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The Dynamic Variation of Particle Capture Efficiency During Ash Deposition in Coal-Fired Combustors

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Abstract

Dynamic growth of ash deposits was studied in a carefully controlled environment using high speed video cameras and temperature controlled deposition probes. Deposition data are reported as a function of coal type, extent of particle burnout, and time. Five coals varying in rank from bituminous to lignite were tested. The coals were tested at conditions simulating three locations in a boiler: the near-flame region, the superheater region, and the convection pass. Details of deposit formation were monitored for 90 minutes for each coal at each test condition. A particularly interesting result is that particle capture efficiencies, the fraction of flyash particles which adheres to the probe upon contact, have a strong time dependence, varying from near zero to near unity during deposit formation. Dependence of ash deposition on coal rank and location of the boiler is also discussed.

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Introduction

Mineral matter in coal is referred to as the "nemesis of coal-burning industries" and is cited as the dominant factor in design, operation and fuel selection of boilers.¹ Mineral matter detrimentally affects nearly every aspect of modern boiler operation. This paper discusses one of these aspects: the deposition of material on heat transfer surfaces of boilers. The term *deposition* is intended in a broad context, including both fouling and slagging processes and mechanisms ranging from thermophoresis to inertial impaction.

Ash deposition on heat transfer surfaces of pulverized-coal-fired boilers is influenced by both vapor and particulate properties of combustion gases. Several mechanisms of deposition have been identified, including inertial impaction, thermophoresis, photophoresis, and vapor condensation.²⁻⁴ Recent preliminary models of deposit formation and physical properties are also available.⁵ However, a satisfactory and complete model of deposit formation in practical systems has not yet appeared.

This paper explores one of the complexities of deposit formation: the dynamic variation of particle capture efficiency. Particle capture efficiency, together with the related parameters of impaction and collection efficiency, are defined in this paper as follows. *Impaction efficiency*, η , represents the fraction of particles within the projected target cross section that impact on the target. *Capture efficiency*, γ , represents the fraction of particles that remain (are captured) on the target after they impact. The product of the impaction and capture efficiencies is the *collection efficiency*, and represents the fraction of particles within the target cross section that are collected on the target.

Particle impaction efficiencies on a single cylinder in cross flow have been studied by a number of investigators.^{1-2,6} The dependence of this parameter on particle and gas properties is reasonably well understood, at least for large particles. Most investigators tacitly assume the capture efficiency of particles is uniformly unity. This assumption is reasonably valid when the target surface is viscous. It is the objective of this paper to demonstrate that this assumption is not always valid under conditions common to pulverized-coal fired boilers.

This paper documents a systematic study of deposition rates and characteristics as a function of both coal type and extent of particle burnout under conditions similar to those in three critical regions of commercial-scale boilers. In situ analyses are performed, where possible to help determine the capture efficiency.

Experimental Equipment and Design

The major experimental equipment and facilities used in this study include the multifuel combustor, a deposition probe, and high-speed video cameras. Experimental conditions were selected to represent conditions in commercial-scale, pulverized-coal-fired boilers. The fuels used in the experiment are all industrially relevant, both

in terms of their mineral properties and their use in operating boilers. Facilities, gas conditions, and fuel types will be discussed, in that order.

The Multifuel Combustor

The multifuel combustor (MFC) simulates the local environment commonly experienced by a coal particle as it travels through a commercial-scale boiler. The MFC simultaneously provides sufficient control of and access to the reacting stream to perform scientific measurements. A schematic diagram of the MFC is presented in Fig. 1.

The MFC is vertically oriented with gas flowing from top to bottom. A methane-air flame is stabilized in a gas burner at the top of the MFC. This flame is used to preheat the air stream and supply a vitiated flow for a series of seven heated/insulated modules. Each of these modules provides access ports for fuel lances and thermocouples. The first six modules contain silicon carbide heating elements between refractory layers to control heat loss from the vitiated flow. A more detailed diagram of a module is shown in Fig. 1.

Fuels are introduced into the MFC through any one of the ports. Residence time of the fuel increases as the fuel insertion point is moved up the combustor, and can vary from 0.2 to 3.5 s.

At the exit of the series of modules is an open test section. The test section allows optical and probe access to the particle-laden flow. In these studies, particle size distribution and velocity were measured using a laser-based, *in situ* diagnostic.⁷ Particle behavior was also monitored with high speed video cameras focused on and above a deposition probe, both of which are discussed later. After passing through the test section, the particle-laden stream is vented by an exhaust duct.

Deposition Probe

Deposits from the the particle-laden flow are collected on a deposition probe inserted at the combustor exit. A schematic illustration of the probe is shown in Fig. 2. Compressed air is throttled through the inside of the probe to control the exterior surface temperature. A thermocouple attached to the outside of the probe monitors surface temperature. The probe used in this experiment is made of 3/8-inch (0.95 cm) carbon steel tubing.

The probe is immersed in the particle-laden flow exiting the MFC for 30 minutes prior to each experiment and cleaned with a wire brush immediately before data collection begins. The progress of deposition is monitored as a function of time for 90 minutes. Samples of particulate (char or flyash) are collected for analysis during the experiment. An on-line oxygen analyzer monitors oxygen mole fraction. At the end of the experiment, deposit samples are collected for analyses. Deposit compositions reflect those found in boilers. For example, deposits collected under conditions

Figure 1. A schematic diagram of the Multifuel Combustor. This diagram illustrates the coal insertion lance in the top electrically heated module.

representative of the near flame region of a boiler using high-rank, high-pyrite coals show up to 40 percent enrichment in iron. This iron enrichment decreases to about 20 percent under conditions simulating the superheater region and to about 10 percent under conditions simulating the convection pass.

Figure 2. A schematic diagram of the deposition probe used in this experiment.

High-Speed Video Camera

Spin Physics SP 2000 video cameras were focused on the probe during the experiment. The cameras were operated at 2000 frames per second and recorded a magnified image of the particles interacting with the probe. Segments of film were recorded at 15 minute intervals to monitor the development of the deposit on the probe. Longer time exposure images were also collected to provide streak paths of particle motion. Streak paths provide a measure of the degree of elasticity associated with particles bouncing off the probe.

The combination of lighting, image magnification, and camera resolution allowed particles as small as approximately $25\text{ }\mu\text{m}$ to be resolved. This accounts for most of the particle mass when simulating near-flame conditions and a small fraction of the flyash mass when simulating the convection pass conditions.

Gas and Particle Conditions

These experiments were designed to simulate conditions at three locations in a commercial pulverized-coal-fired boiler. These locations are illustrated in Fig. 3. The firing rate of the MFC was approximately 10 kW/m^2 for the high-rank coals, with some coal-type variation. Typical gas and particle properties at each location are summarized in Table I; the precise properties varied with coal type.

Figure 3. Locations in a commercial-scale boiler simulated by the MFC experiments.

Table I.
Typical Gas and Particle Properties in the MFC
at Conditions Simulating Three Boiler Locations (see Fig. 3)

Property	Location 1	Location 2	Location 3
Gas temperature (°C)	1500	1200	1000
Oxygen mole fraction	0.04	0.03	0.03
Particle residence time τ (s)	0.2	1.1	2.1
Particle burnout (daf)	0.70	0.94	0.99
Particle temperature (°C)	1650	1300	1050
Deposit probe surface temperature (°C)	600	500	500

Coals

Five coals were used in these tests, the most relevant properties of which are tabulated in Table II. Definitions used for the fouling and slagging indices are indicated in the Table and are further discussed by Weingartner.⁸ The variable X in these definitions represents a mass fraction of the indicated component in the ash.

One approach to managing the problem of inorganic deposition in boilers is the use of blended coals as fuels. Deposition behavior of these blends is not necessarily related to those of the parent coals in a simple way. Therefore, one coal blend was included in these experiments. In general, the coals and mineral properties tabulated in Table II form a representative cross-section of industrially important coal and mineral properties.

Table II. Properties of the Five Fuels Used in These Experiments

Property	Beulah	Ill. #6	Ky. #9	Pitt. 8	Blend
Percent ash (dry)	14.4	10.1	14.2	10.68	8.67
Fe ₂ O ₃ (% in ash)	11.7	19.7	19.4	29.0	17.0
High heating value (Btu/lb dry)	10196	12553	11886	13004	13933
Softening temperature (°C, reducing)	1190	1092	1114	1082	1332
Base/Acid ratio	1.12	0.45	1.33	0.54	0.30
Fouling factor $((\sum X_{\text{bases}}/\sum X_{\text{acids}})X_{\text{Na}_2\text{O}})$	8.01	0.67	0.37	0.22	0.11
Slagging factor $((\sum X_{\text{bases}}/\sum X_{\text{acids}})X_{\text{S}})$	2.02	1.91	0.39	2.59	0.50

Results and Discussion

The rate of deposition of inorganic material on surfaces is known to depend on coal type, particle residence time, deposition tube surface temperature, flue gas composition and temperature, and firing rate. The fuel characteristics tabulated in Table II reflect some of these dependencies, as discussed by several authors.⁸⁻⁹ A particle capture efficiency is sometimes used to relate the rate of deposition to the mass flux of particles colliding with a surface. This capture efficiency, which we designate γ , typically is thought of as the propensity of particles to stick on a surface upon collision.¹⁰ The total mass of deposit accumulated on a surface can be expressed in terms of this coefficient as follows:

$$m_d(t) = \int_0^t \gamma(\dot{q}\eta) dt' + O(t) \quad (1)$$

where m_d is the total mass of the deposit per unit surface area and $(\dot{q}\eta)$ is the mass flux of particles colliding with the surface. The term O accounts for other influences on the mass of the accumulated deposit, such as soot blowing. No influence other than those of particle impaction and fluid mechanics was studied during these experiments; therefore, the term O is neglected. A distinction is made between elapsed time t , as in this equation and residence time τ , as in Table I.

Two methods are used in these experiments to evaluate the capture efficiency γ . The first method employs the rapid framing rate of the video camera to resolve the details of particle interactions with the probe. This provides a directly observable measure of capture efficiency. Particles with diameters larger than about 25 μm can be distinguished in the video images. *In situ* particle size measurements indicate that approximately 90 percent of the particle mass flow at the first simulated boiler location ($\tau = 0.5$ s) is attributable to particles with diameters larger than 25 μm . Large particles, with correspondingly high inertia, are more likely to impact the probe than the small particles. Therefore, the direct observation technique is a reliable method of evaluating γ at short residence times. The strongest disadvantage of this method is that large numbers of observations are required to determine small values of γ with high accuracy.

At longer residence times, average particle sizes decrease due to combustion and the method of direct observation is not reliable. A second method of evaluating γ is used at all residence times and is particularly important at later residence times. The second method involves calculation of the mass of deposit on the probe as a function of time and differentiation of the result (see Eq. 1). This, too, can be done *in situ* if the physical dimensions and density of the deposit are known. Physical dimensions are determined from the video images in this experiment and the density is approximated from the deposit composition and morphology measured at the end of each experiment. The disadvantage of this technique is that the deposit bulk density is only known

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Figure 5. Representative variation of deposit mass per unit area with time. These data are from the Pittsburgh 8 coal with a particle residence time in the MFC of about 0.5 s.

The initial values of the capture efficiency are very low for all of these coals at all particle residence times studied, with typical values in the range 0 to 0.005. In most cases, the collisions are nonelastic, with large decreases in particle speed after collision. Particles and the deposit already on the tube surface suffer deformation upon collision to account for the difference in kinetic energy.

The capture efficiency initially increases for all coals at all residence times, eventually attaining values as high as 0.5 to 1. The time required to reach the high values depends on coal type and residence time, varying from a few minutes to hours. Maximum values of the capture efficiency are observed to depend on coal type, firing rate, and combustion residence time (location in the boiler).

As the deposit grows, the flow around the probe is altered. This slightly decreases the average value of η , and therefore of $\dot{q}\eta$, as the probe becomes more streamlined. However, this decrease in $\dot{q}\eta$ is small compared to the increase in γ .

As the deposit grows, it often becomes unstable and collapses under its own weight. This collapse is caused by the additional stress of new particles added to the surface coupled with fluid dynamic forces from the turbulent flow. This deposit shedding generally starts rather slowly. However, in cases such as those shown in Fig. 4 for some of the coals and in Fig. 5, it becomes catastrophic. Both slow and catastrophic deposit shedding imply a negative value for the capture efficiency. In the case of the data illustrated in Figs. 4 and 5, the effective particle capture efficiency sometimes attains negative values with large magnitudes (too large to be conveniently represented on Fig. 4). Deposit mass on the probe decreases significantly, but does not become zero. That is, some residual deposit remains on the tube (see Fig. 5). Capture efficiency then becomes positive again, eventually reattaining values on the order of 0.5 to 1 as the deposit thickness begins to increase for the second time. This second growth results in a denser deposit than obtained during the first cycle. In all cases, the deposit thickness obtained during subsequent cycles exceeded that of the first growth. After significant growth, deposit thickness decreased again by shedding. At steady state, if it is ever attained, the value of γ must be zero. However, the value of γ did not become constant during the 90 minutes of observation involved in these tests. Typically, γ maximizes a few minutes before the deposit sheds. Both the maximum value of γ and the time required to attain this value are typically smaller during the first stage of deposit growth than during latter stages.

Two characteristic features of the function γ are its peak value and the time at which the deposit first sheds, i.e., γ becomes negative. Table III summarizes these two characteristics for each of the experiments conducted in this study. Note that several of the deposits did not shed during these experiments, as indicated by dashes (---). However, the value of γ is time dependent for every coal at each simulated boiler location. Note that the coal feed system of the MFC was unable to deliver the lignite at the same firing rate as the other coals; thus the set of data reported in Table III for the lignite is at firing rate about a third of that of the other coals.

The differences in the behavior of the several coals can, in most cases, be related to properties of the ash of the several coals. The Pittsburgh coal ash contains by far the greatest amount of iron (29% as oxide) but has an overall ash loading similar to that of the Illinois #6 coal. The overall higher capture efficiencies for these two coals reflects the strong correlation between this iron content and deposition behavior. This correlation could be related to both the higher density and stickier nature of iron particles in the flyash. The Kentucky #9 coal ash, on the other hand, has an ash composition very similar to that of the Illinois #6 coal but about 40% greater ash loading. The difference in the frequency of shedding of deposits at short particle residence times correlates with the total amount of ash being deposited. In the case of the Kentucky coal, this total ash is high because of overall ash loading. In the case of the Pittsburgh coal, the rate of deposition is high because of high iron in ash. Finally, the blend of eastern coals, which has the lowest overall iron content and the lowest overall ash loading, exhibits deposition behavior that is strongly influenced by the high-iron Pittsburgh #8 component of the blend. The maximum rate of deposition

before shedding occurs earlier in residence time than is expected based on its ash loading, composition, and the results from the other three high-rank coals.

Table III.
Peak Values and Time at which γ becomes Negative as a Function of Coal Type and Simulated Boiler Location in a Commercial-Scale Boiler

	Coal	Peak value of γ (--)	Time to first deposit shedding (min)
Location 1			
Beulah Lignite	0.05	---	
Pittsburgh 8	0.8	45	
Illinois #6	0.7	75	
Kentucky #9	0.5	55	
Blend		0.2	75
Location 2			
Beulah Lignite	0.6	---	
Pittsburgh 8	0.6	60	
Illinois #6	0.5	75	
Kentucky #9	0.4	60	
Blend		0.1	---
Location 3			
Beulah Lignite	0.7	---	
Pittsburgh 8	0.1	90	
Illinois #6	0.2	---	
Kentucky #9	0.1	---	
Blend		0.05	---

Later in residence time, the lignite dominates the deposition rates. This is attributed to the much larger fraction of condensable species in the flyash. The overall lower rates of deposition at early particle residence times are attributed to the lower firing rate of the lignite (about 6.5 kW/m²).

These particle capture efficiencies show considerable variability, not only with coal type and combustor conditions, but also with time. These time variations are likely associated with changes in deposit properties with time and coupling of fluid dynamic forces with deposit strength. A complete description of surface deposition requires a detailed understanding of these latter two phenomena.

Conclusions

A laboratory-scale combustor has been developed that faithfully reproduces many conditions within commercial-scale combustors. This combustor also allows careful control and analysis of ash deposits and flyash under conditions representing several critical regions of a commercial boiler. This combustor has been used to study key aspects of ash deposition in such boilers.

The data shown in Figs. 4 and 5 and Table III are dependent on the composition, material, and geometry of the surface, gas and surface temperatures, and other parameters that depend on operating conditions of a commercial-scale boiler. Hence, the actual magnitudes observed are specific to the experimental conditions. However, significant qualitative conclusions can be drawn.

Particle capture efficiencies on surfaces of coal combustors are complex functions of coal type, combustor conditions, and time. These series of experiments show peak capture efficiencies that vary by factors of four or more under conditions that differ only in the type of coal being used. Variations of peak particle capture efficiency as high as a factor of 8 are observed under conditions that simulate different locations in a boiler. In addition to these variations, a complex dependence of particle capture efficiency with time is observed for all coals at all simulated locations. This temporal dependence is a feature of capture efficiencies not commonly discussed in the literature. A fundamental understanding of this dependence will require detailed information about the dynamic chemical and physical changes in the surface deposit.

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