ash deposit form.

High temperature fouling occurs in regions of the utility boiler where temperatures exceed the stability of the sulfate-bearing phases (>1700 ^{o}F). Low-temperature ash deposition occurs at temperatures in the range of 1000-1650 ^{o}F. In systems which exhibit low temperature fouling, the sulfate phases dominate the matrix or bonding mechanism between particles. Detailed examination of low temperature deposits shows high level of calcium in the deposits [3]. Formation of low temperature deposits is dependent upon the availability of small calcium oxide particles and the process of sulfation. Low temperature deposits form when small calcium oxide particles in a deposit undergo sulfation through reaction with sulfur dioxide in the gas stream. This reaction produces calcium sulfate which causes particle-to-particle bonding and fills in the available space in the deposits. This pore filling produces very strong, brick-like deposits which are very difficult to remove. Deposits in the convection 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 ability of a deposit to be removed from a heat transfer surface depends upon the strength of the bond between the deposit and heat transfer surface and the strength of the deposit. The methods currently used to remove deposits include soot blowing with steam or air, water blowers/lances, and temperature decrease (causing thermal shock and physical cracking of the deposit) through unit load reduction. The effectiveness of the deposit removal methods depends upon their ability to breakup the deposit and its bond with the heat transfer tube surface. Soot blowers work by breaking the bonds between the deposit and the heat transfer surface, by physically breaking up the deposit with the impact force, and by thermally shocking the deposit causing it to crack. Unfortunately, removing deposits formed on the downstream side of the tube is not possible using conventional soot blowing techniques.

Many power plants which were designed to operate with high sulfur content eastern and central U.S. bituminous coals have been converted to burn lower sulfur but higher non-organic mineral content coal from the western part of the U.S. The ash behavior exhibited for a low-sulfur Western coal is much different than the bituminous coals. The bituminous coals are more prone to produce radiant section wall slagging, while the low-sulfur coal produce convective pass $CaSO_4$ based deposits that are extremely difficult to remove. Fouling of the convective pass surfaces such as the economizer, primary superheater and reheater regions are encountered when firing these western U.S. coals [3]. These sulfate-based deposits, which form on both the upstream and downstream sides of the tubes, significantly reduce heat transfer, thus decreasing efficiency. Pulse detonation technology, which offers the potential of both strong shear forces and shock wave reverberation, has the potential to remove these sulfate-based deposits, even on the downstream side of tubes.

PULSE DETONATION TECHNOLOGY

A detonation wave is physically a combustion process initiated by a shock wave. Detonation waves are very high strength, high velocity combustion waves which are similar to normal shock waves. The detonation wave is a coupled shock wave and combustion process as illustrated in Figure 2. The shock front increases the pressure and temperature similar to a normal shock wave. Immediately following the shock the combustion process adds heat at constant volume. The Zeldovich-Von Neumann-Doring (ZND) spike seen in Figure 2 is the initial shock wave and the combustion process takes a finite amount of time so it follows behind the initial wave. It travels at a supersonic velocity and consequently involves extremely high pressure differentials. A normal deflagration wave, on the other hand, propagates at a subsonic velocity, does not involve shock compression and hence pressure differentials involved are negligible. Depending on the strength and velocity of the combustion shock, waves are known as detonation and deflagration. A deflagration wave is, in many ways, much more complex than a detonation wave. A full strength detonation wave is referred to as a Chapman-Jouget (C-J) wave. Its velocity is approximately 2200 m/sec and its maximum pressure jump approximately 20 times that of the unburned reactants. The velocity of a detonation wave (relative to fresh mixture and normal to itself) is expected to be the same order of magnitude as the velocity of thermal motion of the molecules in the burnt mixture. Typically, for a stoichiometric hydrogen/oxygen mixture at $T_s = 291\ {}^oK$, $P_s = 1$ atm the detonation velocity, final temperature and pressure respectively may be calculated as 2,806 m/sec, 3,583 ^oK, and 18.05 atm. A detonation wave can also be created by adding sufficient energy in a sufficiently short period of time, such as with an arc discharge. This results in an almost immediate detonation wave but requires a very large amount of energy input.

Wave strength and velocity are the important variables for slag/fouling deposit removal applications. The direct impact of shock waves on slag surfaces and its pressure force and thermal impact are basically the major cause of destruction and subsequent removal of the slag deposit. In addition to the shearing potential, wave reverberations established in slag or fouling deposits could be more effective in breaking up and removing ash/slag deposits over large areas. Besides, the wave reverberation in the deposits, the wave also reverberates in the convective path upon which ash is deposited, and, thus remove the deposits on both sides of tube. More probably it is a joint and simultaneous action of several factors associated with or generated by the shock wave that contribute each in its own way to the final effects.

Although it is difficult to give an exact explanation of the complex mechanism that occurs, a simplified picture of individual actions can be summarized as follows:

- Shock wave impinges the slag surface directly and its pressure force causes to remove the slag
- The direct impact of K.E. of exhaust gases from the detonation chamber.
- Deposit cracking and loosening due to stress developed by thermal shock.
- Produce multiple reverberations in cavities of slag.
- Reflection of waves facilitate the removal of slag.
- No moving parts.

The thermal stress due to thermal shock play an important role in particularly low temperature surfaces. In addition to the heating of the deposit surfaces by thermal shock itself, a series of waves impacting into the tubes, will cause the mechanical binding forces among molecules of the deposit to weaken, while a sequence of waves with a high temperature front will generate large temperature gradients and consequent thermal stress, contributing to loosening and breaking of the deposited material. The vibrations excited by the shock waves also play important role in removing slag deposits. After the shock impact, the tubes are displaced from the equilibrium position and start to oscillate with amplitudes that depend not only on the tube stiffness and tube length and natural frequency, but also on the character, quantity and distribution of the deposited material [9]. The overall effects of deposit removal as well as side effects on equipment structure depend upon the initial energy of the shock wave at the detonation chamber exit [10], which can be assumed to be proportional to the product of the volume of the combustible mixture in the active part of the chamber and square of the flame propagation velocity at its open end. The flame propagation velocity depends on the mixture reactivity, its composition, temperature, and pressure, as well as on turbulence [11].

EXPERIMENTAL SET UP AND PROCEDURE

A pulse detonation facility specially designed to study detonation waves at the University of Texas at Arlington (UTA) was utilized to perform experiments on removing boiler slag. The main component 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 the detonation tube, three different type of fixtures to hold the tubes with sample at different axial positions and orientation were fabricated. 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 schematic of the test chamber is shown in Figure 3. The three segment lengths are 7.62 cm, 15.24 cm, and 30.38 cm. Each section has an inner diameter of 7.62 cm and an outer diameter of 13.97 cm. A flange of 1.905 cm thickness 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. The ignition plug is mounted in a 7.62 cm 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. The chamber is sealed by fastening a Mylar diaphragm, 0.254 - 0.381 mm thick, to the open end of the chamber. The closed end of the chamber is sealed by bolting a 1.905 cm thick steel plate to the chamber. This has seven holes in it in addition to the eight bolt holes used to fasten it to the test chamber. One of these holes is used as a sensor port and the other six are used for the injection system. The fuels and oxidizers are injected separately into the test chamber through the end plate.

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. Once the mixture is ignited, the process of the experiment is monitored using three types of sensors. One of each type of sensors is located at each axial station. The first set of sensors used is a set of seven PCB dynamic pressure transducers model 111A24. These transducers measure a change in pressure from initial value of zero to 6894.8 kPa with a response time of 1 microsecond. The second type of sensors used is Type E thermocouples model TCB-031-E, from Medtherm, with a response time of 1 micro second and a temperature range of up to 1000^{o}C. Finally platinum thin film gauges, model PTF-100-20292 from Medtherm, are used to measure heat transfer rates. These gauges have a response time of 2 micro seconds and a full scale range of 16.34 MW/(m^2.^{o}C). Six of these transducers may be used along the wall of the chamber and the seventh one in the end plate. 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 increments with the capability for all types of sensors to be mounted at the same axial locations. The instrumentation 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. The system has 512 kilobytes of memory available for distribution to the channels being utilized. The data acquisition system is controlled by a PC which retrieves the data, stores it on a hard drive, and analyzes the data.

RESULTS AND DISCUSSION

Experiments were performed to investigate the removal effects of detonation waves on the types of slag used and the distance of the slag from the exit of the detonation tube. Voltage readings from the pressure transducers were converted into pressure readings and plotted against time. The pressure plots were used to obtain experimental wave diagram. The time interval between the observed abrupt rise in pressure from adjacent transducers was used to calculate wave propagation speed. All the data were to measure pressure and velocity of detonation waves inside the detonation tube. No measurements were taken at the sample locations.

The pressure developed within the test chamber varied from 250-350 psi for weak and 450-650 psi for strong detonation waves. On the other hand, velocity varied from 1800-3000 ft/sec for weak and 2200-8000 ft/sec for strong detonation waves. Figures 4 and 5 show typical pressure and velocity plots for strong detonation waves. The pressure and velocity are expected to decrease drastically as the wave leaves the exit of the detonation tube. Before every experiment the weight of the tube with the slag attached were measured. After the experiment it was again measured. The difference in the weight of the two measurements gave the amount of slag removed by the detonation wave. The results on slag removal by the detonation waves are discussed below:

Effect of axial location

To study the effect of distance of the slag from the exit of the detonation tube, weak detonation waves were used. The soft slag from air-heater inlet deposit (MTI 96-54) were used. Experiments were performed with slags at distances of 5 cm, 10 cm, 15 cm and 20 cm from the exit of the detonation tube. Two experiments were performed at every location to observe repeatability. Figure 6 shows the percentage removal as function of the distance. The waves were found to chip off about 95% of the slag from all three positions at 5 cm, 10 cm, and 15 cm. From the exit of the detonation tube. The removal dropped to about 90% at 20 cm. This is expected because the wave continuously expands in the chamber after exiting the detonation tube. All eight experiments for this case were performed with weak detonation wave.

Effects of Slag Types

In addition to the distance from the exit of the detonation tube, slag type is also an important parameter. The detonation wave can remove soft slag more easily than the hard ones. Experiments were performed with three different types of slag. The soft slag was the air-heater inlet deposit, medium soft slag was the economizer deposit and the hard slag was reheater deposit. Experiments were performed at two axial locations, 5 cm and 15 cm from the exit of the detonation tube. Again weak detonation waves were used for the experiments. Figure 7 shows the percentage of slag by weight removed for the three types of slag at the two axial locations. The results show that removabilty decrease quite drastically for reheater slag as the distance increases. The weak detonation wave was capable of removing about 65% at 5 cm. It reduced to about 40% at 15 cm.

CONCLUSIONS

The purpose of the present work was to study the feasibility of applying pulse detonation waves for removing coal-fired utility boiler slag. Several conclusions to the development of alternative method over the existing methods of removing slag/ash deposits can be made from this study. The effectiveness of slag removal depends on the strength of the slag. Softer slag are easier to remove. The strength of the wave is also a very crucial factor. Stronger waves are more effective. Studies are required to determine the optimum wave strength which will maintain the pipe integrity at the same time effectively removing slag deposit. Another important parameter is the wave reflection. Thus detonation waves will be more effective on slags deposited in tube bundles as in practical applications.

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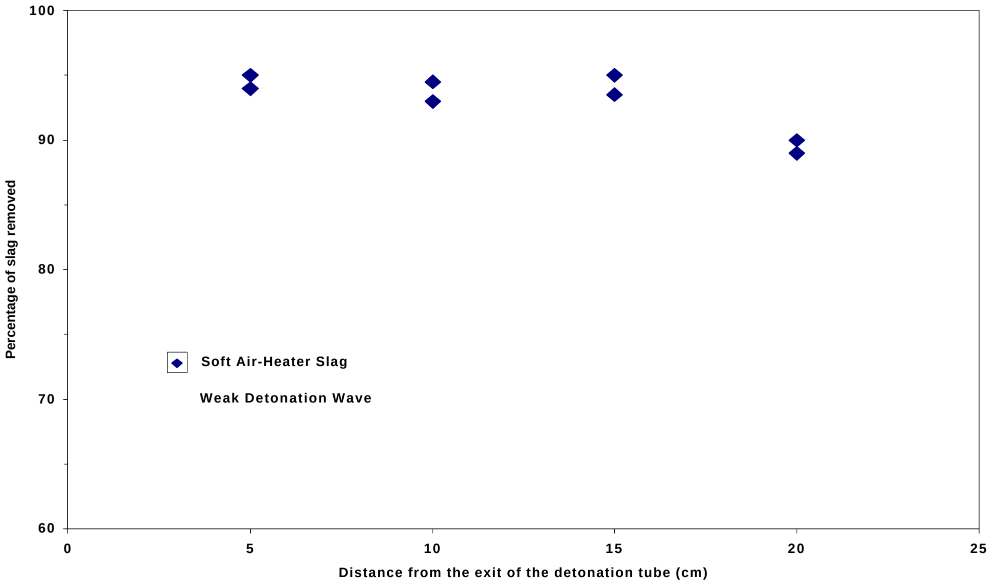

Figure 6. Effect of Axial Positions on Slag Removal

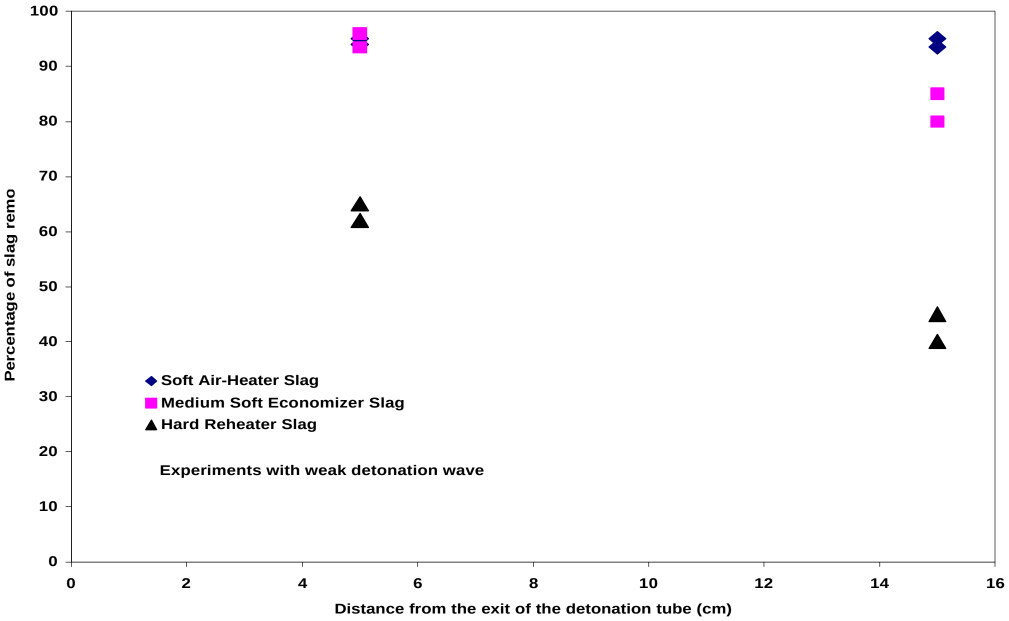

Figure 7. Effect of Slag Type on Slag Removal