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TIME-DEPENDENT DEPOSITION CHARACTERISTICS OF FINE COAL FLYASH IN A LABORATORY GAS TURBINE ENVIRONMENT

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ABSTRACT

Time-dependent deposition characteristics of fine coal flyash were measured in the Turbine Accelerated Deposition Facility (TADF) at Brigham Young University. Two samples of subbituminous coal fly ash, with mass mean diameters of 3 and 13 µm, were entrained in a hot gas flow with a gas temperature of 1250°C and Mach number of 0.25. A nickel base super alloy metal coupon approximately 0.3 cm thick was held in a hot particle-laden gas stream to simulate deposition in a gas turbine. Tests were conducted with deposition times of 20, 40, and 60 minutes. Capture efficiencies and surface roughness characteristics (e.g., Ra) were obtained at different times. Capture efficiency increased exponentially with time while Ra increased linearly with time. The increased deposition with time caused the surface temperature of the deposit to increase. The increased surface temperature caused more softening, increasing the propensity for impacting particles to stick to the surface. These data are important for improving models of deposition in turbines from syngas flows.

INTRODUCTION

The combustion of coal-derived syngas in gas turbines has been the subject of much research. Integrated gasification combined cycle (IGCC) processes combine the abundance of coal resources with the efficiency of a gas turbine combined cycle system. IGCC also allows for cleaner use of coal in that it facilitates CO_2 capture [1] and SO_x , NO_x , and particulate emissions are reduced [2] and [3]. Modern gas turbines can operate with turbine inlet temperatures (TIT) in the range of 1200-1450°C. Small ash particles originating in the coal and remaining in the syngas stream, even after filtration, become soft at these temperatures and begin to deposit on hot turbine surfaces. Crosby et al. [4] investigated the effect of gas temperature on particle deposition and reported a threshold temperature of 960°C, below which no deposition occurred. Above this temperature, deposition increased steadily as gas Thomas H. Fletcher Department of Chemical Engineering Brigham Young University Provo, Utah, USA

temperature increased. This temperature is well below the TIT of modern gas turbines, meaning that ash deposition is bound to occur.

Models, such as those presented by Ai et al. [5] and Tafti et al. [6] have been developed to help predict deposit growth in gas turbine systems. These models take into account parameters and conditions such as gas temperature, particle size, and particle viscosity.

Kim et al. [7] studied the deposition of volcanic materials on hot turbine components. These studies showed that the capture efficiency (the ratio of the mass of material deposited to the mass of material fed through the system) increased with exposure time. To improve existing deposition models, a better understanding of ash deposition as a function of time is required.

The time-dependent deposition characteristics of fine coal flyash (such as that found in syngas streams) were measured in the TADF at Brigham Young University. This includes measuring the time-dependent nature of surface temperature, capture efficiency, deposit thickness, deposit roughness, and ash viscosity. These data can be used to improve upon already existing deposition models.

NOMENCLATURE

- CMM Coordinate Measuring Machine
- d_p Mass Mean Particle Diameter
- h Deposit Thickness
- P_s Sticking Probability
- Ra Centerline-averaged roughness parameter
- t time
- T_g Gas Temperature
- T_{s} Surface Temperature
- T_p Particle Temperature
- T_{soft} Softening Temperature
- TADF Turbine Accelerated Deposition Facility
- TIT Turbine Inlet Temperature

SIC	Silicon Carbide		
η_{cap}	Capture Efficiency		
μ μ _{crit}	Critical Viscosity		

EXPERIMENTAL SETUP Deposition Facility

Experiments were performed in the Turbine Accelerated Deposition Facility (TADF) at Brigham Young University, shown in Figure 1. The TADF is used to simulate deposition that occurs in gas turbines using syngas (such as in an IGCC power plant) on a laboratory scale. The deposition occurs in an accelerated manner, simulating 8000 hours of exposure time in 1 hour by increasing particle loading in the exhaust gas. The use of accelerated deposition testing was validated by Jensen et al. [8].





The combustion chamber is located at the base of the TADF. Natural gas is burned in the combustor and the facility is capable of reaching gas temperatures (T_g) similar to the TIT of modern gas turbines. Coal ash is fed into the base of the combustor and flows up with the combustion gases to simulate particulate in exhaust gas from syngas combustion. The hot combustion gases flow up through a cone that converges toward an equilibration tube. The cone accelerates the gas to velocities of 200 m/s and greater. The equilibration tube is 0.8 m long and allows the gas and particulate flow to reach thermal and velocity equilibrium.

The particulate laden gas exits out the top of the equilibration tube and impinges on a nickel superalloy coupon

held at a 45° angle directly above the equilibration tube. This coupon is the surface upon which deposition occurs. The rate at which deposition occurs is dependent upon the impingement angle of the gas stream on the coupon, with deposit thickness increasing as impingement angle increases [8]. The 45° angle was chosen to allow for an appreciable amount of deposit to be collected in the 1 hour time frame. Coolant air can flow through the coupon holder, allowing for backside cooling of the coupon. For the current series of tests, no cooling was used and the cooling channel behind the coupon was packed with insulation, creating an adiabatic testing condition.

Upgrades

The original TADF was constructed of Inconel 601 and had a maximum operating temperature of $1200^{\circ}C$ [8]. To allow for testing at higher T_g, the inconel acceleration cone and equilibration tube portion of the combustor was replaced with a silicon carbide (SiC) cone and tube. The Grade SC-2 Reaction Bonded Silicon Carbide has a maximum temperature limit of $1500^{\circ}C$. To protect the coupon holder, which is also constructed of Inconel 601, the holder was rebuilt so that a SiO₂ faceplate could be attached to the front side of the holder. The new holder design is shown in Figure 2. The SiO₂ faceplate is shown in Figure 3.



Figure 2: Redesigned coupon holder



Figure 3: SiO₂ faceplate protecting the redesigned coupon holder from high gas temperatures.

Comparison with the Original Facility

After the modifications were completed, a series of tests was conducted to compare the operation of the upgraded facility to the original facility. The tests were conducted at the same conditions as a series of tests performed on the original facility [9]. The capture efficiencies of both series are compared in Figure 4. The capture efficiency is defined as the ratio of the mass of ash deposited on the coupon to the mass of ash fed through the system. It was discovered that deposition was occurring inside the SiC equilibration tube, which did not occur inside the original inconel tube. This deposition surface (i.e. the value of ash fed through the system used in the calculation of capture efficiency). This deposition inside the tube was taken into account by calculating the capture efficiency as

$$\eta_{cap} = \frac{m_{dep}}{m_{fed} - m_{tube}},\tag{1}$$

where m_{dep} is the mass deposited on the coupon, m_{fed} is the amount of ash fed into the TADF, and m_{tube} is the mass of ash that was deposited on the inside of the equilibration tube. After completing a test, m_{tube} was measured by removing the acceleration cone and equilibration tube portion of the combustor and then collecting and weighing the ash deposited in the tube.

When this deposition is taken into account, the calculated capture efficiencies for the upgraded facility are consistent with those obtained from the original facility, as seen in Figure 4. For the tests with a T_g of 1150°C, the maximum difference in capture efficiency between the original facility and the upgraded facility is 1.51%. For the 1100°C tests, there is greater scatter of the new data around the old data, with a maximum difference of 27.2%.

Some of this variation can be attributed to experimental error. The largest contributors to experimental error are tube position, T_g , and deposit recovery.

The tube was removed after each test to gather the ash that deposited inside the tube. The tube position is marked before removing the tube to help ensure that it was placed back in its original position. However, some variation in tube position did occur, affecting how much of the ash deposited on the coupon rather than the holder, which then caused variation in the calculated capture efficiency.

 T_g was controlled manually by adjusting the mass flow of natural gas to the combustor. During the test, the temperature fluctuated around the desired temperature with an average standard deviation 4.5°C. This fluctuation in temperature likely contributed to variation in the calculated capture efficiency.

After the tests, the deposits were collected as soon after shutdown as possible. While the facility is cooling down, some of the deposit on the coupon flaked off of the coupon. Efforts were made to reduce this flaking and to collect any deposit that did flake off. However, this flaking caused some error in measuring the mass of ash that deposited on the coupon. This flaking was more prone to happen at lower temperatures, which resulted in larger variations in the calculated capture efficiency at 1100°C than at 1150°C.



Figure 4: Comparison of capture efficiencies obtained from tests on the original (old) TADF and the upgraded (new) TADF.

Coupons

Metal coupons were provided by industrial contacts. The coupons are made of a nickel based superalloy specific to the turbine manufacturer. An example of the coupons used in this study can be seen in Figures 2 and 3. Each coupon has a front side diameter of 2.5 cm and is 0.3 cm thick.

Ash

The ash used in this study was a subbituminous flyash obtained from the Jim Bridger Power Plant, in Wyoming, through PaciCorp. The as received flyash had a mass mean diameter (d_p) of 13 μ m. Some of the as received flyash was passed through a wheat grinder to obtain samples of flyash with a d_p of 3 μ m. Both the 13 μ m flyash and 3 μ m flyash were used in this test series.



Figure 5: Particle size distribution of flyash used in this study

The particle size distributions for the 13 μ m ash and the 3 μ m ash are shown in Figure 5. The bulk density is 0.99g/cm³ and the apparent density is 1.98 g/cm³ [9].

Temperature Measurement

Two K-type OMEGACLAD thermocouples were placed in the gas stream at the top of the equilibration tube to measure the T_g . Another K-type thermocouple was located 4 cm from the back of the coupon. This thermocouple is normally used to measure the steady state temperature of the coolant. In this case, since no coolant was used, the coolant thermocouple was simply used to determine when steady state was reached.

The temperature of the front side of the coupon was measured using an optical measurement technique. An RGB camera was used to take pictures of the coupon, using XCAP image analysis software. The intensity of the red and blue channels was used to calculate an emissivity and surface temperature (T_s). A temperature map of the whole coupon surface was obtained, along with an average T_s . A more detailed discussion of this method of temperature measurement is discussed by Ai et al. [10] and Lu et al. [11]. The backside temperature of the coupon can normally be measured by the same process. In these tests, however, the backside of the coupon was insulated, making it impossible to take a picture of the backside.

Test Conditions/Process

The test conditions are summarized in Table 1. All of the tests were conducted with a gas temperature of 1250° C. The 13 μ m flyash was used in 7 of the 9 tests and the 3 μ m flyash was used in the remaining tests. Test times ranged from 20 minutes to 60 minutes. The backside of the test coupon was insulated, so heat flux through the coupon is close to 0.

Test #	$T_{g}(^{\circ}C)$	d _p	Time	Particles/m ³	Void
	5	(µm)	(min)	in flow	Fraction
1	1250	13	33	3.34E6	0.9999
2	1250	13	60	3.80E6	0.9999
3	1250	13	60	3.86E6	0.9999
4	1250	13	20	2.49E6	0.9999
5	1250	13	20	2.73E6	0.9999
6	1250	13	40	3.57E6	0.9999
7	1250	13	40	3.48E6	0.9999
8	1250	3	40	4.25E8	0.9999
9	1250	3	20	4.02E8	0.9999

 Table 1: Summary of test conditions

Combustion air entered the TADF at a rate of 0.0214 kg/s and the natural gas flow was adjusted until T_g reached a value of 1250°C. While the target T_g was achieved very quickly, startup of the TADF lasted approximately 1 hour, until the temperature measured by the coolant thermocouple reached steady-state. Once steady-state was achieved, a picture was taken with the RGB camera to get an initial frontside

temperature measurement and the particle feeder was turned on, slowly entraining the flyash into the TADF gas flow. For deposition testing, time was equal to zero until the particle feeder was turned on.

An image was captured with the RGB camera every 10 minutes until the pre-determined end times were reached. This is the case for each test, except for test #1, which ended at the 33 minute mark. Early shutdown was required in this case, resulting in a unique test duration.

After the deposition period, the TADF was slowly shutdown. The coupon and the ash deposit had different coefficients of thermal expansion, causing them to contract at different rates as they cooled down. If the rate of contraction differed too greatly, the ash deposit cracked and flaked off of the deposition surface. This was avoided by shutting the reactor down slowly, lasting 30 min on average. After the TADF cooled sufficiently (usually overnight), the ash deposit was collected and analyzed.

Analysis

The three main parameters that were measured and calculated to characterize the ash deposit after testing were capture efficiency, centerline averaged surface roughness (Ra), and deposit thickness. Capture efficiency was calculated according to Eq. (1).

It should be noted that not all of the ash that deposited after exiting the tube deposited on the coupon. Some of the ash impinged and deposited on the faceplate surrounding the coupon, as shown in Figure 6. This ash was not taken into account when calculating capture efficiency. Only the mass of ash that deposited on the coupon was used in calculating capture efficiency.



Figure 6: a) Coupon and faceplate before any deposition occurred b) Coupon and faceplate after deposition. The circle represents the coupon area. Only ash deposited within this circle was used in calculating capture efficiencies.

After the ash deposit was collected, a surface scan of the deposit was performed using a ROMER INFINITE portable CMM and PC-DMIS metrology software, providing a cloud of xyz points from which peak and valley heights were obtained. The Ra value was then calculated as

$$R_a = \frac{1}{IJ} \sum_{i=0}^{J-1} \sum_{j=0}^{J-1} \left| z_{i,j} \right|, \tag{2}$$

where z is the height of an individual roughness element and I and J are the number of roughness elements in the x and y directions respectively. The roughness analysis was performed on a square section taken from the center of the coupon scan, as shown in Figure 7.



Figure 7: a) 3D surface map of the scan of test 3, b) side view of the surface scan, c) area used to determine Ra for test 3

Given that the CMM scan gives the height of each individual element, the CMM data was also used to obtain the deposit thickness. The deposits were removed from the coupon and placed on a flat surface while being scanned. Since only the deposit was scanned, the deposit thickness is simply the difference between the lowest point and the highest point measured, illustrated in Figure 7b where h is deposit thickness.

The probability that an ash particle will stick to a surface on which it impinges is partly a function of the viscosity of that particle. To better understand the manner in which capture efficiency, surface roughness, and deposit thickness develop over time, the change in particle and deposit viscosity over time was also studied. The viscosity of the ash was calculated using a process outlined by Senior et al. [12] Viscosity can be calculated as

$$\log\left(\frac{\mu}{T_p}\right) = A + \frac{10^3 \cdot B}{T_p},$$
(3)

where μ is viscosity, T_p is the particle temperature, and A and B are parameters dependent upon ash composition.

Tafti et al. [6] discuss the idea of a sticking probability (P_s) , calculated as

$$P_s(T_p) = \frac{\mu_{crit}}{\mu_{T_p}},\tag{4}$$

where μ_{crit} is the critical viscosity, calculated as the viscosity at the softening temperature (T_{soft}) of the particle, and μ_{Tp} is the viscosity at the particle temperature. Any particle with a viscosity equal to or lower than μ_{crit} is assigned a P_s of 1, meaning that the particle is guaranteed to stick when it impinges on the surface. In order to calculate μ_{crit} , T_{soft} is calculated according to the regression formula found in [13]

$$T_{soft} = 92.55 \cdot SiO_2 + 97.83 \cdot Al_2O_3 + 84.52 \cdot Fe_2O_3 + 83.67 \cdot CaO + 81.04 \cdot MgO + 91.92 \cdot a - 7891$$
, (5)

where SiO_2 , Al_2O_3 , Fe_2O_3 , CaO and MgO are weight percents of the respective oxides in the ash and

$$a = 100 - (SiO_2 + Al_2O_3 + Fe_2O_3 + CaO + MgO).$$
(6)

For the ash used in this study, μ_{crit} was calculated to be 9960 Pa·s.

RESULTS AND DISCUSSION Surface Temperature

The increase of surface temperature with time can be seen in Figures 8-9. As an example, Figure 8 shows the development of T_s over the entire surface of the coupon for test 3. Figure 9 shows the increase of the spatially-averaged T_s with time for each test conducted. While each test exhibited its own trend, the overall result was that T_s increased linearly with time. An interesting result can be seen in Figure 9. Tests 1, 3, and 4 each had an initial T_s that differs significantly from the initial T_s of the other tests. However, as time passed and T_s increased for these tests, the T_s became similar to the T_s of the remaining tests.



Figure 8: Surface temperature maps, at 10 minute increments for test 3 ($T_g = 1250^{\circ}C$, dp = 13µm)



Figure 9: Increase of spatially-averaged coupon surface temperature with respect to time

Capture Efficiency

The capture efficiency was calculated according to Eq. (1) for each of the 9 tests and is shown in Figure 10. The capture efficiency increased non-linearly with time. As time approaches zero, the capture efficiency levels off, rather than approaching zero. This behavior is to be expected. A capture efficiency cannot exist at time equal to zero because there is no value for either the numerator or denominator. As soon as ash reaches the coupon surface there will be a certain percentage that adheres to the coupon surface. Thus, at no time can there exist a capture efficiency equal to zero.

A particle size effect can also be seen in Figure 10. The 13 μ m particles exhibited capture efficiencies an order of magnitude greater than those of the 3 μ m particles. This effect of particle size on capture efficiency was previously reported by Ai et al. [14] and Crosby et al. [4]. The current study resulted in a greater difference in capture efficiency between the two particle sizes, but this may be due to the fact that in both of the previous studies, tests were run at a T_g of 1183°C, while the current study used a T_g of 1250°C.

The 13 μ m data can be described by the regressed exponential equation

$$\eta_{cap} = 0.203 \cdot e^{0.0529 \cdot t} + 13.79, \qquad (7)$$

where t is time in minutes. It is suspected that the capture efficiency of the 3 μ m particles also increases exponentially. However, only two tests were successfully completed with the 3 μ m particles. For this reason, only two data points remain and an exponential of the same form as that used for the 13 μ m data cannot be adequately regressed for the 3 μ m data until data are obtained for a 60 minute test.



Figure 10: Time-dependent growth of capture efficiency

Deposit Thickness

The growth of the deposit thickness with time is shown in Figure 11.



Figure 11: Deposit thickness growth with respect to time. 98% confidence band is shown for the 13 µm data.

The deposit thickness increased linearly with time. The best fit linear relationship for the 13 μm data was

$$h = 0.112 \cdot t + 0.0812 , \qquad (8)$$

where h is deposit thickness in mm and t is time in minutes. The y-intercept for this equation was close to zero, which should be expected. At time equal to zero, no ash had yet been fed through the TADF, so no deposit had yet formed on the coupon. When the intercept is forced to be exactly zero, the equation simply became

$$h = 0.112 \cdot t \,, \tag{9}$$

resulting in no change in the first three significant figures of slope. The slope represents an accrual rate of ash on the coupon, with the rate being 0.112 mm/min.

The effect of particle size on deposition was seen again in deposit thickness growth. Using the 20 and 40 minute data points from the 3 μ m series and forcing the intercept to zero, the deposit thickness for 3 μ m particulate can be described as

$$h = 0.0553 \cdot t$$
, (10)

giving an accrual rate of 0.0553 mm/min.

It should be noted again that these are rates for the accelerated deposition testing. For use in industry, these should be scaled appropriately based on the particle density in the flow.

Deposit Roughness

The final parameter that was calculated for deposit characterization was Ra, which was calculated according to Eq. (2), and the results are shown in Figure 12.



Figure 12: Centerline-averaged surface roughness (Ra) development over time. 98% confidence band is shown for the 13 μ m data.

The Ra of the deposit increases linearly with time. The best fit linear relationship for the 13 μ m data was

$$Ra = 10.55 \cdot t - 24.85 \,. \tag{11}$$

It should be noted that the y-intercept of this linear fit is a negative value, which is not physically possible. The initial Ra value of the coupon before testing was $0.3-0.6 \ \mu\text{m}$. Also, it is possible that the coupon surface becomes rougher during startup of the TADF due to heating and possible oxidation of the coupon surface at high temperatures, which would result in a greater Ra value at time equal to zero.

While the linear fit described the data in the 20 to 60 minute range well, it did not work for the whole range of zero to 20 minutes. One possible explanation for this is that the surface roughness develops slower in the zero to 20 minute range as the deposit is first forming and then shifts to the fit given in Eq. (11). Another possible explanation is that the negative y-intercept is simply due to statistical error. The magnitude of the y-intercept is small compared to the reported Ra values and, when extrapolated to zero, the 98% confidence bands take in positive values of Ra, suggesting that the negative intercept falls within statistical error.

Using the 20 and 40 minute data points, the best fit linear regression for the 3 μ m data was

$$Ra = 1.487 \cdot t + 53.71 \,. \tag{12}$$

This regression is questionable because it is only based on two data points. More data, particularly at 60 minutes, is required to obtain a more valid regression.

Ash Viscosity

The viscosity and sticking probability of the ash was calculated according to Eqns. (3)-(4). The viscosity of the ash particles in the gas stream, with T_p equal to 1250°C, was calculated to be 53900 Pa·s, giving a P_s of 0.185. This sticking probability should remain constant during the test because T_g , and therefore T_p , was held constant throughout the duration of the test.

The conditions of the surface on which the particles impinge also have an effect on deposition. For this reason, the viscosity and sticking probability of the ash on the surface of the deposit were calculated as well. The temperature maps, like those shown in Figure 8, were used to calculate the viscosity and sticking probability of the surface ash. After deposition started, the measured surface temperature was the temperature of the ash at the surface of the deposit. For this reason, each pixel on the temperature map was treated as an ash particle and the sticking probability was calculated for each pixel. Rather than representing the probability of a particle at a certain temperature sticking to a surface upon impaction, this probability represents the probability of a particle sticking to a surface ash particle of a particular temperature.

After the P_s values were calculated for each pixel of the temperature map, the P_s values were averaged together, giving a mean P_s for each temperature map. The mean, maximum, and minimum P_s , with respect to time, are shown in Figures 13-15 respectively.

The particles in the gas stream had a T_p equal to T_g . This is the maximum possible temperature for any ash particle, whether it was in the gas stream or deposited on the coupon. For this reason, the maximum P_s possible was 0.185. However, when measuring the surface temperature by taking pictures with the RGB camera, it was possible for the pixel intensity to be too great, resulting in pixel saturation. When this occurred, the temperature could not be accurately calculated for that pixel, resulting in T_s greater than T_g, which was not physically possible. This in turn resulted in P_s values greater than 0.185. To correct for this, any calculated temperature greater than 1250°C was omitted from the calculations for P_s. On average, only 0.77% of the calculated pixel temperatures were omitted.



Figure 13: Increase in average P_s of the surface ash with time.



Figure 14: Increase in the maximum P_s of the surface ash with time.



Figure 15: Increase in the minimum P_s of the surface ash with time.

 P_s can be seen to increase with time as the surface temperature increases. While P_s of the particles in the gas stream is significantly larger than the average P_s of the surface ash particles (ranging from 52.6 times larger at the beginning of the test to 3.96 times larger at the end of the test for the 13 µm data) both probabilities do contribute to the total probability that an ash particle will deposit on the coupon. Therefore, this variation in surface ash sticking probability contributes to the increase in capture efficiency over time.

The distribution of P_s over the entire surface of the deposit for the tests using 13 μ m ash is shown in Figure 16. As expected, the peak in the distribution decreased and the wings of the distribution increased with time. The broadened distributions were due to increased temperatures over more of the deposition surface.



Figure 16: Distribution of sticking probability for pixels over the observed face of the coupon as a function of time.

CONCLUSIONS

The time-dependent deposition characteristics for fine coal flyash from a subbituminous coal were measured in the TADF at Brigham Young University. Two different size distributions of flyash were used in this study, with mass mean diameters of 13 μ m and 3 μ m. Time time-dependent nature of surface temperature, capture efficiency, deposit thickness, deposit surface roughness, and ash viscosity were measured and calculated, resulting in the following conclusions:

1. Net capture efficiency increased exponentially with time.

2. Surface roughness and deposit thickness both increased linearly with time.

3. Surface temperature increased linearly with time, and as such, viscosity and the probability of a particle sticking to the surface increased with time.

4. This increase in sticking probability, along with the increase in surface roughness, likely causes the increase in net capture efficiency.

These data and conclusions provide necessary information to be used to further improve and expand current deposition models to allow for transient modeling.

While the 3 μ m particles are believed to behave in a similar manner to the 13 μ m particles, there is currently insufficient data to obtain confident regressions. More tests with the 3 μ m particles are required at 20, 40, and particularly 60 minute exposure times to obtain the required data for regression.

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