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Tensile Strength of Ash Cake Beds at High-Temperature Conditions

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Tensile Strength of Ash Cake Beds at High-Temperature Conditions

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Abstract

The Energy & Environmental Research Center (EERC) is working with Electric Power Research Institute (EPRI) and a consortium of companies in partnership with the U.S. Department of Energy (DOE) to perform the research necessary to determine the factors that cause hot-gas cleanup filters to be blinded by ash or to develop deposits that can bridge the filters and cause them to fail. The primary deliverable will be a graphics-driven computer model that can be used as an engineering tool to help predict ash-related hot-gas filter problems based on analyses of coal and sorbent, as well as system operating parameters.

This paper presents preliminary testing data on determining the tensile strengths of coal ash particles at elevated temperatures and simulated combustor gas conditions. The range in temperatures for tensile testing is ambient to 900°C. The simulated gas atmosphere includes carbon dioxide, water vapor, oxygen, sulfur dioxide, sodium chloride, hydrochloric acid, and nitrogen. At present, all testing has been performed using ash from the Westinghouse advanced particle filter (APF) at the American Electric Power Service Corporation (AEP) Tidd pressurized fluidized-bed combustor (PFBC) demonstration plant in Ohio. Other sources of filter ashes, including several from non-American PFBC systems, will also be evaluated.

Key Words: hot-gas cleanup, powder tensile strength, filter blinding, filter cakes, ceramic filters, high-temperature testing

INTRODUCTION

Large-scale hot-gas testing over the past several years has revealed numerous cases of cake buildup of filter elements that have been difficult, if not impossible, to remove. At times, the cake can bridge between candle filters, leading to high filter failure rates. Physical factors, including particle-size distribution, particle shape, and the aerodynamics of deposition, as well as system temperature contribute to the difficulty in removing the cake. It is speculated that chemical as well as physical effects are playing a role in leading the ash to bond to the filter or to itself.

The Energy & Environmental Research Center (EERC) at the University of North Dakota is working with Electric Power Research Institute (EPRI) and a consortium of companies in partnership with the U. S. Department of Energy (DOE) to perform the research necessary to determine the factors that cause hot-gas cleanup filters to be blinded by ash or to develop deposits that can bridge the filters and cause them to fail. The consortium sponsors are Novem/ECN (Netherlands), PowerGen (United Kingdom), Electricité de France (EDF) (France), Lurgi-Lentjes-Babcock (LLB) (Germany), Schumacher America (Germany/USA), Westinghouse (USA), ABB Carbon (Sweden), and Electric Power Development Corporation (EPDC) (Japan). The research effort is composed of the following four tasks:

- Task 1 – Detailed sampling at large-scale, operational, hot-gas filter test units as well as gathering representative archived samples from completed programs.

- Task 2 – In-depth thermochemical equilibrium modeling, followed by laboratory measurements of the rates and mechanisms of tensile strength development in ash cakes.

- Task 3 – Bench-scale testing of the formation of ash in pressurized fluidized-bed combustors and gasifiers.

- Task 4 – Creating a graphic-driven computer model to tie all of the knowledge together and make possible the prediction of rates of filter blinding and bridging.

This paper presents preliminary data, from Task 2, on determining the tensile strengths of coal ash particles at elevated temperatures and simulated combustor gas conditions.

BACKGROUND

Many factors control the ultimate adhesive properties of ash deposition and the ultimate formation of cakes on rigid ceramic filters. The numerous physical properties coupled with intrinsic forces of attraction create an extremely complicated scenario for laboratory determination. Some of the most pertinent discussions for the description of significant particle characteristics and how they interact to form adhesive properties are addressed in this paper.

The prediction of the ways in which a powder will agglomerate and form cakes is not just a matter of understanding all the ways in which particles can attract one another, but of understanding the way in which the particles fit together in the bulk. Particle shape and size are of importance in controlling the packing and caking properties of powders. Because most particles are not spherical, the first problem is the mathematical representation of the shape of the particles. The term sphericity has been defined as the ratio of the surface area of a sphere having the same volume as a given particle to the actual surface area of that particle (Parfit and Sing, 1976). Particle size and shape are generally expressed as some kind of equivalent spherical diameter.

If the interparticle forces were known, the strength of the cake compact could then be calculated by specifying three-dimensional shapes with specified surface forces and then calculating the strength of the resulting cake compact. This problem is then reduced to size and shape studies on one hand and packing studies on the other. Any attempt to sum the microscopic contributions made by the particles themselves must take into account three factors, all associated with the nature of the particle surface: interparticle forces, the three-dimensional shape of the particle, and the way in which the particle interacts geometrically to form a packed structure.

Most powders are not easily characterized in terms of these microscopic quantities. If the size of a single particle is given as its equivalent spherical diameter, then the definition of particle size by a single parameter is somewhat arbitrary, and in any theoretical study, it will be necessary to use a description of the particle that will define its shape equivalencies. The situation is no less complicated with interparticle forces which are subject to changes in environment and to the effect of their previous history. In real powders, these forces can be of a variety of types (Berbner and Löffler, 1994), including:

- Mechanical forces caused by interlocking of irregular particles.

- Surface tension forces, particularly with powder containing a variable moisture content.

- Forces arising from plastic welding caused by contact points between particles coalescing under high loads.

- Electrostatic forces, particularly for surfaces which easily become charged

- Solid bridge forces, where crystallization at contact points causes joining of the particles.

- Molecular (or van der Waals) forces, particularly significant for particles of small diameters, say less than 10 μm.

It has been stated (Christ et al., 1995) that the main cohesive forces between particles in filter cakes are van der Waals forces. This is especially true for elevated temperatures and small filtration velocities when capillary forces or sinter effects are negligible. The interparticle forces, causing hot-gas filter ashes to become "sticky," are subject to changes in a combustion environment. These forces can be of varying types including those previously identified.

Earlier results show that tensile strength, aerated porosity, and packed porosity measurements are appropriate methods to quantify the adhesive properties for coal ashes. Ash cakes with tensile strengths of less than 50 N/m^2 (0.5 g/cm^2) are likely to have significantly greater dispersement of fine particles, after back-pulsing, than ash cakes with tensile strengths greater than 250 N/m^2 (Miller and Laudal, 1992).

In general, a filter cake detaches from the filter medium when it is subjected to a tensile stress that exceeds its strength. The cake "fails in tension" when the imposed stress exceeds either the internal cohesive strength of the cake or the strength of adhesion to the medium or to a residual dust layer. Most commonly, the cake detaches from a residual dust layer which is finer and more strongly held by the medium. Regardless of how the cake is cleaned from the filter, the maximum stress in the cake occurs at the junction between the cake and the medium.

At present, it is not possible to predict the stresses required to detach an ash cake from a filter media. One approach is to predict qualitatively the tensile strength of a particle compact by using the classic model of Rumpf (Koch et al., 1992). He obtained the tensile forces by summing the strengths of the particle-to-particle contacts which must be broken across a surface in the compact. If the particles are spheres of diameter d_p, the tensile strength is determined by

$$\delta = \frac{f(\epsilon)}{d_p^2} F_H$$

where F_H is the interparticle force action at each contact and $f(\epsilon)$ relates the number of contacts to the void fraction. According to Rumpf (1970):

$$f(\epsilon) = \frac{(1 - \epsilon)}{\epsilon}$$

In terms of the surface energy of the particles (γ), the strength of each contact is given by:

$$F_H = \pi \gamma d_p$$

Other models of particle-to-particle contact give slightly different numerical values, but predict the same dependence on γ and d_p for F_H. Combining the three previous equations:

$$\delta = \frac{\pi (1 - \epsilon)}{\epsilon} \frac{\gamma}{d_p}$$

At present, it is necessary to measure cake detachment stresses directly, because γ depends on dust surface composition, while ϵ and the proportion of active contacts depend on the conditions under which the cake is deposited. The measurements must again be made under conditions as close as possible to those in the real application.

FILTER ASH CHARACTERIZATION

The American Electric Power Service Corporation (AEP) and Ohio Power Company have furnished ash samples from the Westinghouse advanced particle filter (APF) assembly at the Tidd pressurized fluidized-bed combustor (PFBC) demonstration plant. The APF vessel at the Tidd PFBC demonstration plant is approximately 3.0 meters in diameter and 13.4 meters in length. The vessel can contain up to 384 candle filters. The candles can be arranged in three clusters to three different levels. Each cluster contains three plenums, with 38 candles in each of the top and middle plenums and 52 candles in each of the lower plenums.

The APF experienced ash bridging and pressure drop increase during a series of test runs while firing Pittsburgh No. 8 coal and a Plum Run greenfield (PRG) dolomite. There was extensive buildup of ash on all filters. Four series of ash samples have been collected from the Tidd Station. The operation conditions are described in Table 1. During the end of 1994, less ash buildup occurred on the filters, primarily because of the detuning of the P11 cyclone upstream of the APF. Testing at Tidd during 1995 has shown little ash buildup on filters. One reason is the complete spoiling (essentially no particulate removal) of the P11 cyclone in 1995, but coals and sorbents were also changed during the last series of tests. Additional archived samples have been added to the characterization testing program. However, the most substantial testing to date has been on the Tidd samples. Therefore, this paper concentrates on laboratory results from the Tidd Station.

The size distribution of Tidd ash sampled in May 1994 and February 1995 are given in Figure 1. The comparison clearly indicates the finer particle sizes in the "stickier" 1994 ash sample. The upset condition in 1995 resulted in more coarse-grain ash particles getting into the APF vessel, causing the agglomerated ash deposits to be less adhesive than previously observed.

TENSILE TESTING

A measurement of tensile strength of powder deposits is useful for determining the magnitude of the cohesive forces which cause the powder to agglomerate. Key cohesive characteristics that are well defined and can be quantitatively measured are tensile strength and porosity (Miller and Laudal, 1993). A direct correlation exists between the porosity of a powder bed and the tensile forces required to fracture the bed. At ambient testing conditions, as porosity decreases, the tensile strength increases. Meanwhile, porosity is a function of bed compaction and particle-size distribution.

Several procedures and methods exist for determining tensile strengths of powder beds. One such method in use at the EERC is a commercially available instrument called a Cohetester, from Hosokawa Micron International Inc. This instrument directly measures the tensile strength of bulk powders as a function of

TABLE 1

Operating Conditions at the Tidd PFBC

Parameter	May 1994	October 1994	February 1995	May 1995
Coal	Pittsburgh No. 8	Pittsburgh No. 8	Pittsburgh No. 8	Consol and Pittsburgh No. 8
Sorbent	PRG dolomite	PRG dolomite and Bucyrus limestone	Mulzer dolomite	PRG dolomite
Bed Temp., °C (°F)	818 (1504)	855 (1571)	861 (1581)	856 (1572)
Cyclone Inlet Temp., °C (°F)	748 (1378)	793 (1385)	799 (1471)	787 (1449)
APF Inlet Temp., °C (°F)	727 (1340)	760 (1400)	802 (1475)	NA
APF Pressure, kPa (psig)	890 (129)	890 (129)	945 (137)	NA
Upstream P11 Cyclone	Partially spoiled	Partially spoiled	Completely spoiled	Completely spoiled
Filter Cakes	Difficult to clean	Difficult to clean	Easy to clean	Easy to clean

compaction pressure. It consists of a horizontal split cell, 5 cm in diameter, with one-half of the cell movable and the other half fixed. The cell is suspended so that it can be pulled apart with minimal force when no sample is in the cell, minimizing error from external friction forces. However the Cohetester, like all other tensile-testing apparatuses, is designed to evaluate powder beds under ambient temperatures. For the hot-gas filter ash characterization project, tensile strength testing needs to be performed at elevated temperatures (700°–900°C) and in atmospheres similar to PFBC conditions.

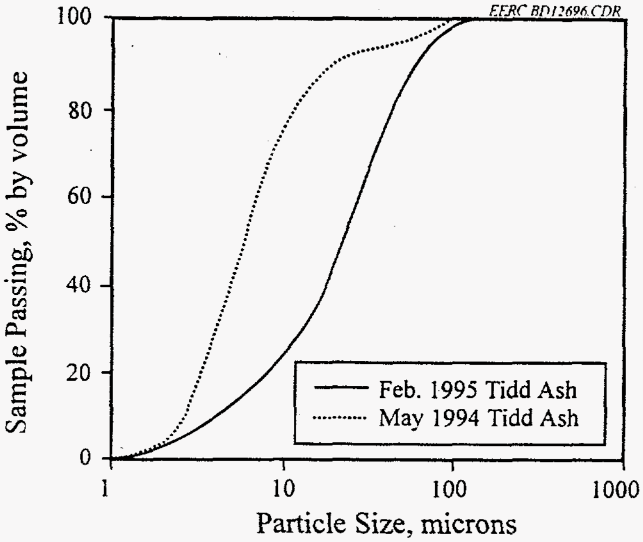

Figure 1. Size distribution of Tidd ash from May 1994 and February 1995.

To evaluate tensile strengths of powders in elevated testing environments, a modification to the Cohetester is used. A schematic of the high-temperature powder tensile strength tester is shown in Figure 2. As in the design of the Cohetester, alleviation of friction problems is accomplished with the use of a movable split cylinder suspended and free to move with minimal resistance. The oven is split in half, with the top portion retractable to allow the specimen chamber to be prepared for sample testing. The suspended spit cylinder half is pulled away from the stationary cylinder half, and the load is measured with a transducer or load cell. Several blank loads, cylinder chamber containing no ash cake sample, have been performed at a range of temperatures. The blank loads are very consistent of one another regardless of testing temperature, generally 10–12 grams force.

The ash samples were prepared for testing by first baking in a 200°C oven. They were then placed directly into the sample holder in the high-temperature tensile tester and allowed to cool for ambient tests. The results of the Tidd ash evaluation from February 1995, at elevated temperatures, is given in Figure 3. In general, strength increases considerably as the ash cakes are compressed and porosity decreases. The blank-load testing (using no ash) showed that the increases in strength were not because of instrument effects caused by the higher temperature of the sample cell.

There is a noticeable trend in the tensile strength increasing with increasing temperature and decreasing void fraction. In addition, the prepared ash cakes have exhibited substantial sintering action at the higher levels of compaction (lower porosity). This indicates that at higher levels of particle packing, which is

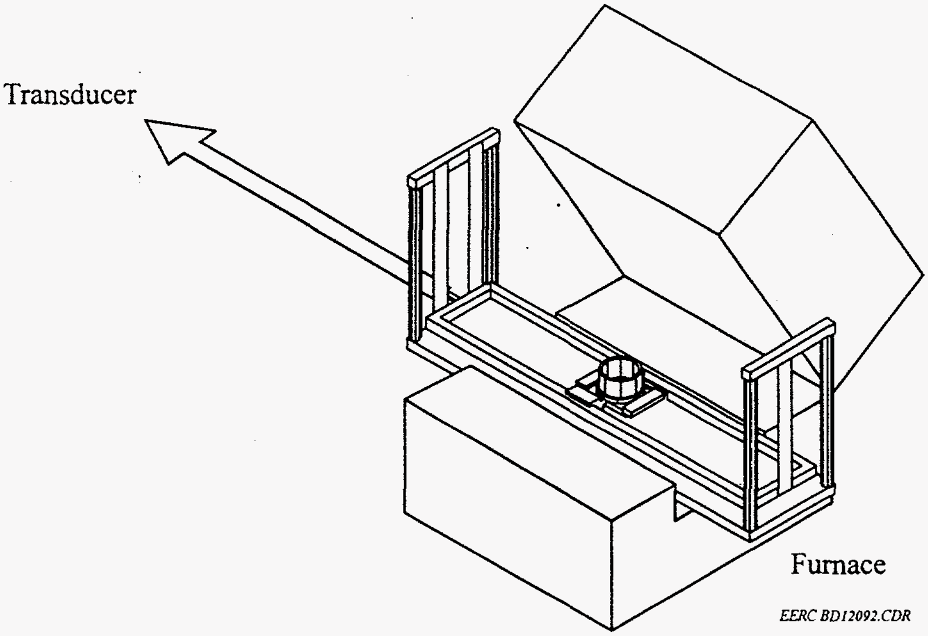

Figure 2. Schematic of the high-temperature powder tensile strength tester.

a function of size distribution, the ash cakes will sinter and gain strength at a higher rate. The cake porosity, which seems to correlate to sintering action, can be used to correlate to pressure drop as well.

The bulk ash from the Tidd Station (February 1995) is also being classified into size fractions for evaluating the effects of size distribution on tensile strength. The size distribution bands of caliper diameter are greater than 10 μm, 3–10 μm, 1–3 μm, and less than 1.0 μm. It is a general understanding that the finer size particles, particularly submicron, have a significant impact on the stickiness behavior of problematic ash. However, introducing larger-size ash particles are not necessarily the solution because of the increased potential to candle filter damage and subsequent corrosion of the gas turbine. An ideal particle-size range is necessary to allow an ash cake to form on a candle, with sufficient adhesive strength to allow the cake bed to be detached without redistributing the residual ash particles elsewhere in the system. All of these properties need to be understood at atmospheres similar to those in the real system.

The high-temperature tensile tester is designed to evaluate powder cake tensile strength while exposed to elevated temperatures and simulated gas environments for short periods of time (less than 1 hour), such as the active cake on a filter.

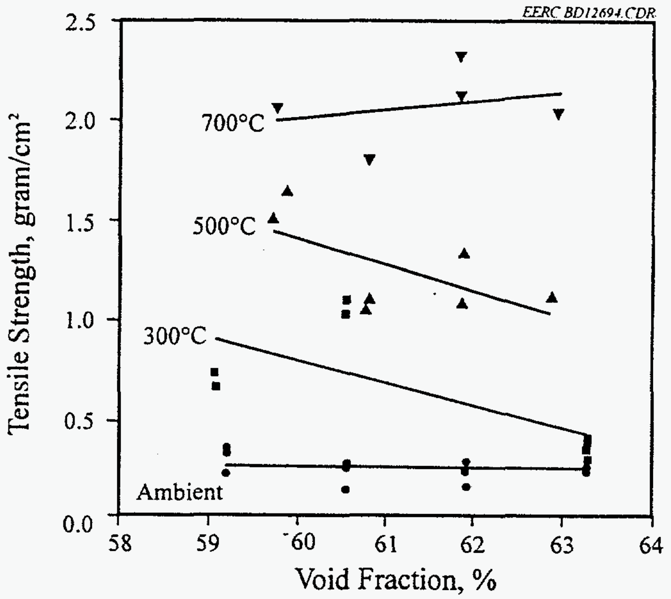

Figure 3. Tensile strength of February 1995 Tidd ash at elevated temperatures.

However, passive ash deposits such as residual cake or shroud deposits may be present for much longer times, possibly sintering to greater strength than can be measured by the high-temperature tensile tester. To test ash strength development over long periods, the long-duration sintering test was developed. A schematic of the sintering chamber is shown in Figure 4. This apparatus will allow the preparation of multiple samples simultaneously. The specimens will measure 1.0 cm in diameter by approximately 1.5 cm in length. The sintered specimens will be tested in diametral compression (Figure 5). This method is commonly used for predicting tensile forces while testing is performed in a compressive mode.

Two tests have been completed thus far for long-term pellet sintering. The first test, using February 1995 Tidd ash, was run at 900°C for 50 hours in an air atmosphere. The second test, using May 1994 Tidd ash, was also run at 900°C, but lasted 120 hours and was in an atmosphere of 30% O_2, 15% H_2O, 3300 ppmv SO_2, 1100 ppmv HCL, 10 ppmv NaCl, and a N_2 balance. In the air atmosphere, little or no sintering occurred. In the simulated PFBC atmosphere, slight sintering does appear to occur, but the resulting strength is still very small. Work on thermochemical equilibrium modeling has indicated that eutectic temperatures, present in hot-gas cleaning environments, might be causing softening of particle surfaces and, consequently, causing the surface stickiness. However, this assessment is at very early stages of the thermochemical equilibrium task and still need to be further assessed. Now that sintering has been correlated to cake porosity and particle packing, pellet sintering can be performed on variable compaction levels and particle-size distributions. More tests will be run at 900°C under the corrosive environment previously mentioned, but for longer periods of time.

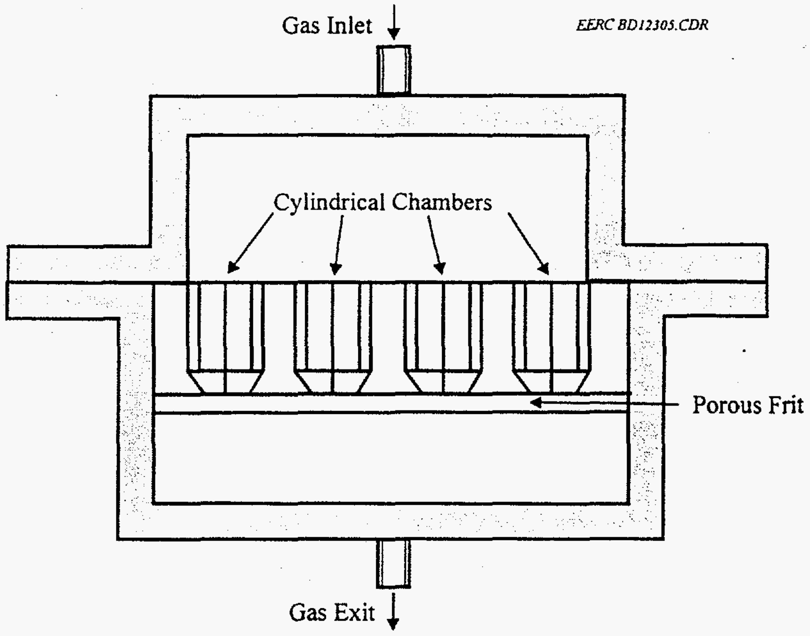

Figure 4. The long-duration ash sintering chamber.

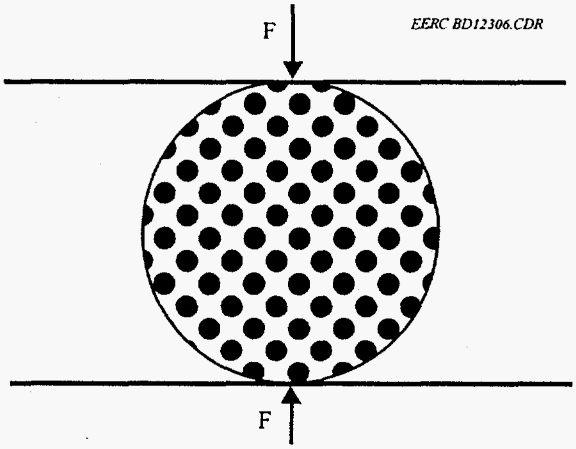

Figure 5. Schematic of the diametral compression test: the stress state is tensile (directed perpendicularly) along the diameter joining the loading points.

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