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Modifying Char Dustcake Pressure Drop Using Particulate Additives

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Introduction

Coal gasification produces residual particles of coal char, coal ash, and sorbent that are suspended in the fuel gas stream exiting the gasifier. In most cases, these particles (referred to, hereafter, simply as char) must be removed from the stream prior to sending the gas to a turbine, fuel cell, or other downstream device. Currently, the most common approach to cleaning the gas stream at high temperature and pressure is by filtering the particulate with a porous ceramic or metal filter. However, because these dusts frequently have small size distributions, irregular morphology, and high specific surface areas, they can have very high gas flow resistance resulting in hot-gas filter system operating problems.

Typical of gasification chars, the hot-gas filter dustcakes produced at the Power Systems Development Facility (PSDF) during recent coal gasification tests have had very high flow resistance (Martin et al, 2002). The filter system has been able to successfully operate, but pressure drops have been high and filter cleaning must occur very frequently. In anticipation of this problem, a study was conducted to investigate ways of reducing dustcake pressure drop. This paper will discuss the efficacy of adding low-flow-resistance particulate matter to the high-flow-resistance char dustcake to reduce dustcake pressure drop. The study had two parts: a laboratory screening study and confirming field measurements at the PSDF.

The pressure drop across a particulate dustcake is a function of the morphology of the particles in the cake, the particle size distribution, the dustcake porosity, and the dustcake areal loading. Adding particles that have benign morphology or size or that produce more porous dustcakes could be useful in reducing the overall flow resistance of a dust mixture. However, there are a number of potential problems with this approach:

- It can be difficult to maintain a constant rate of additive injection and to achieve uniform dispersion of the additive particles within the gas stream.

- The filter vessel char discharge system may not be able to handle the extra volume of material.
- The increased areal loading of the dustcake could offset the effect of the decreased flow resistance, resulting in little or no reduction in pressure drop.
- To control the baseline pressure drop, it may be necessary to begin additive injection during startup and continue the additive injection without interruption.
- The cyclonic action of the filter vessel at the PSDF can prevent large additive particles from reaching the filter elements.
- The costs of installing the additive injection equipment and purchasing and handling the additive may be prohibitive.

Despite the potential problems, the threat of extremely high pressure drops and severe restrictions on filter operations was sufficient to motivate the study of various low-flow-resistance additives. Although high pressure drop problems had not yet been encountered at the PSDF, modifications were planned to the gasifier that had the potential to change particle properties substantially. The remainder of this paper will discuss the additives and char selected for the experiments, the laboratory procedure and results, followed by the results of a pilot-scale test of selected additives at the PSDF.

In the following discussion, the flow resistance of a dustcake will be described by the normalized drag or simply "drag". Normalized drag (R) is a function of the pressure drop across the dustcake (ΔP_d), the areal loading of the dustcake (L_a), and the face velocity through the dustcake (V_f), as shown by:

$$R = \frac{\Delta P_d}{(L_a \bullet V_f)}$$

in which R is the dustcake drag in mbar/(g/cm^2)/(cm/sec) or inwc/(lb/ft^2)/(ft/min), ΔP_d is the pressure drop across the dustcake in mbar or inwc, L_a is the dustcake areal loading in g/cm^2 or lb/ft^2, and V_f is the face velocity in cm/sec or ft/min.

Additive Selection

A number of additives were chosen for use in this study, all of which had inherently low drag, and thus, were perceived to have the potential to reduce the drag of a mixture containing high-drag char. Most of the additives were chosen for their ready availability and low cost, but two more-expensive additives were chosen for the unusual structures of their particles. The descriptions of the additives tested are shown in Table 1. The pulverized limestone, sand, coal ashes, and low-drag char were on hand or readily available either at the PSDF or at nearby power plants. The limestone, sand, and PSDF combustion ash were made up mainly of solid, non-spherical, particles. The coal flyashes from Alabama Power's Miller and Gaston power plants tended to be more spherical in nature due to the high temperature of combustion that occurs in pulverized-coal-fired boilers. The AZS-45 material is a catalyst support substrate that was composed of hollow ceramic spheres. Celite is a diatomaceous earth product provided by World Minerals, Inc. The Celite has a very complex structure (see Figure 1) that we thought would be particularly useful in producing an open dustcake structure that would lower the drag of the mixture.

Char Selection for the Laboratory Study

The char that had been produced at the PSDF at the time of the lab measurements did not have sufficiently high drag to be useful for this study. The drag of the PSDF char that was produced during the early gasification programs was only about twice the drag of the additives to be tested. Although some preliminary work was conducted with the PSDF char, most of the data were collected on char generated at the Transport Reactor Development Unit (TRDU) located at the University of North Dakota (Swanson, 2001). The TRDU is similar to the gasifier installed at the PSDF except that the TRDU had a more efficient recycle cyclone system. The TRDU test run was conducted in November 1996 (Test P050) and, as at the PSDF, utilized PRB coal with dolomite as the sorbent. The normalized drag of the TRDU char was three times higher than the drag of the PSDF char and over seven times higher than that of the additives. The higher drag presumably resulted from the more efficient recycle loop and improved gasification. The TRDU char was very fine with a mass-median-diameter of 4.7 microns and, prior to treatment, had a normalized drag over 1400 mbar/(g/cm^2)/(cm/sec) (140 inwc/(ft/min)/(lb/ft^2)).

Laboratory Test Procedure

The effect of particle additives on drag was measured using a system that resuspended both the char and additive particles in a gas stream and collected the resulting dustcake mixture under flowing conditions, as occurs in an actual filter vessel. This system is based on a technique that Schumacher has used for years (Haag and Schultz, 1998), although a number of improvements were implemented for this study (Dahlin and Landham, 2002). The major components of the system are shown in Figure 2. The dust to be measured is resuspended in gas using a fluidized-bed dust generator. The suspended dust enters the center tube of an annular distribution nozzle at the top of the dustcake collection chamber. The outer annulus of the nozzle has a separately controlled gas stream for adjusting the flow patterns in the chamber to produce a uniform dustcake and avoid buildup on the walls. The dust is then collected on a sintered-metal collection filter at constant face velocity. (Since the measurement is made at room temperature, the velocity through the dustcake is corrected for the change in viscosity at high temperature to better simulate conditions in the actual hot-gas filter.) When sufficient dustcake is accumulated for an accurate thickness measurement, the dustcake pressure drop is recorded and the sample collection ended. A measurement jig is fitted to the lower section of the filter chamber and very accurate measurements of dustcake thickness are made at 16 locations over its surface. The sample is then removed from the filter and weighed to calculate areal loading and porosity.

The resuspended dust permeability device has several advantages over other types of permeability measurements. Particularly with dusts that have dissimilar morphology, such as char and additives, collection under filtering conditions may produce more realistic dustcakes. (Results from this study obtained with mechanically mixed dustcakes have convinced us that collecting the dustcake under filtering conditions is critical to accurate simulation of the effect of the additive.) Collecting the sample under flowing conditions also allows an estimate of the porosity of the dustcake in addition to the drag.

Another benefit to simulating the effect on the filter vessel located at the PSDF is the size selective nature of the fluidized-bed dust generator. As operated for these tests, the fluidized-bed will not evolve very large particles (>50 μm). The Siemens-Westinghouse filter vessel at the

PSDF has a tangential gas entry with a shroud that results in some cyclonic separation of large particles before the dust reaches the filter elements. As can be seen from Table 1, many of the additives tested contained a substantial fraction of large particles that would probably be removed by the filter vessel before reaching the filter elements.

The resuspended permeability measurement system also had a disadvantage. For this study, the main difficulty was in determining the actual concentration of the additive in the collected dustcake. Although the two materials were mixed together in the fluidized-bed dust generator in a known ratio, the two components were generally evolved into the gas stream at different rates because of differences in density and particle-size distribution. Therefore, the resulting fraction of additive in the collected dustcake could not be inferred, but had to be measured. Two different techniques were used to determine the actual additive content of the resulting dustcake. For the inert additives (sand, ash, AZS-45, Celite), the combined sample was ignited, and the weight loss-on-ignition (LOI) was used to determine the concentration of inert material that had been added to the high-LOI char. The LOI technique could not be used for the pulverized limestone, which has an LOI value similar to that of the char. Since limestone and char are very different colors, visual colorimetry was used to approximate the concentration of limestone in the blend.

As mentioned previously, many of the additives tested had a substantial fraction of their mass contained in particles larger than 45 μm. We believed that these particles would be removed by the cyclonic separation system integral to the filter vessel and would not be available to modify the dustcake properties. Therefore, to prevent these particles from confusing the experiment, both the additives and char were sieved to <45 μm before they were loaded into the fluidized-bed feeder system. Although most of the experiments were conducted with sieved dusts, the accuracy of the assumption that the large-particle fraction would have no effect on the results was evaluated at the end of the test program.

Laboratory Results

The numerical results of the permeability tests conducted with additives and the TRDU char are shown in Table 2. Figure 3 plots the normalized dustcake drag as a function of the amount of additive that appeared in the dustcake sample. For most of the additives, the normalized drag of the blended sample approximated a linear relationship between the relative amounts of additive and char and the drags of the two pure materials. Since the fine sand was too coarse to evolve from the fluidized bed, it had no effect on the dustcake and is not shown in this figure. The Celite seemed to reduce dustcake drag more than the other materials, possibly because of its open structure.

Although the linear relationship noted between the concentrations and drags of the particles in the mixtures seems obvious, note that experiments with mechanical dust mixtures indicated a much more optimistic relationship where the effect of additives was much greater than that shown here. We believe that the reduced effect observed with flow-collected dustcakes relates to the way that small particles will follow the gas flow streamlines into passages between large particles and fill the passages with plugs of small particles that have high drag. With mechanically created dust mixtures there is no opportunity for the small particles to realign themselves after the dustcake is created producing a dustcake with lower drag at the same average porosity.

Although it was useful in the lab to use sieved additives, in order to understand the full effect on plant operation we have to consider the total amount of additive that must be injected into the duct. As used here, the "bulk addition rate" includes the amount of material that was sieved out of the original additive samples and the fraction that was added to the fluidized bed during the permeability tests. Figure 4 plots the amount of the additives that would be expected to get into the dustcake as a function of the bulk addition rate. As the figure shows, no matter how much fine sand was added, there was none found in the dustcake. The other materials carried over to the dustcake in amounts that were dependent on their particle-size distribution and density. That is, finer, less dense particles carried over better (in higher percentages).

Although the lab tests were conducted with very high concentrations of additives, there is a practical limit on the amount of additive that can be added to a given particle collection system. At the PSDF, the filter vessel hopper dust removal system was perceived to be the primary limitation on the amount of material that could be added to the inlet gas stream. Even if the largest particles of the injected additive are removed by the cyclonic collection of the filter vessel and do not reach the dustcake to modify drag, that mass must still be removed from the hopper. Based on the amount of char being removed from the hopper in normal gasification operation and the known capacity of the dust removal system it was estimated that a reasonable addition rate limit was about 1 part of additive per part of char. The actual limit at any given time will vary depending on the amount of char exiting the Transport Reactor, but this was a reasonable value to work with. The addition rate limit is represented by the vertical dashed line on Figure 4. When this limit is taken into account, it becomes obvious that some of these additives have severe limitations at the PSDF because of their large particle-size distributions.

When the data showing the effect of additives on dustcake normalized drag (from Figure 3) is plotted against the bulk addition rate, Figure 5 is obtained. At the addition rate limit, the effect of most additives on normalized drag is small. Considered this way, the flyash had the largest effect on drag, primarily because of the small size of the flyash and resulting high carryover rate. However, drawing a conclusion based only on normalized drag data can be very misleading, as discussed below.

The results discussed so far only consider the effect of the additives on the normalized drag, which describes their ability to modify the fundamental flow resistance property of the dustcake. However, there is another issue that is equally important to actual filter system pressure drop performance: dustcake areal loading. Since additional material is being added to the dustcake in the form of the additive, the dustcake areal loading will be increased by additive injection. Both normalized drag and areal loading have a directly proportional effect on dustcake ΔP. While these additives produce a reduction in normalized drag, they will have the opposite effect on areal loading and thus tend to negate the beneficial effect on pressure drop. Figure 6 shows the effect of bulk addition rate on the areal loading of the filter system dustcake. The flyash increases the areal loading the most because, as mentioned previously, it has a relatively fine particle-size distribution (that is, not much of the injected flyash is inertially separated in the filter vessel before it can reach the filter cake).

The combined effect of the increased areal loading and reduced normalized drag can be seen in the solid symbols and connecting lines in Figure 7. The net effect is that, for all but one additive, the increased areal loading completely negates the reduced normalized drag and results in no reduction in filter ΔP. Celite was the one material that showed a net positive effect, suggesting that the addition of Celite affects drag more than it affects areal loading.

As described previously, the laboratory tests represented by the solid symbols in Figure 7 were done on samples of additives that were sieved to less than 45 µm. This was done under the assumption that the large particles would escape neither the laboratory fluidized bed nor the filter system cyclonic action and thus would not affect dustcake properties. Also, because of the very high fractions of large particles in some of the additives we would not have been able to obtain high concentrations of additives in the laboratory dustcake using the bulk material. To test this assumption that sieving did not affect the results, one sample of each additive and char mixture was made using the bulk additive at the maximum actual injection rate of equal parts additive and char, by weight. When this mixture was loaded into the fluidized-bed and evaluated with the permeability tester, the data shown by the open symbols on Figure 7 were obtained. As expected, the large fraction did not carryover as readily as did the sieved material, although some differences from the sieved data were noted. Once again these data indicate that only Celite would be expected to have a net positive benefit to filter system pressure drop. In fact, the bulk Celite produced a result that was three times greater than was obtained with the sieved additive, suggesting that the large (>45-µm) Celite particles were carried over to the dustcake at a higher rate than expected. This is not surprising, considering the open structure and low bulk density of the Celite. The aerodynamic particle size of the Celite is considerably smaller than its physical size, and the larger particles may be even more effective at modifying dustcake structure and changing flow resistance than the smaller particles.

Field Evaluation of Additive Injection

It was previously stated that the drag of the char produced at the PSDF during early gasification runs was significantly lower than for the char produced with the same coal gasified in the TRDU. By the end of the laboratory study this was no longer true. Modifications to the gasifier recycle loop changed the nature of the particulate emissions and resulted in much higher normalized drag and higher filter vessel pressure drop. At times, the back-pulse cleaning interval had to be shortened to 5 minutes (close to the minimum of 3 minutes) to remain below the maximum vessel pressure drop of 250 inwc. Injection of selected additives into the large-scale filter system was undertaken in March 2001 during PSDF test program GCT4.

The lab study had suggested that only Celite could be expected to affect filter pressure drop, so the use of Celite was obvious. However, to validate the lab study and to look for unexpected effects that would not have been detected by the permeability measurement, such as improved dustcake cleanability, addition of fine sand, flyash, and pulverized limestone were also evaluated in the larger scale program.

The additives were fed into the inlet gas stream of the hot-gas filter using the system normally used for adding sorbent to the gasifier. The sorbent feeder utilizes a Clyde weigh feeder to add solids to a nitrogen transport line that is connected to the main duct about 18.3 m (60 feet) upstream of the inlet of the hot-gas filter. The suspended additive particles were introduced through a 2.54 cm (1 inch) pipe that was inserted through an elbow in the duct so that the additive was blown into the center of the 20.3 cm (8 inch) main duct co-current with the process stream.

Limestone, fine sand, and pulverized-coal flyash were successfully fed to the filter at rates approximating 1 part additive per part char. None of these additives had any discernable effect on the pressure drop of the filter. Changes to neither the transient dustcake (most likely) nor the residual dustcake pressure drops could be detected. It cannot be conclusively determined whether the lack of response was due to almost complete removal of the additive by the cyclonic effect of the filter system inlet (probable for the sand) or whether the increase in areal loading negated the effect of reduced drag (likely for ash and limestone), but the net effect was as predicted by the lab measurements.

Because of the very low density and fluffy nature of the Celite, initially it could not be fed through the sorbent feeder. Mixing pulverized limestone with the Celite in equal parts by weight allowed the mixture to be conveyed. However, small batches of the mixture had to be used to prevent excessive separation of the components by the fluidization gas that was introduced through the bottom of the feeder vessel. Several good tests were obtained when Celite was fed in a known and controllable fashion. The results of one Celite test are shown in Figure 8. This figure shows the trace of normalized filter pressure drop (normalized to a filter face velocity of 1 ft/min) as a function of time during a Celite injection test. The normalization had to occur because variations in gas flow during the test changed the pressure drop independent of the dustcake properties. The Celite produced a clear reduction in the pressure drop associated with the transient dustcake (as indicated by the reduction in the peak pressure drop value). The net effect of Celite addition was approximately a 30% reduction in the rate of transient pressure drop increase during a cleaning cycle. These results are consistent with the lab results.

Conclusions

Based on both the laboratory and field results, only one of the additives evaluated here would be expected to produce any significant reduction in filter ΔP. These results suggest that the addition of non-porous materials (flyash, pulverized limestone, etc) increases dustcake areal loading as much or more than normalized drag is reduced. Consequently, these types of materials have no beneficial effect on transient dustcake ΔP.

Unlike the other additives tested, Celite appeared to have a positive effect, probably because of its open structure. The open structure of the Celite allows it to modify the dustcake structure in a beneficial way, and the open structure also results in a beneficial ratio of aerodynamic and physical particle sizes that allows the Celite to be carried over into the dustcake in larger particle sizes and concentrations. There could be other materials with these types of characteristics that may be even better than Celite, but we have not identified any at this time.

Unfortunately, Celite is quite expensive compared to the other alternatives tested ($0.35/lb at the time of this test). Considering the relatively small benefit of the Celite in terms of ΔP reduction, the cost of this material would probably be considered to be prohibitive in most situations. There could also be an issue of availability with this material.

Despite the above, there are situations where additives, even those that don't directly reduce dustcake pressure drop, might be effectively used. If collection of a sticky char in the filter vessel is resulting in an increasing residual dustcake thickness and creeping baseline pressure drop, it is possible that adding a particulate additive to the char dustcake could improve cleanability and help prevent further increases. The same might be true for dustcake consolidation problems like those encountered at the PSDF during combustion of petroleum coke with dolomite as a sorbent (Dahlin, Landham, and Hendrix, 1999). In these cases, an inert additive could simply act as a buffer that would prevent the sticky or reactive particles from coming into contact with one another. By separating the particles that would otherwise tend to consolidate, the additive would provide low-cohesivity sites for the dustcake to fracture during cleaning. While this approach could be an effective means of bringing a creeping baseline ΔP under control, it seems unlikely that it could successfully reduce the baseline ΔP after it has already increased.

This study focused on attempting to reduce filter ΔP without significant hardware modifications by adding a low-drag material to the existing char entering the filter vessel. A better approach may be to reduce the inlet char concentration by increasing the collection efficiency of the upstream recycle cyclone. Figure 9 shows how normalized drag, areal loading, and filter system pressure drop change with char particle-size distribution. These data were generated with the resuspended permeability test device with the size-classification modifications described in a companion paper (Dahlin and Landham, 2002). The data indicate that using a cyclone to reduce the median particle size and particle loading to the dustcake reduces the areal loading much more than normalized drag is increased. Thus, in theory, the more large particles that can be removed from the hot-gas filter inlet stream the lower the pressure drop will be. In actual practice, however, particles tend to become more cohesive as size is reduced, and it is likely that baseline creep problems will be encountered with small particle size distributions. However, with the very low char concentrations that would result with a very small median size distribution, high additive levels could be used to prevent stickiness. The use of additives to prevent stickiness with very low char loadings might be a useful approach to maintaining low hot-gas filter ΔP with high drag chars.

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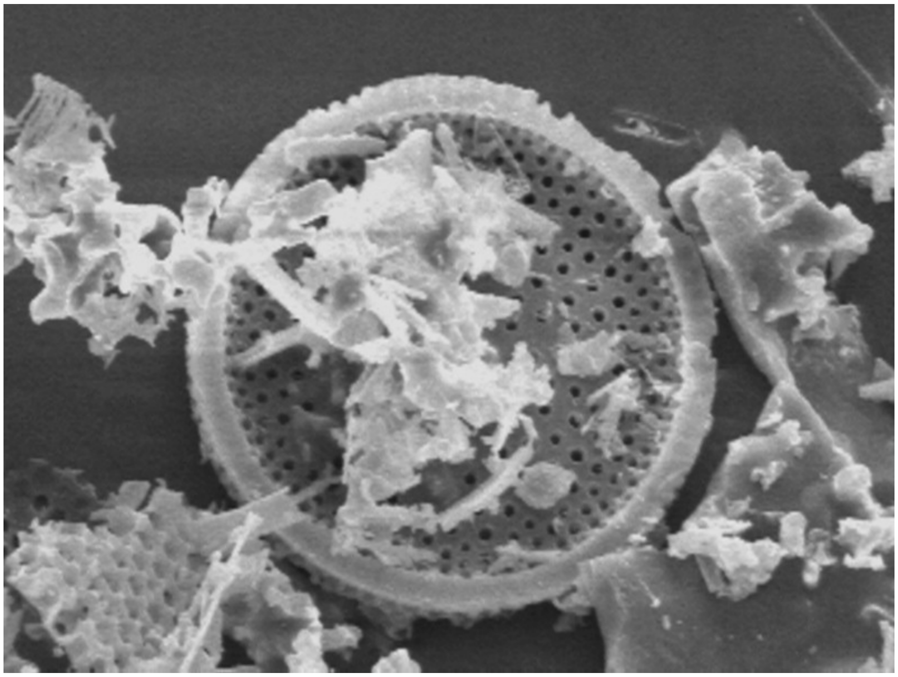

Figure 1. SEM Photo of Celite at 1250x Magnification.

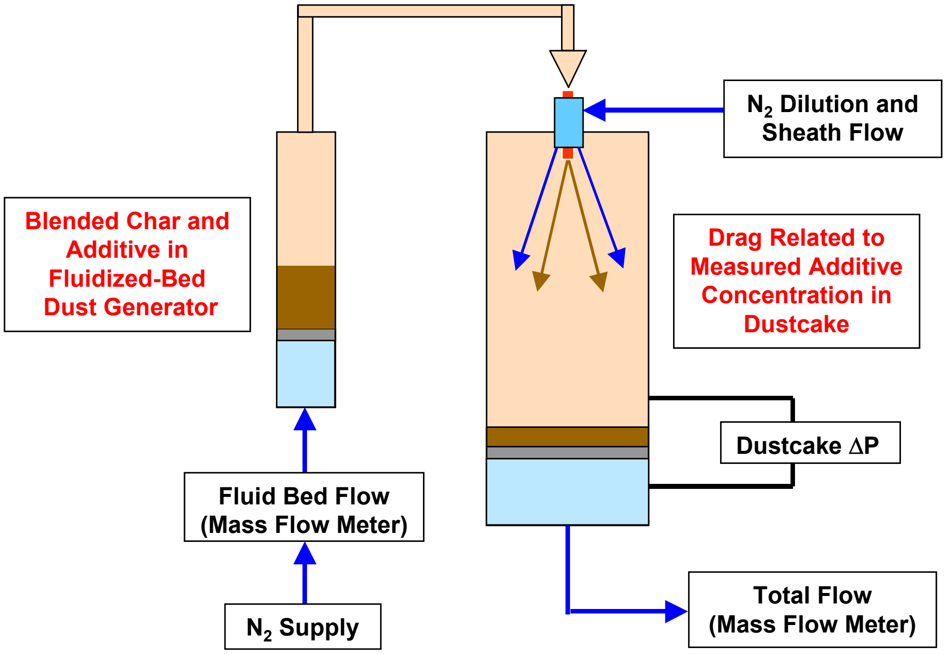

Figure 2. Resuspended Dust Permeability Tester

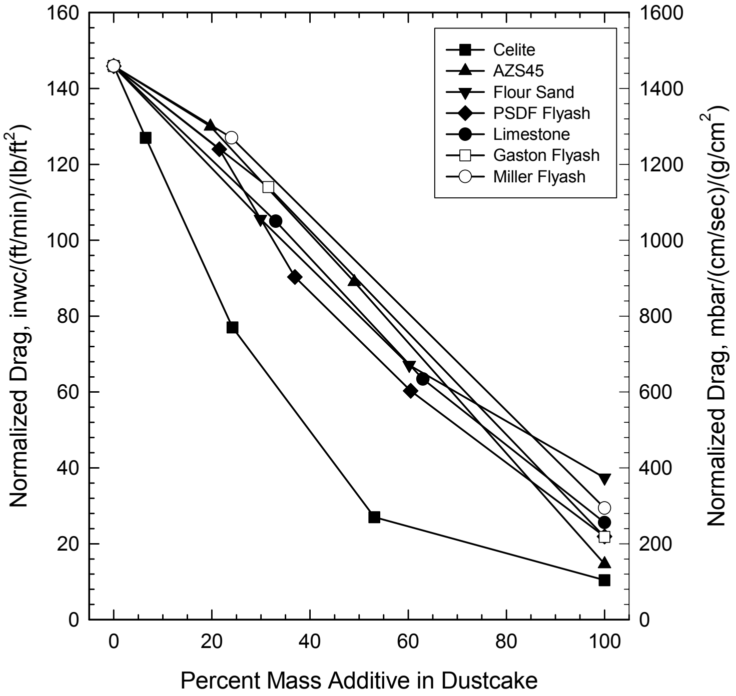

Figure 3. Effect of Additive Concentration on Normalized Drag.

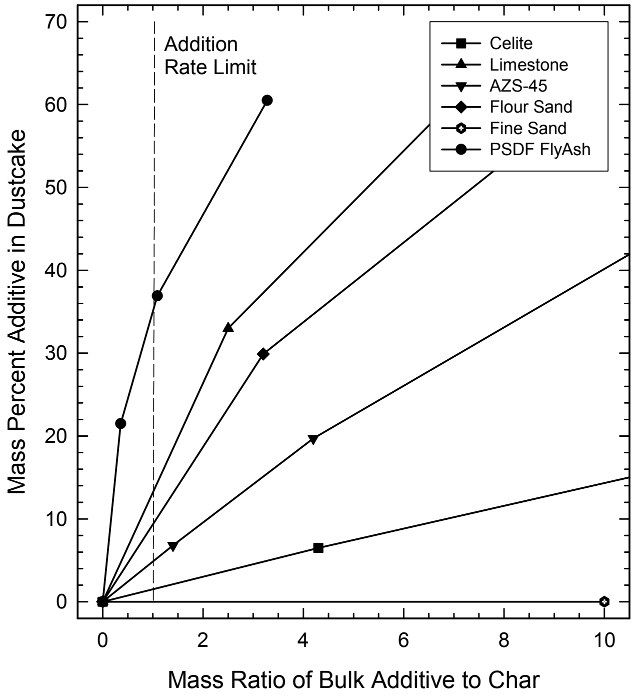

Figure 4. Additive Carryover Rates.

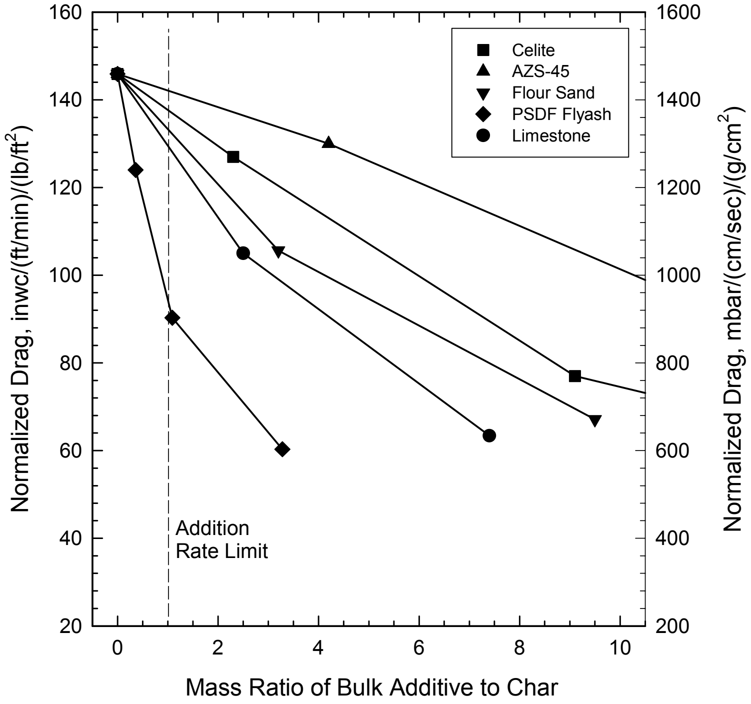

Figure 5. Effect of Bulk Additive Injection Rate on Dustcake Drag.

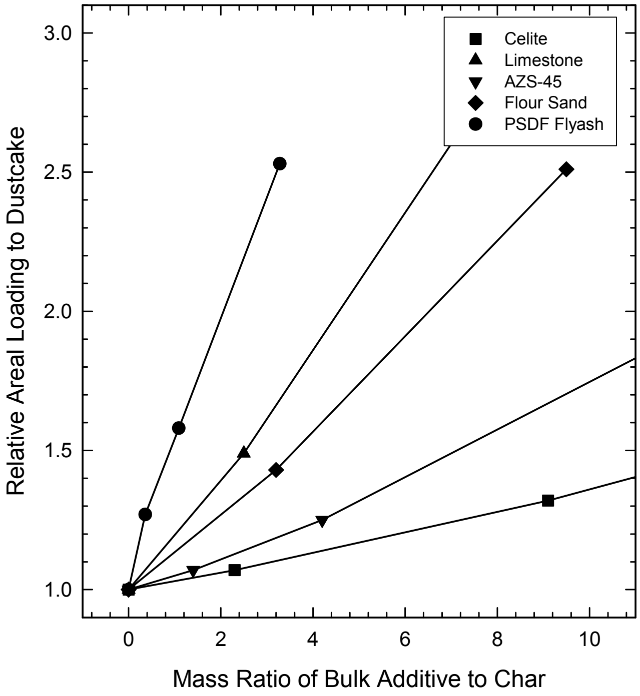

Figure 6. Effect of Bulk Additive Injection Rate on Dustcake Areal Loading.

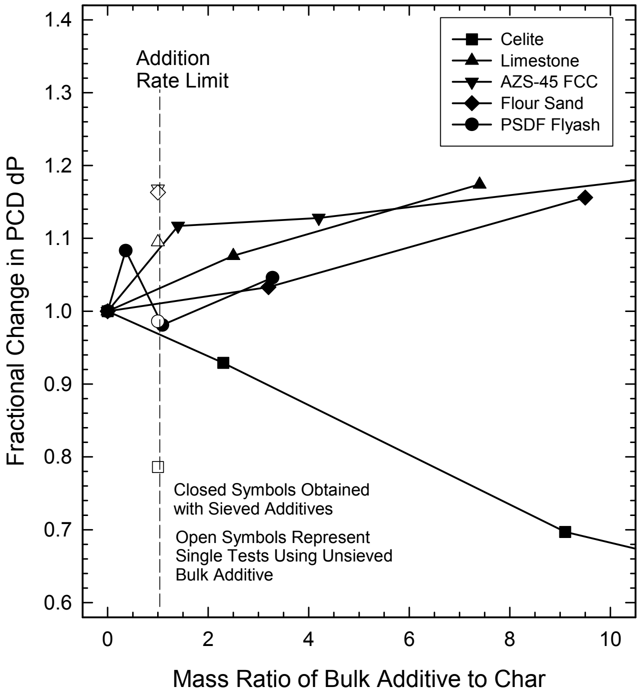

Figure 7. Effect of Bulk Additive Injection Rate on Dustcake Pressure Drop.

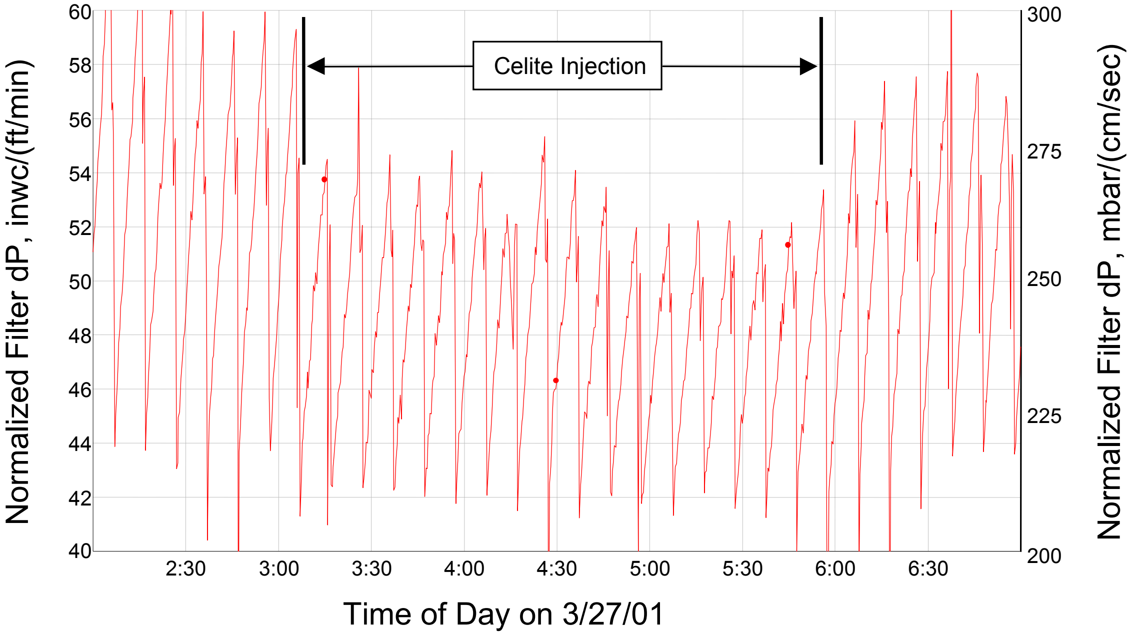

Figure 8. Effect of Celite Injection on Char Dustcake Pressure Drop.

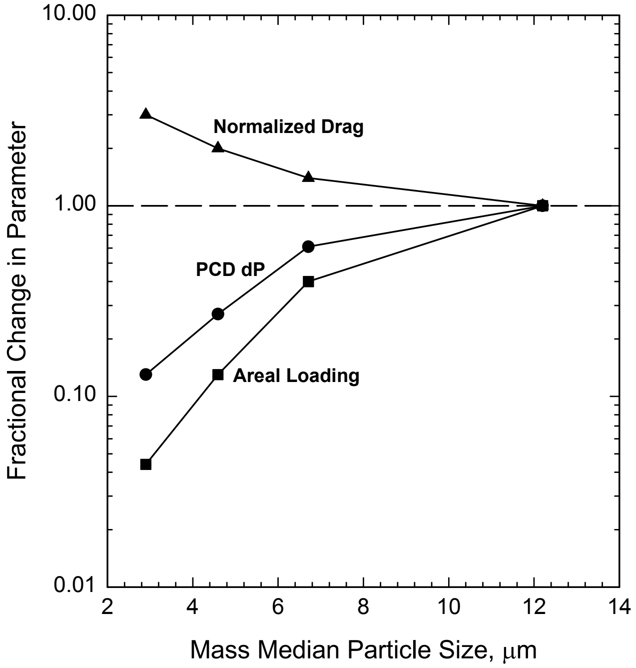

Figure 9. Effect of Char Size Distribution on Dustcake Properties.

Table 1. Additives Evaluated in Drag Reduction Tests

Additive Name	Description	Percent of Additive <45um
Celite	Diatomaceous Earth from World Minerals, Inc.	6
Limestone	Pulverized Longview Limestone	41
AZS-45	FCC Support Media (Spherical Alumina Beads)	24
Flour Sand	Very Fine Pulverized Sand	32
Fine Sand	Wisconsin Fine Sand, Gasifier Startup Bed Material	1
PSDF Ash	PRB Combustion Ash from PSDF PFBC (Run TC05)	91
Gaston Ash	PRB Flyash from PC Boiler at Plant Gaston	70
Miller Ash	PRB Flyash from PC Boiler at Plant Miller	79

Table 2. Drag Results for Resuspended Samples with TRDU Char

Material	% Mass Additive in		Normalized Drag, (1)	Fractional Change in		
	Bed	Dustcake		Norm. Drag	Areal Loading	Dustcake ΔP
Pure TRDU Char	--	--	1465 (145.9)	1.00	1.00	1.00
Celite	20	6.5	1272 (126.7)	0.868	1.07	0.93
	50	24.2	774 (77.1)	0.528	1.32	0.70
	75	53.1	274 (27.3)	0.187	2.13	0.40
	100	100	104 (10.4)	--	--	--
Limestone	50	33	1057 (105.2)	0.721	1.49	1.08
	75	63	637 (63.4)	0.435	2.70	1.17
	100	100	257 (25.6)	--	--	--
AZS-45	25	6.8	1526 (151.9)	1.041	1.07	1.12
	50	19.7	1328 (132.2)	0.906	1.25	1.13
	75	49	894 (89.0)	0.610	1.96	1.20
	100	100	147 (14.6)	--	--	--
Flour Sand	50	29.9	1061 (105.6)	0.724	1.43	1.03
	75	60.2	674 (67.1)	0.460	2.51	1.16
	100	100	376 (37.4)	--	--	--
Fine Sand	50	0	1500 (149.4)	1.00	1.00	1.00
PSDF Combustion Ash	25	21.5	1245 (124.0)	0.850	1.27	1.08
	50	36.9	907 (90.3)	0.619	1.58	0.98
	75	60.5	606 (60.3)	0.413	2.53	1.05
	100	100	220 (21.9)	--	--	--
Flyash (Plant Gaston)	50	31.5	1145 (114)	0.781	1.46	1.14
	100	100	219 (21.8)	--	--	--
Flyash (Plant Miller)	50	26	1323 (131.7)	0.903	1.35	1.22
	100	100	295 (29.4)	--	--	--

1. Units of: mbar/(cm/sec)/(g/cm^2) and inwc/(ft/min)/(lb/ft^2)