Could cyclone performance improve with reduced inlet velocity?

P.A. Funk a,⁎, K. Elsayed b, K.M. Yeater c, G.A. Holt d, D.P. Whitelock a

a USDA Agricultural Research Service, Southwestern Cotton Ginning Research Laboratory, Mesilla Park, NM, USA
b Mechanical Power Engineering Department, Helwan University, Egypt
c USDA Agricultural Research Service, Plains Area, Fort Collins, CO, USA
d USDA Agricultural Research Service, Cotton Production and Processing Research Unit, Lubbock, TX, USA

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ABSTRACT

Emission abatement cyclone performance is improved by increasing collection effectiveness or decreasing energy consumption. The object of this study was to quantify the pressure drop and fine particulate (PM2.5) collection of 1D3D cyclones (H = 4Dc, h = 1Dc) at inlet velocities from 8 to 18 m s⁻¹ (Stk = 0.7–1.5) using heterogeneous particulate as a test material at inlet concentrations from 3 to 75 g m⁻³. Cyclone exhaust was passed through filters. Laser diffraction particle size distribution analysis was used to estimate PM2.5 emissions. Response surface models showed a strong correlation between cyclone pressure loss (Euler number) and inlet velocity and predicted a 46% reduction in pressure loss for a 25% reduction in inlet velocity (Stokes number). The model for PM2.5 emissions was less definitive and, surprisingly, predicted a 31% decrease in PM2.5 emissions when operating 25% below the design inlet velocity. Operating below the design inlet velocity (at a lower Stokes number) would reduce both the financial and the environmental cost of procuring electricity. The unexpected co-benefit suggested by these trials was that emission abatement may improve at the same time, though other empirical trials have shown emissions to be independent of inlet velocity and Stokes number.

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1. Introduction

1.1. Fine particulate (PM2.5) is a criteria pollutant

In the interest of protecting the public health, the United States Clean Air Act required states to develop a general plan to attain and maintain National Ambient Air Quality Standards (NAAQS) in all areas of the country and a specific plan to attain the standards for each area designated as non-attainment for a NAAQS. These plans, known as state implementation plans (SIPs), are developed by state and local air quality management agencies and submitted to the U.S. Environmental Protection Agency (EPA) for approval. Particles less than 2.5 μm in aerodynamic equivalent diameter (PM2.5) were first included in the NAAQS in 1997. In 2006 EPA NAAQS for PM2.5 were lowered, to 15 μg m⁻³ [1], and in 2012 they were lowered again, to 12 μg m⁻³ [2]. As SIP authors may try to comply with EPA regulations through controlling anthropogenic sources of PM2.5, more stringent operating permit qualifications for agricultural processing facilities may arise.

1.2. Cyclones are used for particulate abatement

Many agricultural processing facility exhaust flows are controlled with cyclones. Cyclones have no moving parts and a relatively low initial cost. Their operating costs are primarily due to the electrical energy required for fans to overcome the friction losses (pressure drop, related to Euler number) in the cyclone and connected ducts. Since generating electricity results in emissions at the power plant, reducing the energy required to operate cyclones potentially helps the environment [3]. Cyclone performance is a function of both particle separation and energy consumption. Cyclone performance may be improved by reducing pressure drop, and thus energy use, as well as by increasing collection efficiency. One option may be to operate cyclones below their traditional design inlet velocity [4]. Research has shown that operating cyclones that are 41% larger than normal, so the inlet velocity was 50% of the design inlet velocity, resulted in pressure losses that were only 28% of normal [5]. While numerous modeling studies have examined monodisperse particles, and empirical studies have reported the impact of inlet velocity on total particulate collection efficiency, this study is the first to report the impact of cyclone inlet velocity on PM2.5 emissions for heterogeneous material.

1.3. Cyclones are robust to inlet velocity

The cyclone design called the ‘1D3D’ was first introduced by Texas A&M University [6]. Collection efficiency improvements brought about
by design modifications were confirmed through USDA ginning lab tests [7,8]. Modified 1D3D cyclones are widely used in agricultural processing, such as by the U.S. cotton ginning industry [9]. Fig. 1 shows dimensions in cm of the modified 1D3D cyclones that were tested, with the overall height, $H = 4$ diameters ($D$), and the barrel height, $h = 1D$, with the inlet height, $a$, and width, $b$, equal to 0.5 and 0.25$D$, respectively. The diameter of the gas outlet, $D_e = 0.5D$, the vortex finder insertion depth, $S = 0.625D$, and the particle outlet diameter, $B = 0.33D$.

The design inlet velocity for the 1D3D cyclone is $16.26 \pm 2.03 \text{ m s}^{-1}$ [10,11], corresponding to a Stokes number of 1.4 for PM$_{2.5}$ in the conditions tested. But as publications presenting empirical cyclone collection efficiencies at various inlet velocities have shown [12–15], cyclones of this design, and other designs, work well over a range of inlet velocities.

Fig. 1. Modified 1D3D cyclones used in this study were 30.5 cm (12 in.) in diameter. This design, both with and without the expansion chamber, is widely used in agricultural processing. Note the protrusion of the vortex finder below the tangential inlet and the cone below the top of the expansion chamber. Two cyclones were built to the same specifications for this experiment. Dimensions are in cm.

Differences in cyclone design, cyclone diameter, particulate inlet concentration and particle size distribution prevent direct comparisons of published results. However, a plot of the collective results (Fig. 2) illustrates that gravimetric total suspended particulate (TSP) collection efficiency does not have a clear relationship to inlet velocity (or Stokes number) over the range of inlet velocities reported. This experiment was designed to test the relationship between PM$_{2.5}$ emissions and inlet velocity for the 1D3D cyclone.

1.4. Cyclone performance indices

Gas cyclones performance characteristics are estimated using the static pressure drop from the inlet to the outlet ($\Delta P$) and the grade efficiency curve. The static pressure drop ($\Delta P$) between the inlet and gas outlet of a cyclone is proportional to the square of the flow rate ($Q$), with a proportionality resistance coefficient ($\xi_c$) defined on the basis of the inlet velocity ($V_i = Q/ab$), thus:

$$\Delta P = \xi_c \frac{\rho g V_i^2}{2}. \quad (1)$$

Alternatively, Dewil et al. [16] recommended avoiding the inlet velocity as a characteristic velocity and replacing it with the average velocity in the cyclone body ($V_c = \frac{Q}{\pi D_e^2}$). Thus the Euler number (Eu) is related to $V_c$ and the pressure drop as:

$$Eu = \frac{\Delta P}{\frac{1}{2} \rho g V_c^2}. \quad (2)$$

In this study (following the recommendation of Svarovsky [17]), $Eu$ will be used as a dimensionless performance parameter [18].

The separation (grade) efficiency of cyclones represents the variation of the separation efficiency with the particle size. The particle size recovered at an efficiency of 50% is called the cut-size or $d_{50}$ [16]. For estimating the cut-size, two different approaches are found in the literature [17]. In the first approach, the cut size is reported in μm. The second approach uses the Stokes number. The Stokes number based on the above-mentioned recommendation, the Stokes number based on the cut-size is:

$$Stk_{50} = \frac{d_{50} \rho_p V_c}{18 \mu D_e} \quad (3)$$
where \(d_{50}\) is the particle diameter, \(\rho_p\) is the particle density, and \(\mu\) is the gas viscosity. In this study, a similar Stokes number will be used for the Stokes number when the particle diameter equals 2.5 \(\mu m\) as:

\[
Stk_{PM2.5} = \frac{(2.5 \times 10^{-6})^2 \rho_p v_c}{18 \mu D_c}.
\]

### 1.5. Test objective

An agricultural processing facility typically has several pneumatic conveying systems that use cyclones to control emissions. Each system has a fixed airflow requirement based on pipe size and minimum carrying velocity. Cyclone inlet concentration varies with processing rate. Cyclone inlet velocity could be modified by substitution of a different sized cyclone. The object of this study was to evaluate the performance (pressure drop and PM\(_{2.5}\) particulate collection) of 1D3D cyclones over a range of inlet velocities using typical agricultural processing facility particulate matter over a range of inlet concentrations.

### 2. Materials and methods

#### 2.1. Test cyclones

Two modified 1D3D cyclones, 30.5 cm in diameter, were fabricated for this study (Fig. 1). The 1D3D cyclones had a barrel that was one diameter in height (1D) and a cone that was three diameters in height (3D). All dimensions in Fig. 1 were determined based on published ratios to barrel diameter [9]. The percentage of processing facilities using the modified 1D3D design has continued increasing as older abatement devices and older cyclone designs have been replaced through repairs or new construction. This design is called “modified” because it has a 0.5D × 0.25D inlet and a D/3 particle outlet, both of which were not part of the original design [6]. There also was an expansion chamber (product receiver, or dust bin) at the bottom; this modification is not as widely used as the first two, but it is still common. These test cyclones were fabricated following current industry practices and using 24 gage galvanized lock forming-quality steel sheet metal. All seams were lapped away from the direction of airflow, spot welded and polished until smooth. All joints between connected sections (i.e., cones and barrels) were sealed to prevent leaks. A sealed container 28 cm in diameter by 30.5 cm high was affixed to the bottom of the expansion chamber to hold collected particulate and to prevent air flow (though industry applications are not always able to prevent air flow at the dust outlet.)

#### 2.2. Test apparatus

Testing was conducted using an apparatus specifically built for this research (Fig. 3). A variable speed feed conveyor belt was used to meter test material into the blades of a variable speed trash fan (MF7, Murray Co., Dallas, TX) with a 1.49 kW DC motor (M-200-A, T.B. Wood’s Sons Co., Chambersburg, PA). The trash fan conveyed the test material in air through a Venturi tube, through a 10.2 cm diameter pipe, and into the test cyclone. All cyclone exhaust air passed through a filter aided by a filter fan (2206 Alum, New York Blower, Willowbrook, IL) with a 5.59 kW AC motor (M3769F, Baldor, Ft. Smith, AR). Prior to each test a Pitot-static tube was used to measure the air velocity in the duct before the cyclone in order to set the cyclone inlet velocity (by adjusting the speed of the trash fan) according to the velocity called for by the experimental design. During each test the differential pressure through the Venturi tube was monitored, providing feedback control for a variable frequency drive (VFD) (VLT 8000 AQUA, Danfoss, Nordborg, Denmark) that controlled the filter fan’s motor. The filter fan produced...
additional fan pressure to maintain constant air flow as flow through the filter became more restricted with particle accumulation.

Ambient and cyclone exhaust air temperatures (type K thermocouples), and differential pressures across the Venturi tube, the cyclone, the filter and the Pitot-static tube downstream of the filter fan were also measured and recorded. The recorded differential pressure from the Pitot-static tube downstream of the filter fan provided an independent value of instantaneous air velocity throughout each test. The 4–20 mA pressure transmitter signals (Model 614, Dwyer Instruments, Inc., Michigan City, IN) were converted to voltages by a custom-made signal-conditioning card. Voltage signals were recorded continuously at 1 s intervals using a data logger (Model 34970A, with 34908A switch units, Agilent Technologies, Santa Clara, CA) and averaged over the duration of the test to determine their respective values.

2.3. Filters

Particulate matter escaping the dust cyclone was collected on 56 cm × 61 cm hydrophobic filter media (Type FP2063, Hi-Q Environmental Products Co., Inc., San Diego, CA) made of borosilicate glass microfibers with a minimal amount of an acrylic resin binder to maintain filter integrity. Filters had 97% collection efficiency for 0.3 μm dioctyl phthalate [19]. Filters were conditioned in a controlled atmosphere environmental chamber (21 °C and 35% relative humidity) for 72 h or more before weighing, following guidelines published by the EPA [20]. Each filter was carefully handled with gloves, folded in quarters, and stored and weighed in a dedicated 4 mil anti-static polybag (Part No. 49115, Protektive Pak, Chino, CA) to prevent the incidental loss of glass fiber or particulate. The bagged and conditioned filters were weighed before and after testing in an environmental chamber for at least 48 h at 21 °C and 35% relative humidity. Bagged filter was carefully handled with gloves, placed in a transparent box to minimize the effects of air currents and vibrations. Each filter was weighed three times. If the standard deviation of the weights exceeded 10 mg, the filter was re-weighed.

2.4. Experimental design

This response surface experiment used a central composite design. There were nine combinations of two continuous variables: inlet concentration and cyclone inlet velocity. Five replicates at the center point estimated variability (Fig. 4). Four corner and four axial points were equidistant from the center to attain a rotatable design with uniform precision of estimation in all directions. Commensurately, the resulting five levels of inlet velocity and five levels of particulate inlet concentration provided an estimate of curvature for potential non-linear responses. The experiment design called for inlet velocities of from 8 to 18 m s⁻¹ (corresponding to a PM₂.₅ Stokes number between 0.7 and 1.5). This range was selected based on earlier work [5] and included the design inlet velocity for 1D3D cyclones (16.26 m s⁻¹). The experiment design called for inlet concentrations from 3 to 75 g m⁻³, the range of inlet concentrations from published research [21].

A comparison was made between two identical cyclones (A and B) across the full range of inlet velocity and inlet concentration. Thirteen runs (four corner points, four axial points, and five replicated center points) were conducted with each cyclone for a total of 26 experimental runs. The runs were conducted in a completely randomized design. Uncontrolled variables such as air temperature were measured throughout the six weeks of testing to control for potential covariance.

2.5. Particle size distribution analysis

All filters, cyclone catch and feed material samples were sent to the USDA-ARS Air Quality Laboratory in Lubbock, TX for particle size distribution (PSD) analysis. These were conditioned in an environmental chamber for at least 48 h at 21 °C and 35% relative humidity. Bagged cyclone catch and feed samples from each test were weighed on an electronic balance (A & D HP-20K, Data Weighing Systems, Elk Grove, IL). After removing sample material, the bags were reweighed. Cyclone catch from each test were sieved using standard procedures [22] and equipment (Ro-tap, W.S. Tyler, Mentor, OH) to obtain coarse gradation above 106 μm. Particles larger than 100 μm aerodynamic equivalent diameter (AED) have a high probability of being captured by the cyclone. The fine portion (below 106 μm) was sub-sampled three times for PSD analysis.

Particle size analyses were conducted on a laser diffraction (LD) system (Beckman Coulter LS230, Beckman Coulter Inc., Miami, FL) with software version 3.29 to calculate the PSD. The instrument measured particles over the range of 0.375 to 2000 μm that were suspended in a 5% lithium chloride/methanol electrolyte solution. The LD particle-size analyses consisted of the following procedures: The electrolyte was pre-filtered using a filtration system that removed all particles larger than 0.2 μm. A background count of the filtered electrolyte was made with the LD system to ensure that there was minimal particulate contamination. The electrolyte background counts of less than 300 particles per cm² of electrolyte were considered acceptable. For PSD analysis of particulate on filters, the particulate must be extracted from the filter media and suspended in the electrolyte solution. Particulate was extracted from the loaded filters by cutting three 2-cm diameter samples from a heavily loaded area of the filter, placing the samples in a 100-ml beaker with 50 ml of electrolyte, and processing the sample in an ultrasonic bath for 5 min. The particulate/electrolyte solution was then introduced into the fluid module of the LD system to run a PSD analysis.

Optical model parameters used with the LD system software to determine the sample PSDs were 1.56 for the real part of the sample refractive index, 0.01 for the imaginary part, and 1.326 for the suspension fluid refractive index. [These values are used in the Lorenz–Mie solution to Maxwell’s equations. These equations describe light scattering by spherical particles in a transparent medium.] LD system results in terms of equivalent spherical diameter were corrected to aerodynamic equivalent diameter (AED) by multiplying equivalent spherical
diameter by the square root of the product of the density (2.65 g cm$^{-3}$) divided by the shape factor (1.40). This PSD analysis was used to estimate PM$_{2.5}$ emissions (particulate 2.5 μm AED and smaller).

2.6. Test material

Since this research was intended to assist agricultural processing facilities with energy conservation as well as regulatory compliance, agricultural particulate from the cotton ginning industry was used. The range of particulate inlet concentration values chosen for this study, from 3 to 75 g m$^{-3}$, was influenced by that reported by earlier empirical studies: 2–16 g m$^{-3}$ [5]; 7–15 g m$^{-3}$ [23]; 8–10 g m$^{-3}$ [24]; 8–100 g m$^{-3}$ [25]; and 75 g m$^{-3}$ [7].

The test material consisted of soil particles, fibers, leaf particles, and stems. The composition of this test material represents the type of material that might be handled by dust cyclones at an agricultural processing facility. Each test run used 0.8 kg of test material so that the filter would have close to its maximum load of dust (pre-trial runs with more than 0.8 kg resulted in filter damage). The largest possible quantity was selected to minimize experimental error by maximizing test run time and filter weight, and hence signal-to-noise ratio. Eight sub-samples each weighing 100 g were evenly distributed on eight contiguous sections 30.5 cm long on the variable speed feed conveyor. The conveyor speed was set before each test so that the test material metered into the airstream of the test apparatus at the dust inlet concentration required by the experimental design. Lower inlet concentration trials took more time; time was recorded to independently verify inlet concentration.

2.7. Test material characterization

Nine samples of test material were collected throughout the test period for particle size distribution analysis. The size distribution of the test material was somewhat bi-modal. The major constituents were leaf particles (in the size range between 250 and 850 μm) and soil particles (greater than 10 μm and less than 106 μm), as presented in Table 1. Note that for this test material, considered representative of that handled by cotton gin cyclones, only a small part (6%) was particulate less than 10 μm and considerably less than that (0.9% of the total) was fine particulate less than 2.5 μm.

The sieved portion of each feed sample, the 40.8% that was below 106 μm, was sub-sampled three times for particle size distribution analysis. The sieved test material had an aerodynamic equivalent mass median diameter (AED) of 41.56 μm and a geometric standard deviation of 3.07. The percentage of sieved material ≤2.5 μm was 2.266%, with a standard deviation of 0.389 percentage points (17%); the percentage of sieved material ≤10 μm was 14.742%, with a standard deviation of 2.893 percentage points (20%). Fig. 5 presents the size distribution of the sieved portion of the test material. Test material variability had the potential to contribute to uncertainty in the results.

2.8. Reported units — PM$_{2.5}$ per kg fed

Publications analyzing cyclone performance historically have reported collection efficiency as the collected percent of mass entering, or they have reported the cut point — that particle size for which the collection efficiency is 50% [26,27]. The fraction escaping is quantified by isokinetically sampling a portion of the exhaust as per EPA Method 201A [28], or by passing all of the cyclone exhaust through a filter weighed before and after the test under standard conditions (as with this study). The mass lost is compared to the sum of the mass collected and lost, or to the weight metered into the air stream (as in these tests), or the exhaust concentration is compared to results isokinetically sampling the inflow. In all cases, whether sampling a portion of the gas flow or filtering all of it, whether reporting overall collection efficiency or cut point, results have also varied with the inlet concentration and particle size distribution of material entering the cyclone [29].

Reporting emissions concentration would have been confusing in a test where inlet concentration varied over a wide range. Since the rate of material escaping a cyclone has nearly a direct relationship to the rate of material entering it, emissions concentration would have been confounded by inlet concentration. Therefore, emitted PM$_{2.5}$ was normalized to 1000 g of feed material. Emissions values are presented as grams PM$_{2.5}$ collected on the filter per kg of all material entering the cyclone. The PM$_{2.5}$ mass on each filter was multiplied by 1 kg and divided by the mass of material entering the cyclones for each test run (nominally 800 g). The normalized mass of PM$_{2.5}$ escaping the cyclone and collected on the filter was expected to give an independent indication of performance that would reveal the influence of inlet concentration and inlet velocity. Since the same mass of feed material was used in each test run, reporting fine particulate mass escaping the cyclone per run is similar to reporting an emissions factor, as is done with AP 42 process rate tables [30]. This relative performance metric is specific to these trials; it is not an indication of absolute collection efficiency, nor is it a universal predictor of emissions concentration.

2.9. Data analysis

The theoretical collection efficiency of a cyclone is largely determined by particle velocity [21] and particle velocity is closely related to air velocity. For this reason, actual values of local air density (based on temperature, barometric pressure and relative humidity) at the time of each test were calculated and used to determine the Pitot-static tube velocity pressure corresponding to the desired inlet velocity and inlet concentration. Uncontrolled variables (run number, date, barometric pressure, temperature, relative humidity, air density and cyclone) were tested for significance (proc mixed, SAS 9.2, SAS Inc.,

<table>
<thead>
<tr>
<th>Particle size</th>
<th>&lt;2.5 μm</th>
<th>&lt;10 μm</th>
<th>&lt;106 μm</th>
<th>&lt;150 μm</th>
<th>&lt;250 μm</th>
<th>&lt;850 μm</th>
<th>&gt;850 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category percent</td>
<td>0.90%</td>
<td>5.10%</td>
<td>34.80%</td>
<td>6.10%</td>
<td>7.80%</td>
<td>31.20%</td>
<td>14.00%</td>
</tr>
<tr>
<td>Cumulative total</td>
<td>0.90%</td>
<td>6.00%</td>
<td>40.80%</td>
<td>46.90%</td>
<td>54.80%</td>
<td>86.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
Research Triangle Park, NC) at the 5% level to verify that they did not significantly impact the response variables (PM$_{2.5}$ emissions and pressure drop). Insignificant uncontrolled variables thus could be omitted from the analysis.

Response surface methodology was performed using experimental design and analysis software (Design-Expert 8.0.7.1 (DX8), Stat-Ease, Inc., Minneapolis, MN). Actual values for inlet velocity and inlet concentration (based on local air density) were used in constructing the response surface models. Two responses, PM$_{2.5}$ emissions (emitted grams per kg of material entering the cyclone), and pressure drop (Pa), were modeled. Numerous models were tested in the process of arriving at the “best” one; the criteria for choosing one model over another, in decreasing order of importance, were as follows: 1) its terms made sense from the standpoint of the laws of physics; 2) it was simpler; 3) it had a better interpretation (ANOVA) than a lower-order model, or adding the higher order terms made sense from the standpoint of the laws of physics; 4) its lack of interaction (Fig. 6).

The selected pressure drop model included terms for inlet velocity to first and second power. The adjusted $R^2$ of the selected model for pressure drop was 0.9396. Considering the range of predicted and measured values for pressure drop in antecedent publications, which vary by a factor of 2.8 for this particular design [31], and the fact that this model had only inlet velocity as a predictor, it fit this data fairly well. The influence of inlet concentration on pressure drop has long been documented [32]. Pressure drop decreases as inlet concentration increases up to about 200 g m$^{-3}$ [33]. Inlet concentration levels were below that range for this experiment, but this study lacked the necessary power to detect statistical significance for that variable. In these trials the Stokes number for PM$_{2.5}$ was directly proportional to inlet velocity ($Stk = 0.0863 \cdot Vi$), and the Euler number was a linear function of pressure drop ($Eu = 21.72 + 0.074 \cdot Pr$).

When substituting an inlet velocity of 12.19 m s$^{-1}$ for 16.26 m s$^{-1}$ in the selected response surface models (a 25% reduction, equivalent to

### Table 2

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Uncontrolled</th>
<th>F value</th>
<th>Pr &gt; F</th>
<th>Controlled</th>
<th>F value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$ (g/kg)</td>
<td>Run number</td>
<td>0.46</td>
<td>0.5051</td>
<td>Inlet velocity</td>
<td>15.92</td>
<td>0.0011</td>
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<tr>
<td></td>
<td>Date</td>
<td>0.72</td>
<td>0.4083</td>
<td>Barometric pressure</td>
<td>0.21</td>
<td>0.6552</td>
</tr>
<tr>
<td></td>
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<td>0.21</td>
<td>0.6552</td>
<td>Temperature</td>
<td>0.25</td>
<td>0.6251</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>0.75</td>
<td>0.6572</td>
<td>Relative humidity</td>
<td>0.03</td>
<td>0.8656</td>
</tr>
<tr>
<td></td>
<td>Relative humidity</td>
<td>0.03</td>
<td>0.8656</td>
<td>Air density</td>
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<td>0.6268</td>
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<td></td>
<td>Air density</td>
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<td>0.6268</td>
<td>Cyclone A or B</td>
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<td>0.7474</td>
</tr>
<tr>
<td></td>
<td>Cyclone A or B</td>
<td>0.11</td>
<td>0.7474</td>
<td>Inlet concentration</td>
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<td>0.0114</td>
</tr>
<tr>
<td></td>
<td>Inlet concentration</td>
<td>8.16</td>
<td>0.0114</td>
<td>Velocity * concentration</td>
<td>2.73</td>
<td>0.119</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Response</th>
<th>Model</th>
<th>Model adj. $R^2$</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$ (g/kg)</td>
<td>$= + 0.0051617 + 0.036549 \times V - 0.0028133 \times C$</td>
<td>0.6599</td>
<td>0.095</td>
</tr>
<tr>
<td>ΔP (Pa)</td>
<td>$= + 80.679 - 14.504 \times V + 2.5314 \times V^2$</td>
<td>0.9396</td>
<td>40.87</td>
</tr>
<tr>
<td>PM$_{2.5}$ (g/kg)</td>
<td>$= + 0.0051617 + 0.42351 \times Stk - 0.0028133 \times C$</td>
<td>0.6599</td>
<td>0.095</td>
</tr>
<tr>
<td>Eu</td>
<td>$= + 21.72 + 0.074 \times (80.679 - 168.065 \times Stk + 339.89 \times Stk^2)$</td>
<td>0.9534</td>
<td>3.024</td>
</tr>
</tbody>
</table>

*a* Eu = Euler number.

*b* $V =$ inlet velocity (m s$^{-1}$), $C =$ inlet concentration (g m$^{-3}$), $Stk =$ Stokes number.
reducing the Stokes number from 1.403 to 1.052) they predicted a 31% decrease in PM$_{2.5}$ emissions; from 0.473 to 0.324 g kg$^{-1}$; a 46% reduction in pressure loss: from 514 to 280 Pa, and a 29% reduction in Euler number, from 59.8 to 42.4, at an inlet concentration of 45 g m$^{-3}$ (Table 4). Table 4 also presents a 95% confidence interval range based on the response variables models (assumed: normal distribution, model standard deviation and number of observations). The lack of overlap for the 95% confidence interval ranges on PM$_{2.5}$ emissions, pressure drop, and Euler number indicate a statistically significant difference between the two inlet velocities; they predict that an agricultural processing facility may both save energy and reduce emissions simply by operating its 1D3D cyclones at a lower inlet velocity.

### 3.3. Discussion

The significance of these results comes from the nexus of emissions and energy. The energy cost of operating cyclone abatement devices is directly proportional to pressure drop, and producing electricity to power abatement devices results in air pollution, favoring lower inlet velocities. At the same time, fine particulate emissions did not increase as expected, but appeared to decrease slightly at lower inlet velocities.

For this particular configuration, set of operating conditions, and inlet material PSD there was a strong correlation between inlet velocity and pressure drop (model adjusted $R^2 = 0.94$), and a weaker association between inlet velocity and emissions (model adjusted $R^2 = 0.66$). The second order pressure drop relationship was expected as it agreed with published results from both modeling and empirical trials. The relationship between emissions and inlet velocity contradicted many classical numerical models [34–36] and some empirical research [37] that predict continuously increasing collection efficiency with increasing inlet velocity. This is best illustrated by Fig. 7, a plot of PM$_{2.5}$ emissions over Stokes number for each run in this trial. A lower Stokes number predicts that a particle will better follow a streamline, implying an increase in emissions as particles would be more likely to be carried out of the cyclone by the air. However, this data set showed emissions decreasing at lower Stokes numbers. Correlation coefficients were between 0.5 and 0.6, partly due to varying inlet concentration. Other empirical research indicates little correlation between emissions and inlet velocity, especially with heterogeneous particulate (Fig. 2), or at least an upper limit to inlet velocity beyond which emissions increase. This conflict has been discussed elsewhere [11]. Some authors hypothesize that turbulence or interior surface roughness induces particle bounce, causing particle re-entrainment [38,39], a phenomenon that is thought to increase with gas and particle velocity. This trial suggested that inlet velocity, and Stokes number, in 30.5 cm diameter 1D3D cyclones handling heterogeneous particulate, may have little impact on emissions. Perhaps particle agglomeration, a mechanism for fine particulate capture, is favored by lower turbulence.

Considering the potential importance of these findings in terms of energy savings and reduced power plant emissions, the challenge of balancing energy savings to the increased capital cost of larger cyclones, and the potential difficulty in terms of changing existing environmental regulations, it is important that these experiments be replicated under field conditions. If confirmation of these experiments were to result in more relaxed regulation, it may lead to reductions in the energy consumption of pneumatic conveying systems at agricultural processing facilities and perhaps elsewhere. This work has a high priority for two reasons. First, energy costs are rising relative to other costs of operation, and pneumatic conveyance fans account for more than half of the energy used by some agricultural processing facilities [40]. Second, energy production is a significant source of air pollution, so reducing energy requirements of abatement devices would benefit the environment [3].

### 4. Conclusion

Cyclones were tested to better understand the effects of inlet velocity and inlet concentration on pressure drop and emissions. Modified 1D3D cyclones were operated at inlet velocities from about half to slightly more than design, from 8 to 18 m s$^{-1}$, over a range of inlet concentrations from 3 to 75 g m$^{-3}$. Cyclone pressure drop, ΔP, was measured directly. Emitted total mass collected on filters and particle size distribution analysis was used to estimate PM$_{2.5}$ emissions, presented in this paper as mass of PM$_{2.5}$ for each kg of total material fed to the cyclone. Cyclone performance models were developed using response surface methodology. Based on the obtained results, the following conclusions were drawn:

- Response surface models showed a strong correlation between cyclone pressure loss and inlet velocity and predicted a 46% reduction in pressure loss for a 25% reduction in inlet velocity, as well as a 29% reduction in Euler number for a 25% reduction in Stokes number.
- The model for PM$_{2.5}$ emissions was less definitive and, surprisingly, predicted a 31% decrease in PM$_{2.5}$ emissions when operating 25% below the design inlet velocity (at a 25% lower Stokes number).
- Operating below the design inlet velocity to reduce pressure losses would require larger, costlier cyclones, but may reduce both the financial and the environmental cost of procuring electricity.
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References


[38] Dr. Paul Funk is an Agricultural Engineer working on diverse projects including non-chemical harvest preparation, renewable energy production, specialty crop mechanization, trace and chemical detection of contaminants, and air quality. He earned an M.S. from the University of Minnesota and a Ph.D. from the University of Arizona, both in Agricultural Engineering. He was a professor of Mechanical Engineering before becoming a Research Scientist with the USDA Agricultural Research Service in Mesilla Park, New Mexico.

[39] Dr. Khairy Elseayed is a Mechanical Engineer working on diverse research projects including cyclone separators, CFD simulations, surrogate based optimization and shape optimization. He earned an M.S. from Helwan University in Egypt and a Ph.D. from Vrije Universiteit Brussel (VUB), both in Mechanical Engineering. He is a Professor/Senior Research Scientist at VUB and Assistant Professor at Helwan University.

[40] Dr. Kathleen M. Yeater is an Area Statistician for the United States Department of Agriculture, Agricultural Research Service, where she provides consultative support to researchers conducting research in the areas of air quality and seed-cotton and lint cleaning. She is actively involved in working with researchers in developing and presenting inferences from statistical results as well as consulting and training a diverse group of research personnel. Kathy received a Ph.D. in Biometry and Statistics from the Department of Crop Sciences at the University of Illinois.

[41] Dr. Greg Holt is the Research Leader at the Cotton Production and Processing Research Unit in Lubbock, Texas. He has conducted research related to development of more efficient pollution abatement devices for cotton gins, optimization of cotton harvesting and ginning machinery, sensor development for microwave imaging of cotton moisture, and value-added processing of cotton byproducts and agricultural fibers. He earned B.S. and M.S. degrees from Texas A&M University in Agricultural Engineering and a Ph.D. from Texas Tech University in Industrial Engineering.

[42] Dr. Derek Whitelock is an Agricultural Engineer conducting cotton ginning and agricultural air quality research at the USDA-ARS Southwestern Cotton Ginning Research Lab in Mesilla Park, New Mexico. He earned B.S. and M.S. degrees from Texas A&M University and a Ph.D. from Oklahoma State University in Agricultural Engineering. His research, mainly in the areas of air quality and seed-cotton and lint cleaning, covers a broad spectrum of issues in both saw and roller ginning.