**Robert S. Dahlin (Primary Contact)**
Southern Research Institute
Power Systems Development Facility
P. O. Box 1069
Highway 25 North
Wilsonville, AL  35186
Telephone:  (205) 670-5068
Fax:  (205) 670-5916
rsdahlin@southernco.com

**E. Carl Landham**
Southern Research Institute
Power Systems Development Facility
P. O. Box 1069
Highway 25 North
Wilsonville, AL  35186
Telephone:  (205) 670-5990
Fax:  (205) 670-5916
eclandha@southernco.com

# Use of Laboratory Drag Measurements in Evaluating Hot-Gas Filtration of Char from the Transport Gasifier at the Power Systems Development Facility

**Key Words:**  Hot-Gas Filtration, Coal Gasification Char, Dustcakes, Drag

## Introduction

The Power Systems Development Facility (PSDF) is an engineering-scale test bed for advanced, coal-based power generation systems.  Operations and testing at the PSDF are conducted under a cooperative agreement between the U.S. Department of Energy and Southern Company Services, with additional technical support and funding provided by the Electric Power Research Institute, Halliburton KBR, Siemens-Westinghouse Power Corporation, Foster Wheeler, and Peabody Coal Company.  Current activities at the PSDF are focused on evaluating the performance of the Halliburton KBR transport gasifier in combination with a Siemens-Westinghouse candle filter. The design and operation of the transport gasifier and the candle filter have been described in previous papers (Vimalchand et al, 1998; Dahlin et al, 1998; Dahlin et al, 1999; Davidson et al, 1999; Gardner et al, 1999; and Smith et al, 2000).  Recent operating experience with the candle filter is reviewed in a companion paper in these proceedings (Martin et al, 2002).

During recent PSDF gasification tests with a Powder River Basin (PRB) subbituminous coal, the recycle loop on the transport gasifier system was modified to improve solids retention in the gasifier.  As a result of the modifications, particulate loadings to the hot-gas filter were reduced by about half, even with the gasifier operating at higher coal feed rates than those that were used before the recycle loop was modified.  At the same time, the changes in the gasifier recycle loop produced a substantial increase in the transient pressure drop (ΔP) across the hot-gas filter. Some of the observed increase in filter ΔP could be attributed to a shift in the particle-size distribution of the gasifier char, but the change in particle-size distribution was not sufficient to account for all of the observed increase in ΔP.  It was clear that a more-detailed study would be required to fully understand the cause of the increased ΔP.

In addition to the specific issue of the PSDF recycle loop modifications, work that was being done elsewhere suggested the need for a systematic study of the effect of particle-size distribution on hot-gas filter performance.  For example, engineers involved with another DOE clean coal demonstration project had expressed concern about the effect of precleaner cyclone design on the performance of their hot-gas filter (Sawyer, 2000; Robertson, 2002). At the same time, researchers at the PSDF, DOE, and elsewhere had speculated that it might be possible to reduce filter ΔP by shifting the size distribution of the particles reaching the filter cake toward larger particle sizes. DOE subsequently commissioned a modeling study to examine the effect of various filter design modifications on the particle sizes deposited on the filter elements (Ahmadi, 2002). The design modifications that were considered included different types of filter inlets (radial versus tangential) and various modifications of the shroud surrounding the filter elements. All of these modifications were predicted to have varying effects on the loading and size distribution of the particles reaching the filter elements.

Because of the interest in the effects of precleaner cyclones and other types of particle-size modification, and because of the need to understand the effects of the recycle loop modifications, Southern Research Institute and Southern Company Services decided to develop a system for systematically studying the effects of particle size on dustcake drag. The result was the laboratory drag measurement system described in this paper. The remainder of this paper will discuss the objectives, approach, and results of the studies done with the new drag measurement system. In all of the subsequent discussion, the term "drag" will be used to refer to the normalized drag ($R$), which is defined as the pressure drop across the dustcake ($\Delta P_d$) divided by the areal loading of the dustcake ($L_a$) and the face velocity through the dustcake ($V_f$).

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

in which $R$ is the dustcake drag in mbar/(g/cm$^2$)/(cm/sec) or inwc/(lb/ft$^2$)/(ft/min), $\Delta P_d$ 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.

## Objectives

The initial objective of this study was to better understand the reasons for the substantial increase in filter ΔP that was observed after the gasifier recycle loop modifications. Beyond this specific objective, a secondary goal was to develop a meaningful method of evaluating the effect of particle size and other particle properties on dustcake drag and filter ΔP. As mentioned earlier, the effect of particle size on dustcake drag and filter ΔP can be a very important consideration in the selection and specification of a precleaner cyclone for use upstream of the hot-gas filter. Installing a cyclone ahead of a hot-gas filter will reduce the transient areal loading of dust to the filter, but the beneficial effect of the reduced areal loading may be offset by an increase in drag associated with a finer particle-size distribution. The overall goal of this study was to better understand these tradeoffs and to ultimately develop a procedure that would be useful in analyzing the performance of hot-gas filters and in sizing new hot-gas filters.

In addition to the obvious effects of a cyclone on dust loading and particle size, other indirect effects on particulate properties and flow resistance may occur when the cyclone is incorporated into the gasifier recycle loop as was the case at the PSDF. To better understand the importance of these other effects, this study sought to separate the particle-size effect from these other effects by measuring the drag of size-fractionated char samples collected before and after the recycle loop modifications.

## Approach

To examine the cause of the increased filter ΔP and the effects of particle size and other particle properties on ΔP, the laboratory system shown in Figure 1 was developed for measuring the drag of char dustcakes as a function of the particle-size distribution of the char. The laboratory apparatus is similar in principal to the test rig developed by USF Schumacher (Haag and Schulz, 1998), but the new system includes several improvements over the Schumacher rig. In place of the mini-eductor used in the Schumacher rig, the new system uses a 6.4-cm (2.5-in.) fluidized-bed dust generator to suspend the char particles in nitrogen. The suspended particles are then dispersed into a vertical chamber and collected on a 10.2-cm (4-in.) sintered-metal disk filter. Both the fluidized-bed feeder and the dispersion chamber are made of clear acrylic tube so that the resuspension and collection of the dust can be observed while the test is being conducted. At the top of the dispersion chamber, sheath gas is introduced through an annulus around the axial dust injection tube. The sheath gas minimizes dust buildup on the walls of the dispersion chamber and helps promote the formation of a uniform dustcake.

As shown in Figure 1, various combinations of small cyclones are installed downstream from the dust generator to adjust the particle-size distribution of the char being collected. The small cyclones that have been used to date are the first three cyclones (Cyclones I, II, and III) in the Southern Research Institute cascade cyclone sampling system (Smith et al, 1979). The cyclones were used in four different configurations: (1) no cyclone, (2) Cyclone I alone, (3) Cyclone II alone, and (4) Cyclones II and III in series. The cyclones were used without modification, except that the collection cup on Cyclone II was enlarged so that it would not be necessary to interrupt a drag measurement run to empty the collection cup. Under the test conditions used in this study, the four different cyclone configurations typically produced filter catches having mass-median particle sizes of about 10 to 15 μm, 6 to 8 μm, 4 to 5 μm, and 2.5 to 3.5 μm.

During operation of the laboratory drag measurement system, the gas flows through the fluidized-bed feeder and through the sintered metal filter are monitored and controlled using Sierra Instruments Model 810 mass flow meters. In a typical run with PSDF gasifier char, the total gas flow through the sintered-metal filter is maintained at about 23 L/min (0.8 $\mathrm{ft}^3$/min). About 40% of the total gas flow is introduced through the fluidized-bed feeder, while the remaining 60% is introduced as sheath gas at the top of the dispersion chamber. During a test, the flows measured at the flow meters are adjusted for the effect of the increasing system pressure in order to maintain a constant face velocity through the dustcake. To better simulate the compressive force exerted by the high-temperature, high-viscosity syngas, the laboratory system is operated at a face velocity that is significantly higher than the face velocities used in the actual hot-gas filter. Experience with the system to date suggests that a face velocity of about 6 cm/sec (12 ft/min) results in a reasonable simulation of the dustcakes formed in the hot-gas filter at the PSDF.

As the dustcake forms on the sintered-metal filter, the upstream system pressure ($P$) and the total pressure drop across the dustcake and the sintered-metal filter ($\Delta P_t$) are monitored with manometers. The pressure drop across the dustcake ($\Delta P_d$) is determined by subtracting out the pressure drop across the clean sintered-metal filter ($\Delta P_c$), which is measured prior to the run with the same total gas flow, but with no gas flow through the fluidized-bed feeder.

$$\Delta P_d = \Delta P_t - \Delta P_c$$

in which $\Delta P_d$ is the pressure drop across the dustcake in mbar or inwc, $\Delta P_t$ is the total pressure drop across the dustcake and sintered metal filter in mbar or inwc, and $\Delta P_c$ is the pressure drop across the clean sintered metal filter in mbar or inwc.

In a typical run, the dustcake is allowed to build up for about 5 to 10 min, but runs as long as several hours have been conducted, depending on the cyclone configuration being used. At the conclusion of a run, the final value of $\Delta P_d$ typically varies from 100 to 600 mbar (40 to 240 inwc), depending on the dust drag and the duration of the test.

After the drag measurement run is completed, the final $\Delta P$ is recorded, and the fluidizing gas and sheath gas flows are turned off. The system is then disassembled to allow access to the dustcake. To obtain an accurate measurement of the final dustcake thickness, a guide plate is placed above the lower portion of the dispersion chamber, just above the sintered metal filter. The guide plate contains 16 holes that are equally spaced at 45-degree intervals along two concentric circles. A digital depth micrometer (Starrett Model 446AZ) is inserted through each guide hole to measure the dustcake thickness at each of the 16 locations, and these values are used to compute an average dustcake thickness. For PSDF gasifier char, average dustcake thicknesses have typically varied from 0.08 to 0.3 cm (0.03 to 0.1 in.) depending on the cyclones and test parameters used.

After the thickness measurements are completed, the dustcake is then removed and weighed to determine the areal loading of the dustcake ($L_a$). Areal loadings obtained with PSDF gasifier char have typically been in the range of 0.015 to 0.065 g/cm$^2$ (0.03 to 0.13 lb/ft$^2$). The areal loading is used along with the corresponding average thickness measurement to determine the bulk density of the dustcake. Bulk densities have typically varied from about 0.3 to 0.4 g/cm$^3$ (19 to 25 lb/ft$^3$) for PSDF gasifier char produced from PRB coal.

Dustcake porosity ($e$) can be calculated directly from the dustcake bulk density ($r_b$) and the true (skeletal) density of the char particles ($r_t$).

$$e = \left[1 - \frac{r_b}{r_t}\right] \bullet 100\%$$

in which $e$ is the porosity of the dustcake in %, $r_b$ is the bulk density of the dustcake in g/cm$^3$ or lb/ft$^3$, and $r_t$ is the true (skeletal) density of the char particles in g/cm$^3$ or lb/ft$^3$. The true density of the char particles is measured independently by helium pycnometry. PSDF gasifier char produced from PRB coal typically has a true density of 2.1 to 2.3 g/cm$^3$ (130 to 140 lb/ft$^3$).

Porosities of dustcakes formed in the laboratory drag apparatus are typically in the range of 83 to 86%, which is in generally good agreement with the limited measurements of porosity that have been made on char dustcakes formed in the hot-gas filter. The latter measurements are difficult to obtain and may be questionable, because they require preservation of the transient dustcake during shutdown. On several occasions, we have attempted to preserve the transient cake by shutting off the coal, air, and steam flows to the gasifier at the end of a filtration cycle without any subsequent pulse cleaning of the hot-gas filter. To date, we have had only limited success in preserving the entire transient dustcake, but dustcake porosity can still be estimated from the thickness and areal loading of the cake that remains after shutdown. These porosities have generally been in the same range as the porosities of the laboratory dustcakes (83 to 86%).

Dustcake drag is determined from the pressure drop across the dustcake, the face velocity through the dustcake, and the dustcake areal loading using the same relationship that was given earlier in defining the normalized drag:

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

in which $R$ is the dustcake drag in mbar/(g/cm$^2$)/(cm/sec) or inwc/(lb/ft$^2$)/(ft/min), $\Delta P_d$ 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.

It is important to recognize that the dustcake drag values determined by the laboratory technique described above are based on resistance to nitrogen flow at room temperature. For direct application to hot-gas filter analysis and design, these values would have to be corrected for the viscosity differences between nitrogen at room temperature and syngas at process temperature. The correction factor varies with syngas viscosity, which depends on the syngas temperature and composition. Since syngas temperature and composition vary with each gasifier run, all of the drag values reported in this paper are adjusted to laboratory conditions (nitrogen at room temperature). This approach allows direct comparison of the drag values measured in the laboratory apparatus with the drag values determined from hot-gas filter operating data.

## Effect of Particle Size on Drag

Using various combinations of cyclones in the laboratory apparatus, drag was measured as a function of the mass-median particle size of the dustcake. All of the laboratory drag measurements were made on char samples taken from the hot-gas filter hopper during gasification of PRB coal. Figure 2 shows a plot of the measured drag as a function of the mass-median particle size in the dustcake. As shown in this plot, the gasification char produced after the recycle loop modifications had higher drag than did the char generated before the modifications. This was true over the entire range of mass-median particles sizes produced (roughly 2.5 μm to 15 μm). For both types of char, the data on drag ($R$) versus mass-median particle size ($D$) were found to fit a relationship of the form:

$$\log(R) = m \bullet \log(D) + b$$

in which $R$ is the measured drag in mbar/(g/cm$^2$)/(cm/sec) or in inwc/(lb/ft$^2$)/(ft/min), and $D$ is the mass-median particle size in μm. The slope of this equation ($m$) varied from about –1.1 for the char produced before the recycle loop modification to about –0.9 for the other char samples obtained after the recycle loop modifications. This result suggests that the drag is very nearly proportional to the inverse of the mass-median particle size.

As shown in Figure 2, there is a definite difference in the drag of the char produced before the recycle loop modifications versus the drag of the char produced after the recycle loop modifications. The difference is consistent across the entire range of mass-median particle sizes. The specific-surface area of the char was identified as one factor that may be contributing to the difference in drag at a given particle size. As shown in Table 1, the high-drag gasification char that was produced after the recycle loop modifications had specific-surface areas in the range of about 160 to 220 $m^2$/g, while the low-drag gasification char produced before the recycle loop modifications had a mean specific-surface area of about 60 $m^2$/g. It may be inferred from these results that the recycle loop modifications produced a significant increase in surface area, and this increase in surface area played a role in the increased drag of the char. The large difference in surface area apparently reflects a change in particle morphology that affects the flow resistance of the dustcake. The cause of the altered surface area and morphology is not thoroughly understood, but it is apparently related to the recycle loop modifications and the resulting improvements in solids retention and carbon conversion within the gasifier.

Also shown in Figure 2 are drag measurements made on the char from the most recent gasification run in which a new lower mixing zone was added to the gasifier. These data continued to show that the drag was higher than it was before the recycle loop modifications, although the drag of the char produced with the new lower mixing zone is somewhat lower than the drag of the other chars produced after the recycle loop modifications. The lower drag of the char from the most recent testing is interesting, because the recently produced char is very similar to the other post-modification chars in terms of surface area and particle-size distribution.

There were two major differences in gasifier operations between the most recent run and the other runs performed after the recycle loop modifications. As already mentioned, the new lower mixing zone was added to the gasifier prior to the most recent run. Secondly, the amount of steam added to the gasifier was generally somewhat higher in the most recent run than in the previous runs. The char characteristics and hot-gas filter performance are currently being studied in more detail to understand whether the lower drag is related to the new lower mixing zone, to the increased steam addition, or to other factors (e.g., variations in the coal supply). The chars are also being examined by scanning electron microscopy (SEM) to detect any differences in morphology that might affect drag. Regardless of the reasons for the reduced drag, the lab results were consistent with the performance of the hot-gas filter, which also indicated a lower drag in the most recent run.

**Validation of Drag Measurement Technique**

To validate the drag measurements made by this technique, the laboratory drag data have been compared to values of transient drag calculated from the rate of increase in the hot-gas filter pressure drop and the rate of increase in the dustcake areal loading using the following relationship:

$$R_t = \frac{\Delta P}{L_a \bullet V_f} = \frac{\frac{\Delta P}{\Delta t}}{\frac{\Delta L_a}{\Delta t} \bullet V_f}$$

in which $R_t$ is the transient drag in mbar/(g/cm$^2$)/(cm/sec) or inwc/(lb/ft$^2$)/(ft/min), $\Delta P/\Delta t$ is the rate of pressure drop increase across the hot-gas filter during a filtration cycle in mbar/sec or inwc/min, $\Delta L_a/\Delta$t is the rate of increase in the dustcake areal loading in g/cm$^2$/sec or lb/ft$^2$/min, and $V_f$ is the face velocity in cm/sec or ft/min. The rate of increase in the dustcake areal loading was calculated from the particulate mass loading and syngas flow rate measured at the inlet of the hot-gas filter using the following relationship:

$$\frac{\Delta L_a}{\Delta t} = \frac{L_i \bullet W}{1 \times 10^6 \bullet A}$$

in which $\Delta L_a/\Delta$t is the rate of increase in the areal loading of the dustcake in g/cm$^2$/sec or lb/ft$^2$/min, $L_i$ is the inlet particulate mass loading in ppmw, $W$ is the syngas flow rate in g/sec or lb/min, and $A$ is the total active surface area of the filter elements in cm$^2$ or ft$^2$.

The value of $\Delta P/\Delta t$ was determined from the hot-gas filter $\Delta P$ trace recorded during the same time period in which the inlet particulate loading ($L_i$) and gas flow rate ($W$) were measured. As shown in Table 1, the inlet particulate loading ($L_i$) was typically about 31,000 ppmw before modification of the recycle loop and was reduced to about 15,000 to 18,000 ppmw after the recycle loop was modified. Depending on the coal feed rate and process conditions, the syngas flow rate varied from about 2.7 to 3.7 kg/sec (350 to 480 lb/min), and the face velocity varied from about 1.5 to 1.9 cm/sec (2.9 to 3.7 ft/min).

To allow direct comparison with the laboratory drag data, the drag values determined from the hot-gas filter operation were corrected to laboratory conditions using the following relationship:

$$R_n = R_t \bullet \frac{m_{nitrogen}}{m_{syngas}}$$

in which $R_n$ is a normalized value of drag that can be directly compared to the laboratory measurement, $R_t$ is the transient drag that was computed from the hot-gas filter performance, $\mu_{\text{nitrogen}}$ is the viscosity of nitrogen at room temperature (184 μPoise), and $\mu_{\text{syngas}}$ is the viscosity of the syngas at the hot-gas filter operating conditions in μPoise.

Figure 3 shows a comparison between the lab-measured drag values and the normalized drag values determined from the ΔP rise in the hot-gas filter. The transient drag values for the hot-gas filter were determined from the filter ΔP and gas flow rate recorded by the plant data acquisition system during time intervals that corresponded as closely as possible to the times when the inlet char loading was measured. The laboratory drag data were obtained from the regression fits of drag versus mass-median particle size at the mass-median particle size of the inlet char sample that was taken to measure the inlet char loading. Again, all of the drag values have been normalized to laboratory conditions for comparison.

As shown in Figure 3, there is considerable scatter in the data, but the overall trend shows that the laboratory measurements do a good job of tracking the normalized drag values from the hot-gas filter. The variation in the hot-gas filter transient drag within each test program may be partly attributable to changes in various process parameters such as air-to-coal ratio, steam-to-coal ratio, and gasifier operating pressure and temperature. These parameters could conceivably have an effect on the morphology and drag of the char, and no attempt has been made to do a systematic study of these effects. Despite these effects, the average values of transient drag calculated for each test program are in good agreement with the corresponding values of the average lab-measured drag. The overall comparison of the laboratory data with the hot-gas filter drag suggests that the drag measurements obtained with the laboratory system are meaningful, and this procedure can be used as a basis for studies of the effect of particle size and other particle properties on drag.

## Conclusions

The increase in filter $\Delta P$ associated with the recycle loop modifications cannot be explained by the changes in particle loading and size distribution. The primary factor contributing to the elevated $\Delta P$ appears to be a dramatic increase in the specific-surface area of the char. Surface area per se may not be the culprit, but it may reflect a change in particle morphology that affects flow resistance. Because of this effect, a modest improvement in the efficiency of the recycle loop resulted in a dramatic increase in dustcake drag and filter $\Delta P$.

In cases where a cyclone is installed upstream of the filter, but *not* incorporated into the gasifier recycle loop, the effects on specific-surface area and particle morphology may be small, and the reduction in particulate mass loading may be sufficient to offset the effect on drag and produce a net reduction in transient $\Delta P$. If the particle-size distribution is shifted too much toward fine particles, however, there may be an adverse effect on the stickiness of the dust, resulting in thicker residual dustcakes and higher baseline $\Delta \mathrm{P}$.

In the absence of any effects on char stickiness, the dustcake drag values measured by the laboratory technique appear to be in good agreement with the normalized transient drag values determined from the hot-gas filter $\Delta P$ rise, face velocity, and inlet particulate loading. The results given here suggest that this type of laboratory drag measurement may be a useful tool to assist in the evaluation of hot-gas filter performance and in the sizing of new hot-gas filters.

In addition to the work described in this paper, the new laboratory drag measurement system has been used to study the effect on dustcake drag of various particulate additives (sand, limestone, pulverized-coal fly ash, and diatomaceous earth). The results of the additive study are discussed in another paper in these proceedings (Landham and Dahlin, 2002). The additive study showed that certain low-drag additives could be used to reduce the drag of char dustcakes, but the reduction in drag was generally offset by the increase in transient areal loading, resulting in no net reduction in filter $\Delta P$. This was true of all of the additives studied, except for one form of diatomaceous earth that had a very open (skeletal) morphology.

## Future Work

At the present moment, the new laboratory drag measurement system is being used to analyze the performance of the hot-gas filter during ongoing gasification runs at the PSDF. The most recent measurements have shown that the drag of the gasification char continues to be higher than the drag of the char produced before the recycle loop was modified. Data from the latest gasification run suggest that a slight reduction in drag has occurred as a result of the addition of the new lower mixing zone or some other change in gasifier operations or in the coal supply. The char characteristics and hot-gas filter performance are currently being studied in more detail in an effort to better understand the factors that are affecting drag. The chars are also being examined by scanning electron microscopy (SEM) to detect any differences in morphology that might affect drag.

Future gasification tests at the PSDF will examine the effects of several different process changes, including: char recycle to the gasifier, oxygen-blown operation, and gasification of different types of coal (bituminous versus subbituminous). All of these process changes have the potential to affect char properties and drag. Additional laboratory drag measurements and a variety of other char characterization tests will be applied to understand the effects of these process changes on the char. This type of work will continue in an effort to develop a better understanding of how these changes affect hot-gas filter performance and to build confidence in the laboratory drag measurement technique as a tool for analyzing filter performance and sizing new hot-gas filters.

Additional work is needed to better understand how char particle size and surface area affect particle stickiness and dustcake buildup. Studies of these effects will require a laboratory system capable of operating at elevated temperatures to simulate the stickiness of the char under process conditions. The feasibility of building such a system is being investigated.

## Acknowledgments

The initial design of the laboratory drag measurement system described in this paper was based on a similar system developed by Schumacher Umwelt und Trenntechnik GmbH in Crailsheim, Germany. Schumacher personnel, particularly Karsten Schulz and Walter Haag, provided many helpful comments and suggestions during the design, assembly, and initial testing of the new drag measurement system. On-site SRI technicians, Terry Hammond and Jamie Barrett, were responsible for operating the drag measurement system and obtaining all of the data discussed in this paper. This work was funded under Cooperative Agreement No. DE-FC21-90MC25140 between the U.S. Department of Energy (DOE) and Southern Company Services (SCS). The Project Managers on this work included James Longanbach of DOE, Howard Hendrix and Xiaofeng Guan of SCS, and Duane Pontius and Vann Bush of Southern Research Institute.

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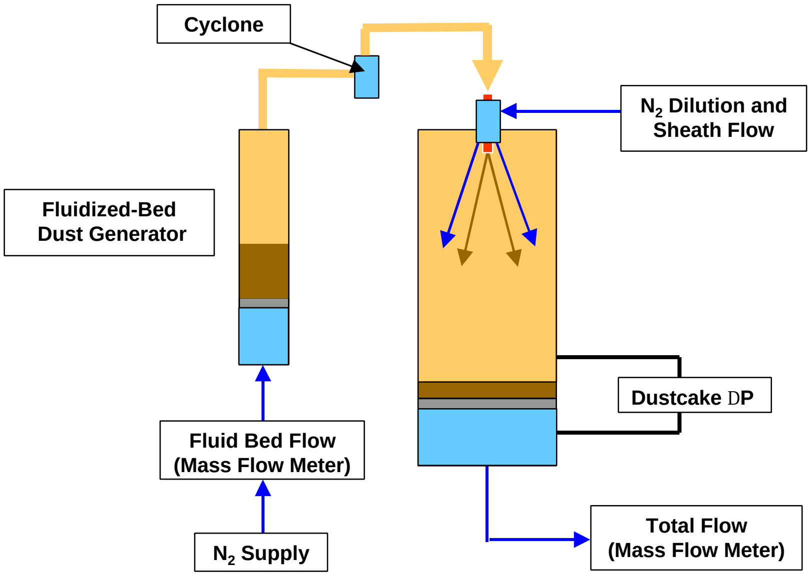

Figure 1. Laboratory Apparatus for Measuring Drag as a Function of Particle Size

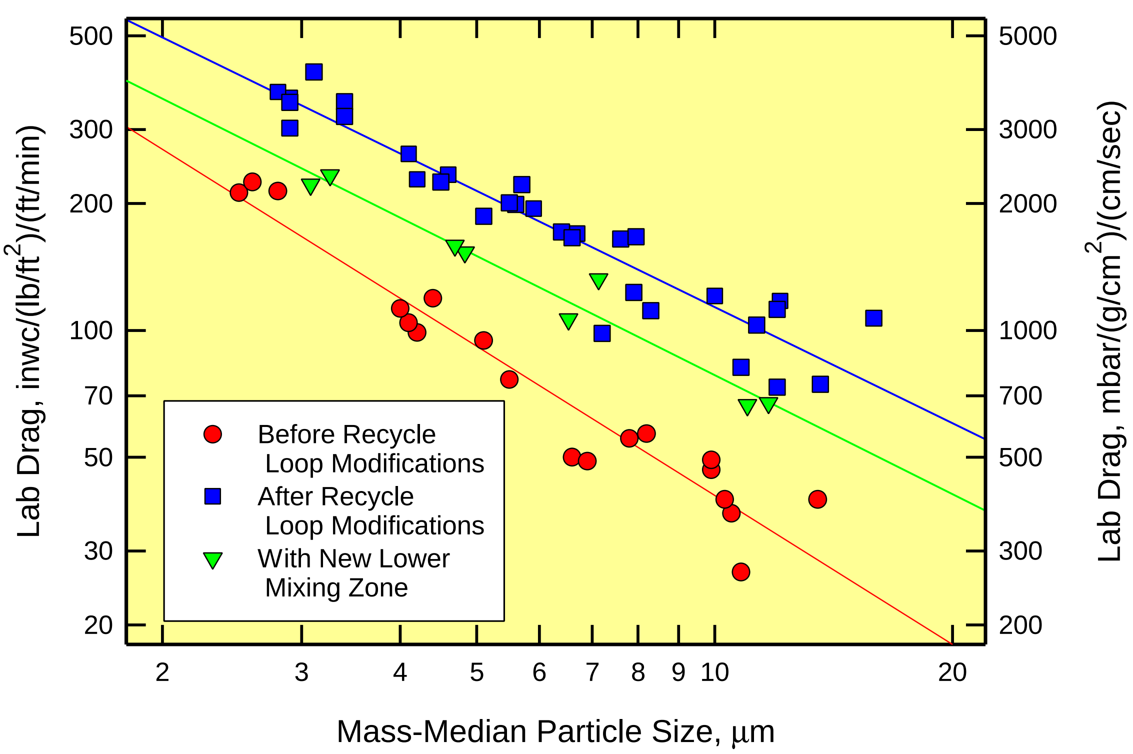

Figure 2. Laboratory Drag Measurements as a Function of Mass-Median Particle Size
(Lab Data Obtained with Various Combinations of Cyclones in System)

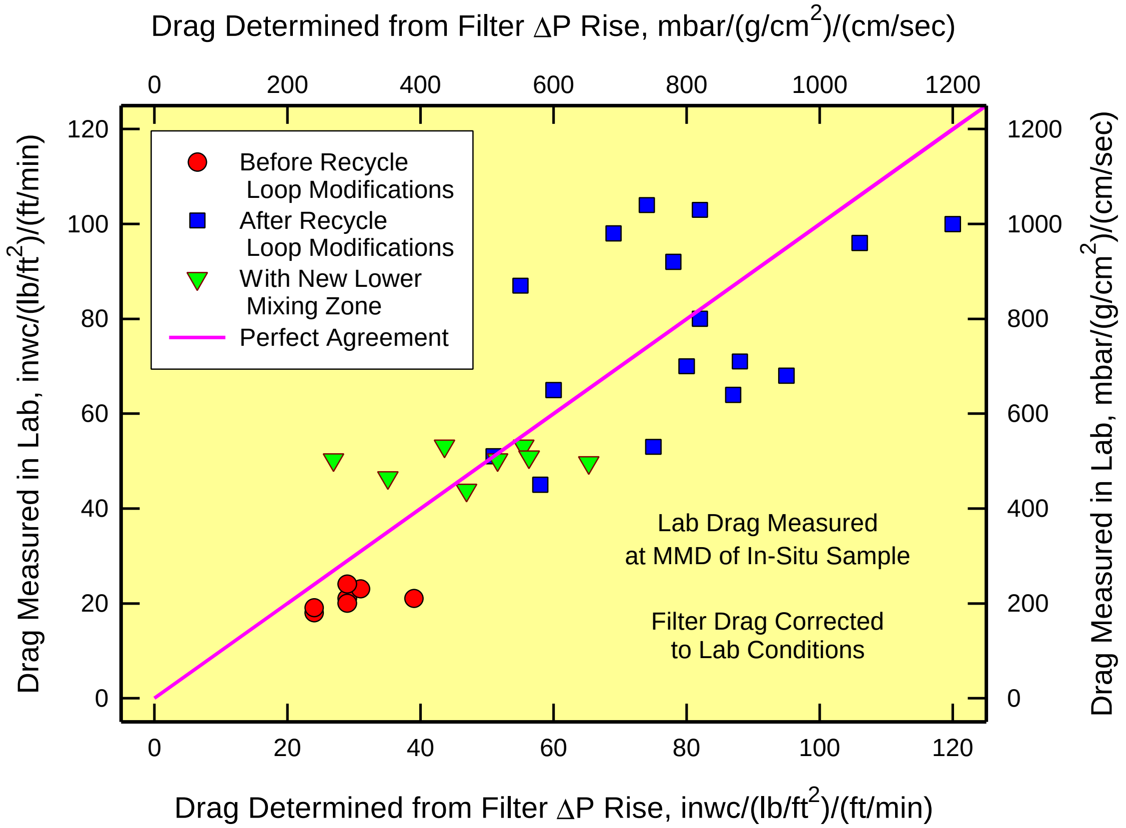

Figure 3. Comparison of Lab-Measured Drag with Drag Determined from Filter ΔP Rise (Lab Drag Values Determined at Mass-Median Particle Size of Inlet Char Sample)

Table 1. Comparison of Inlet Char Properties Before and After Recycle Loop Modification (Average Values)

| Recycle Loop Status | Before Modification | After Modification | |
|---|---|---|---|
| PSDF Run No. | GCT-2 | GCT-3 & -4 | TC06 |
| Particulate Loading, ppmw | 31,000 | 18,000 | 15,000 |
| Mass-Median Diameter, µm | 18 | 15 | 15 |
| Specific-Surface Area, $m^2/g$ | 60 | 160 | 220 |
| Bulk Density, $g/cm^3$ | 0.36 | 0.32 | 0.29 |