CYCLONE PERFORMANCE BY VELOCITY

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Abstract

Cyclones are used almost exclusively in the US cotton ginning industry for emission abatement on pneumatic conveying system exhausts because of their high efficiency, and low capital and operating cost. Cyclone performance is improved by increasing collection effectiveness or decreasing energy consumption. The object of this study was to find the balance between saving energy and capturing emissions by quantifying the pressure drop and fine particulate ($PM_{2.5}$) emissions of modified (fully enhanced) 1D3D cyclones at inlet velocities from 1600 to 3500 fpm using cotton gin trash as a test material. Cyclone pressure drop was recorded during test runs. Cyclone exhaust was passed through filters. Filters were weighed and particulate was removed in an ultrasonic bath. Laser diffraction particle size distribution analysis was used to estimate particle size distribution and calculate $PM_{2.5}$ emissions. As predicted by algebraic and computer models and prior research, there was a strong correlation between inlet velocity and cyclone pressure loss; reducing inlet velocity by 25% reduced pressure loss by about 45%. Algebraic and computer models predict an inverse relationship between inlet velocity and emissions. These laboratory tests found that $PM_{2.5}$ emissions decreased when operating 12 inch diameter cyclones with sealed dust outlets 25% below their design inlet velocity. Operating below the design inlet velocity to reduce pressure losses would reduce energy consumption. The simultaneous reduction in fine particulate emissions was unexpected.

Introduction

Material handling of seed cotton, lint fiber, cottonseed and trash is principally done in U.S. cotton gins using pneumatic conveying (McCaskill, et al., 1977). Once material has been delivered to the next step of the process the air that conveyed it is cleaned of incidental particulate and exhausted to the atmosphere. Due to effectiveness, no moving parts to maintain during the operating season, and their low initial cost, the emissions abatement device used by the ginning industry is the cyclone. The cost of operating cyclones is proportional to their pressure drop, as the pneumatic conveying system fans must overcome this resistance to maintain adequate airflow. On average, the amount of electricity consumed to overcome the pressure drop of a gin's cyclone system is approximately 11% of the total consumed by the gin. The pressure drop of cyclones is less than that of other abatement devices, yet nationwide the seasonal cost of operating them is about $8.16 million, and generating the electricity to operate them results in over 432,000 pounds of criteria pollutants entering the atmosphere at the supplying utility's power plants.

Cyclone pressure drop is a function of inlet velocity to the second power (Gimbun, et al., 2005), citing many others. Therefore, a small reduction in inlet velocity is expected to result in a proportionally larger reduction in pressure drop, and hence energy cost, and the environmental cost associate with generating that electricity. The question this research addressed was, "What would be the tradeoff between particulate emissions at a cotton gin and particulate emissions and emissions of other criteria pollutants at the power plant supplying its electricity?" This required quantifying the relationship between inlet velocity and fine particulate ($PM_{2.5}$) and coarse particulate (PM_{10}) emissions for the particular design favored by the cotton ginning industry (1D3D cyclones, Figure 1) treating air conveying typical cotton gin particulate (which included lint fiber and large pieces of plant material as well as dust). The assumption, based on algebraic and computational fluid dynamics computer models, was that emissions would increase if inlet velocity decreased, even though empirical studies published over the past 50 years reporting total suspended particulate collection efficiency do not support that assumption (Figure 2) (Baker & Stedronsky, 1967) (Wesley, et al., 1972) (Gillum & Hughs, 1983) (Faulkner & Shaw, 2006).

Figure 1. The particulate emissions abatement device used by the US cotton ginning industry is the 1D3D cyclone; this example installation shows the fully enhanced version with modified inlets and expansion chambers.

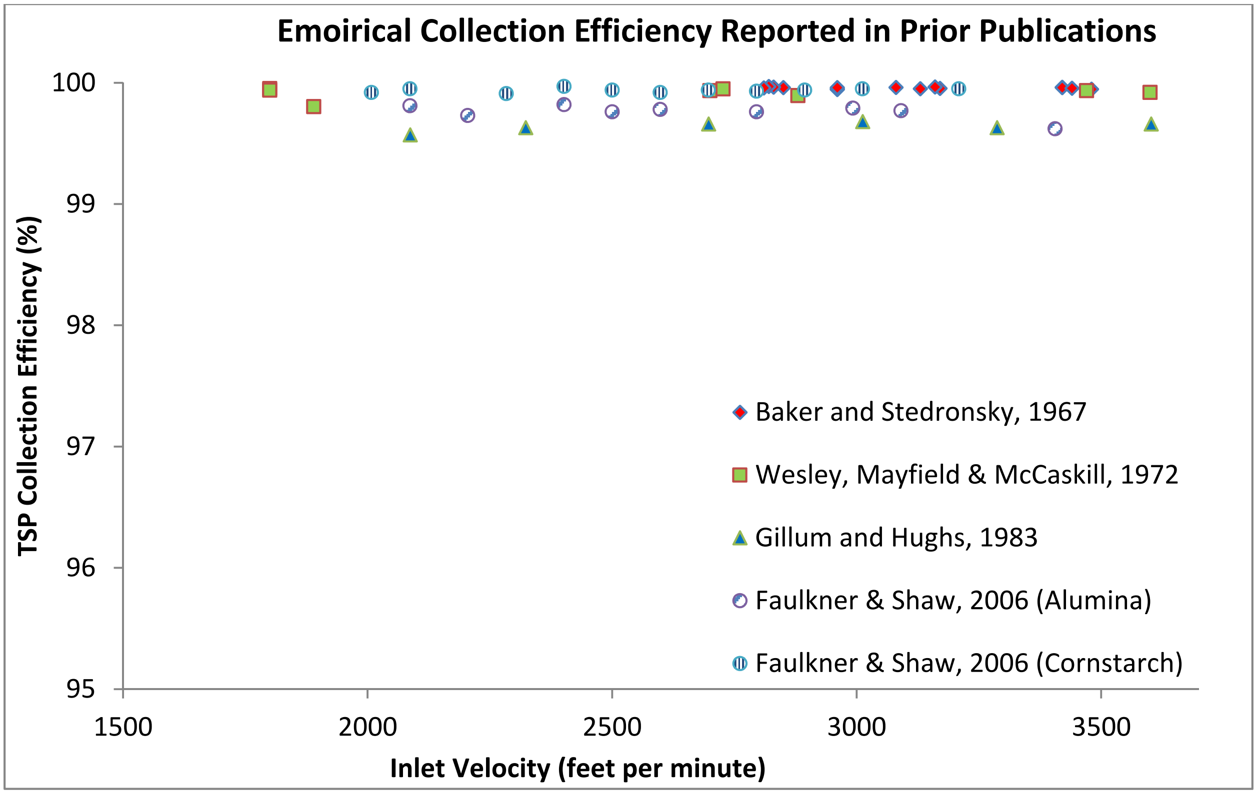

Figure 2. Empirical research over the past half century has shown little correlation between inlet velocity and total suspended particuate; the goal of this research was to establish the relationship for coarse and fine particulate.

Materials and Methods

Two campaigns were launched to determine the relationship between cyclone inlet velocity and the currently regulated criteria pollutants $PM_{2.5}$ and PM_{10}. The first was an exploration of the possible range of variables using a central composite response surface experimental design. In this set of tests inlet concentration varied from 3 to 75 grams per cubic meter and inlet velocity ranged from 1600 to 3600 feet per minute. A push-pull fan system representative of the typical first stage drying and cleaning system was used (Figure 3a). The second set of tests had a constant inlet concentration of 15 grams per cubic meter and included five nominal levels of inlet velocity, each replicated 17 times: 1600, 2000, 2400, 2800 and 3200 feet per minute. To minimize the possibility of particulate being altered or lost, a pull-through fan system was used for these trials (Figure 3b).

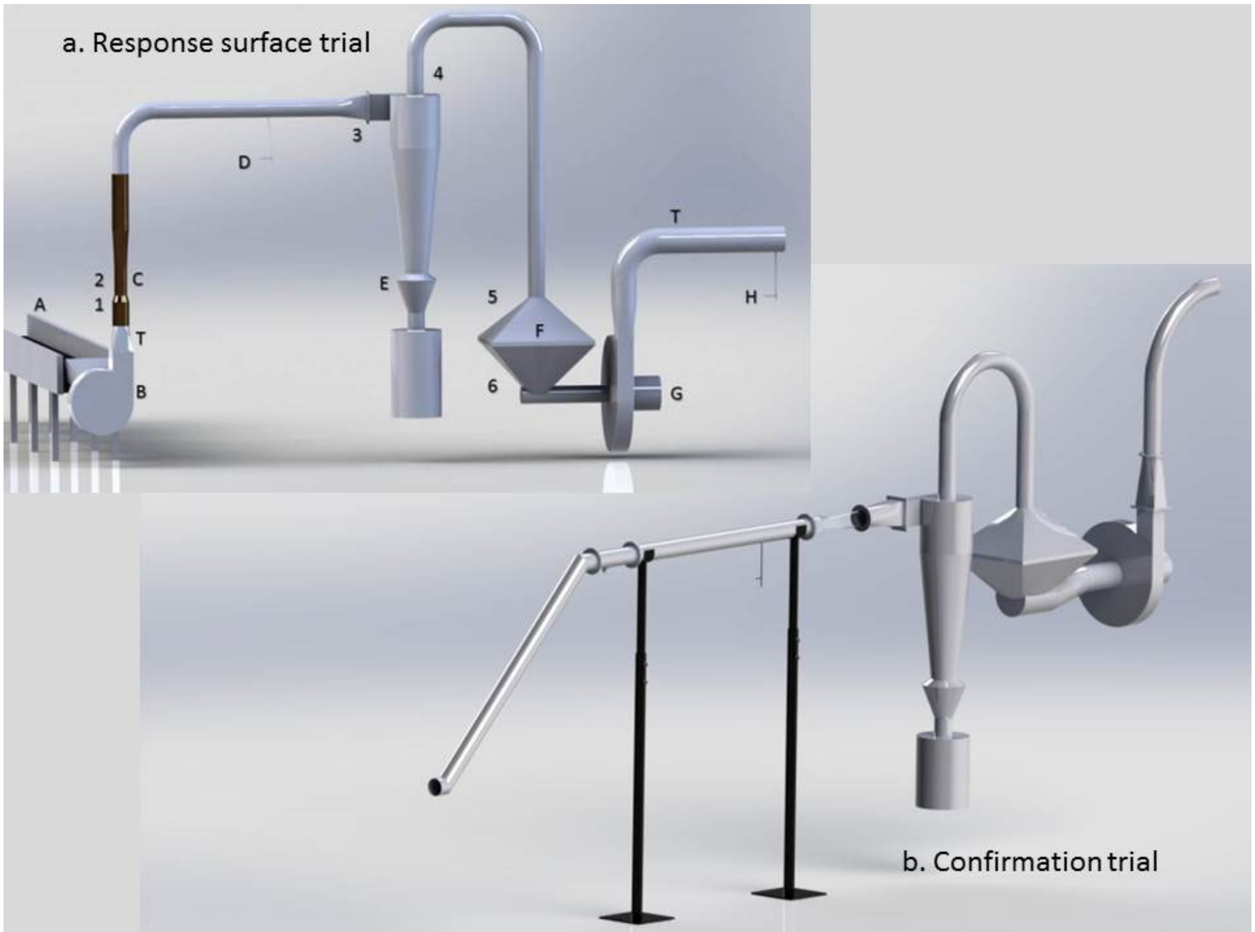

Figure 3. Apparatus used for response surface trials (a) with push-pull fan system and apparatus used in confirmation trials (b) with pull-through fan system. Enhanced 1D3D cyclones were 12 inches in diameter.

For both tests, all the cyclone exhaust was passed through pre-weighed fiberglass filters, conditioned in an environmental chamber at 70 degrees F and 35% relative humidity for > 72 hours before weighing. The same amount of gin trash was used each test. Inlet concentration was controlled by varying the rate and length of time that particulate was introduced into the inlet air. Two 12-inch diameter fully enhanced 1D3D cyclones were randomly assigned, and the inlet velocity was completely randomized for both sets of tests. The catch bucket beneath each cyclone was sealed to prevent airflow. Filters were again conditioned and weighed. Particulate was recovered from filters in an ultrasonic bath. Sample particle size distribution was analyzed by laser diffraction (LS 230, Beckman-Coulter, Brea, CA) and translated to aerodynamic equivalent diameter. The percentage below PM_{10} or $PM_{2.5}$ multiplied by filter mass gave the emissions of those particulate fractions for each test run. Blank LS-230 runs controlled for electrolyte contamination. Blank filters controlled for procedural and filter fiber contamination.

Results and Discussion

In some cases the differences were dramatic even before particle size analysis. Figure 4 shows a filter from a low velocity run (1600 fpm, at left) next to a filter from a run at the highest inlet velocity (3200 fpm, at right). Both runs presented the cyclone with 800 grams of trash, but the mass of particulate that escaped from the cyclone and was captured on the filter at right was three times greater – even though the inlet velocity was nearly double.

Figure 4. The filter at left was from a run with an inlet velocity of 1600 feet per minute, and the filter at right from a run with an inlet velocity of 3200 feet per minute. Both runs presented the cyclone with 800 grams of trash.

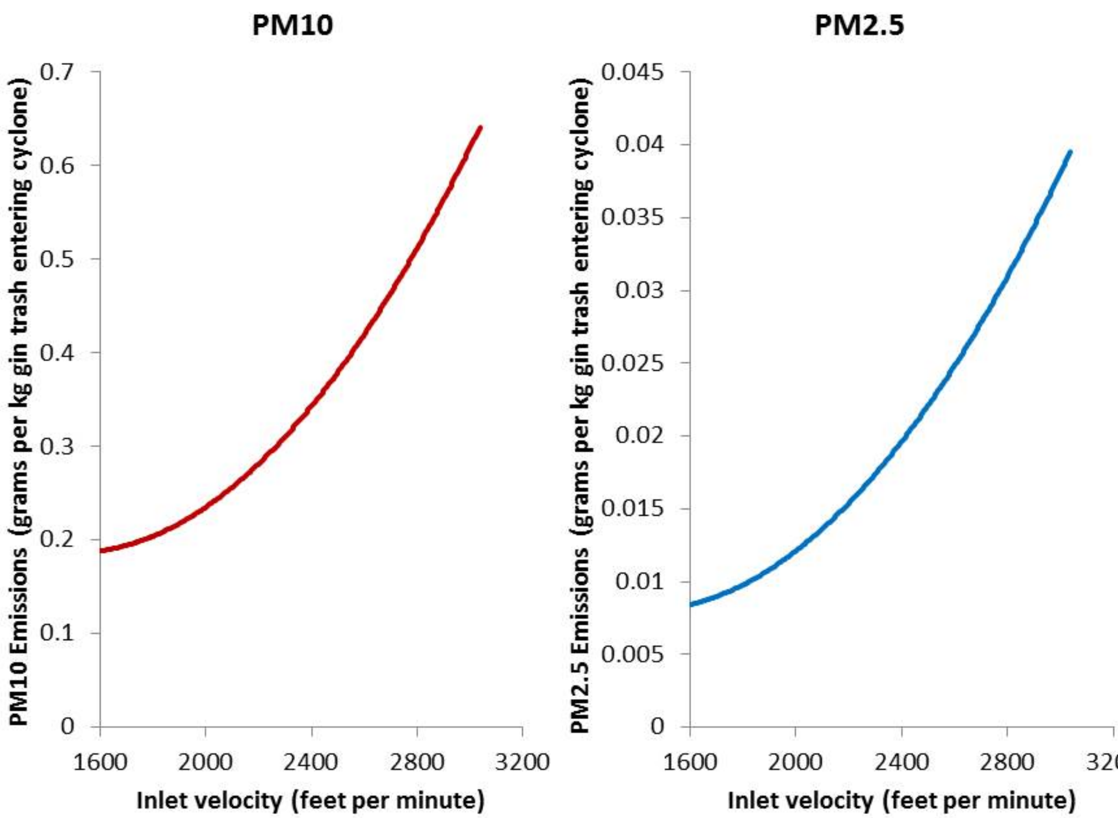

Figure 5. Average criteria pollutant emissions over the tested range of inlet velocities.

Figure 5 shows the average emissions based on a particle size analysis of the particulate escaping from the cyclones (filter catch) for the tested range of inlet velocities (standard air). For particles less than 10 microns aerodynamic equivalent diameter (PM_{10}), the highest inlet velocity resulted in emissions that were about 3.5 times greater than the emissions at the lowest tested velocity (Trendline: $y = 2E\text{-}07x^2 - 0.0006x + 0.6118$; $R^2 = 0.9989$). And when comparing inlet velocities of about 1,600 feet per minute to inlet velocities of about 3,000 feet per minute for $PM_{2.5}$ emissions, the increase was nearly five-fold (Trendline: $y = 1E\text{-}08x^2 - 3E\text{-}05x + 0.032$; $R^2 = 0.9977$).

Summary

The difference between total mass collected on the filters from lowest to highest tested velocity (3-fold) was amplified as particle size decreased, becoming 5-fold for $PM_{2.5}$. Every test run involved feeding 800 grams of trash into the cyclone for the time period required to have the inlet concentration called for by the experiment design. Every test was conducted with relatively small (12 inch diameter) cyclones that were sealed at the bottom where the collected material fell into a bucket. These tests were not vastly different from those published by others. Yet these observed differences were not expected. Antecedent empirical work with gin trash and antique cyclone designs and antecedent empirical work with enhanced 1D3D cyclones and other particulate showed very little correlation between inlet velocity and collection efficiency. If emissions had been constant over the range of inlet velocities tested, these results would have been consistent with published empirical work from the past half century. Simple algebraic models of cyclone performance and sophisticated computational fluid dynamic computer simulations all predict a significant decrease in emissions as inlet velocity increases. If observed emissions had decreased as inlet velocity increased, these findings would have been consistent with published cyclone models and computer simulation results. Instead, these two sets of empirical tests found emissions to increase with increasing inlet velocity, something not in agreement with prior published work. Additional tests are planned to discover possible explanations for these apparent contradictions.

Acknowledgements

The authors wish to recognize the outstanding contributions of their technical staff, including Juan Gomez and Branyan Sanxter at the Southwestern Cotton Ginning Research Laboratory in Mesilla Park, New Mexico, and Bud Welch at the Air Quality Laboratory in Lubbock, Texas.

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