

ENGINEERING AND GINNING

Dust Cyclone Technology – A Literature Review

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ABSTRACT

Dust cyclone research leading to more efficient designs has helped the cotton ginning industry comply with increasingly stringent air quality standards governing particulate emissions. An increase in energy prices motivates research leading to equally effective particle collection designs and operating strategies that use less fan power, while the possibility of future changes in regulation motivates research leading to additional improvements in particle collection. A review of the literature was undertaken to discover recent particulate control technology developments in other industries that may benefit the ginning industry. This inter-disciplinary literature review summarizes dust cyclone designs, algebraic and computer models and recent experiments. As computing costs have decreased and model sophistication has increased, the use of computational fluid dynamics to model cyclone performance has grown. There will, however, always be a need for empirical validation in the laboratory and field. Energy cost related to cyclone pressure drop has been and will continue to be an important consideration.

The cotton ginning industry continues to proactively respond to increasingly stringent air quality regulations promulgated by federal, state and local regulatory agencies. Research conducted at universities and federal labs in cooperation with the ginning industry has led to innovations in the technology used to control cotton gin particulate emissions. Control technologies developed for or by the ginning industry are emulated by other industries (Whitelock et al., 2007).

Cotton harvest mechanization in the 1950s shortened the ginning season and increased the amount of foreign matter in seed cotton, driving the ginning

industry to increase capacities and add cleaning equipment (Funk and Hardin IV, 2012). Pneumatic material handling increased proportionately as did air emissions (Wesley et al., 1972). Federal research addressing trash collection and particulate emissions also began in the 1950s (Harrell and Moore, 1962). Industry publications addressing air pollution control began to appear at that time (The Texas Cotton Ginners Association, 1961). Analyses of the particle size distribution of cyclone exhausts in 1968-1970 showed the “Atomic Energy Commission” or 2D2D cyclone to be virtually 100% efficient on particles larger than 20 microns (Wesley et al., 1972). A 2D2D cyclone has barrel and cone heights each equal to two barrel diameters, as shown in the Shepherd and Lapple model (1939) in Figure 1.

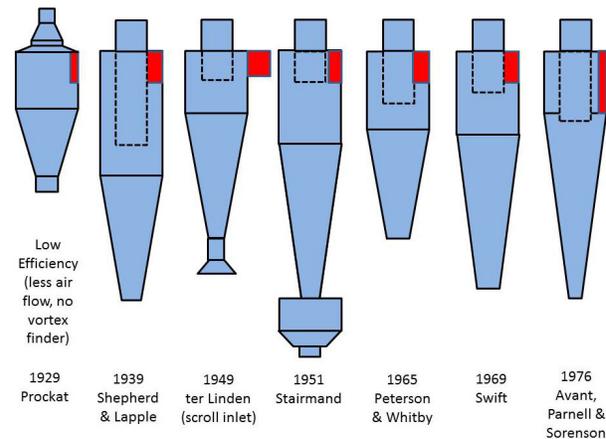


Figure 1. Representative dust cyclone designs.

Dust cyclone research and development has primarily been driven by the need to comply with emissions regulations. This effort has been complicated by frequently changing objectives. As documented in the following paragraphs, there have been: 1) changes in federal law concerning both characteristics and allowable quantities of regulated particulate; 2) legal challenges to federal law that add uncertainty while cases are under appeal; and 3) delegation of enforcement responsibility to states which leads to additional variability as each state may interpret and apply national standards differently.

The U.S. Public Health Service made a compilation of air pollutant emission factors in 1968, with an estimate for cotton gins based on bales processed

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(EPA, 2010). Congress passed the Clean Air Act in 1970, authorizing National Ambient Air Quality Standards (NAAQS) and state implementation plans (SIPs). That same year the National Environmental Policy Act established the U.S. Environmental Protection Agency (EPA). Major amendments were added to the Clean Air Act in 1977, and the third edition of AP-42 process rate tables was published in 1977 (EPA, 2010). Field work was conducted by the USDA Ginning Labs to obtain a more accurate estimate of emissions rates (Kirk, et al., 1979). A second AP-42 table "Particulate emissions factors for cotton gins with controls" was added in the Fourth Edition (EPA, 1985).

The 1987 revisions to the NAAQS significantly changed particulate matter (PM) emissions regulation, adding PM less than 10 microns in aerodynamic diameter (PM_{10}) (EPA, 1987). The Clean Air Act was amended in 1990, establishing an operating permit program administered by individual states under EPA supervision. The National Cotton Council and National Cotton Ginners Association worked with EPA, developing revised emissions factors in 1996 (Wakelyn, 1999). This new AP-42 table included PM_{10} (EPA, 1996). This Fifth Edition is still the current edition.

Collecting fine particulate (particles less than 2.5 microns, or $PM_{2.5}$), became a legal issue when the EPA promulgated revisions to the particulate matter NAAQS in July 1997, regulating $PM_{2.5}$ for the first time. The U.S. Court of Appeals for the D.C. Circuit set aside the 1997 air quality standards in 1999. The court remanded the ozone and $PM_{2.5}$ standards to the EPA for redrafting and ordered the agency to explain why its rule-making process was justified under the U.S. Constitution. Finding that the PM_{10} standard was "arbitrary and capricious," the PM_{10} standard was revoked. The court found that PM_{10} was not an appropriate indicator for coarse particles because it included fine particles in its measurement. In the court's view, this amounted to double regulation of $PM_{2.5}$ and under-regulation of coarse particles (i.e., particles between 2.5 and 10 micrometers in size). Accordingly, the judges directed the EPA to develop a new PM_{10} standard (U.S. Court of Appeals for the District of Columbia Circuit, 1999).

The EPA revised the NAAQS for $PM_{2.5}$ in 2006, establishing an annual average threshold of 15 g m^{-3} and a (lower) 24-hr average limit of 35 g m^{-3} , and making secondary (welfare-based) standards identical to primary (health-based) standards. In

2009, as a result of a suit filed against the U.S. EPA by public health and environmental groups, the U.S. Court of Appeals for the D.C. Circuit remanded the $PM_{2.5}$ NAAQS to EPA for reconsideration of the primary annual level and the secondary standard (U.S. Court of Appeals for the District of Columbia Circuit, 2006). The EPA's final designation of 39 areas as nonattainment with 1997 NAAQS for $PM_{2.5}$ (EPA, 2007) impacted six cotton producing states. Each impacted state is required to develop implementation plans demonstrating how attainment will be reached. State implementation plans include measures to reduce $PM_{2.5}$ emissions regardless of source (Buser et al., 2012).

Reducing $PM_{2.5}$ emissions is done in the interest of protecting the health of the public. There is a correlation between short-term exposure to elevated ambient levels of $PM_{2.5}$ and mortality (Staniswalis et al., 2009). All-cause, respiratory and stroke-related mortality increase with atmospheric fine particulate from combustion sources, especially in the aged segment of the population (Franklin et al., 2007). However, atmospheric fine particulate from agriculture, construction and mining operations does not correlate strongly with morbidity and mortality (Laden et al., 2000). In light of the vastly different compositions of fine particulate from different sources, it seems unlikely that all forms of $PM_{2.5}$ would have identical toxicological properties. Therefore reducing ambient concentrations of some forms of $PM_{2.5}$ may not improve public health (Green et al., 2002).

In many cases state regulators apply the annual-average, region-wide ambient air quality standard as if it were an instantaneous property line limit. Each source may be a different distance from the property line, with different prevailing wind speed and direction. Dispersion is also impacted by other climate variables, the height of the source, and the particle size distribution of the emissions. This results in errors both in dispersion modeling (Powell et al., 2006) and sampling (Wang et al., 2005). Consequentially, enforcement of NAAQS is not uniform or consistent, and the performance demanded of a particular cyclone may depend on location as much as on loading.

"To limit the concentrations of air pollution to which the public is exposed, the EPA has set National Ambient Air Quality Standards (NAAQS). State Air Pollution Regulatory Agencies (SAPRAs) permit emissions sources. Permits govern abatement systems. Frequently computer models are used to estimate downwind concentrations, and most

SAPRAs use the NAAQS as a concentration not to be exceeded at the property line.

The particle size distribution of typical agricultural dust, including dust from cotton gin airflows, has an aerodynamic equivalent mass median diameter of about twenty microns and a geometric standard deviation of about two microns. Consequently, the mass fraction of particles less than 2.5 microns is less than two percent. The mass fraction of particles less than 10 microns (PM_{10}) is roughly twenty percent. The NAAQS for PM_{10} or coarse particulate matter is $150 \mu\text{g m}^{-3}$ at present, with attempts to reduce the NAAQS to less than $85 \mu\text{g m}^{-3}$. The problem for cotton gins is to reduce PM_{10} emissions so that property line concentrations are less than the NAAQS.” (Dr. Calvin B. Parnell, P.E., Regents Professor and Director of the Center for Agricultural Air Quality Engineering and Science, Biological and Agricultural Engineering, Texas A&M University, College Station, TX, personal communication, 10 April, 2012.)

Currently, the cotton ginning industry is documenting typical $PM_{2.5}$, PM_{10} and total emissions from each unique source (Buser et al., 2012). It is probable that most, if not all, gins will be significantly under current $PM_{2.5}$ emissions limits without any further improvement to dust collection equipment. However, it is possible that regulatory changes, whether in rules, modeling, or property-line sampling, may at some time require additional improvements in dust cyclone efficiency for a particular source. Meanwhile, rising energy costs have caused energy to become the ginning industry’s second largest variable expense (Valco et al., 2009). Cyclone design or operating modifications that reduce energy use without decreasing collection efficiency are sought. Therefore a review of the literature was undertaken to discover recent developments in particulate control technology, so that the ginning industry can reduce its energy costs while continuing to comply with air quality regulations, present and future.

Cyclones (also called reverse-flow or axial-flow cyclones) are the particulate control of choice as they have no moving parts and low capital and maintenance costs (Fig. 1). Other industries also use cyclones for emissions control, (Gimbun et al., 2005b), product recovery (Bernardo et al., 2006), process/combustion enhancement (Parker et al., 1981), heating, (Vegini, et al., 2008), spray drying (Koch and Licht, 1977), source sampling and monitoring (Hsiao et al., 2009), etc. They have even appeared

in household vacuum cleaners: (Dyson Technology, 2012; Hong and Lee, 2011, Smith, 2010). A large number of peer-reviewed articles on cyclones have been published over the past eight decades. Since knowledge gained in other industries may be applicable in this one, recently published manuscripts pertaining to gas-particle separation were collected and searched for transferable technology. Technologies deemed impractical for handling fibers and large particles (typical in cotton gin airflows) were excluded; this included any device with internal struts, fins or turning vanes.

Two of the parameters that describe cyclone performance are pressure drop, a measure of the operating energy cost, and collection efficiency, the operational benefit. Optimization is challenging as these two parameters tend to be positively correlated. Collection efficiency traditionally has been reported as total mass efficiency – the collected mass proportional to what was conveyed by the incoming gas flow. As collection efficiency is strongly dependent on particle size, efficiency has also been reported in terms of cutpoint – that particle size for which the collection (or grade) efficiency is 50%. For particles significantly larger than this, collection approaches 100%. The cutpoint for many industrial cyclones is typically less than five microns, normalized for particle density and shape (Koch and Licht, 1977).

DESIGNS

The basic shape and function of dust cyclones has not changed much in over 100 years. The earliest type – the “pot-bellied” or low-pressure design – was soon joined by high efficiency designs that were smaller in diameter relative to the inlet volumetric gas flow. These high efficiency designs captured a greater percentage of incoming particulate due to their higher gas flow (and particle) velocities. Higher velocities also resulted in an increase in pressure drop. Cyclone designs are described by relating the height of the cylinder and cone sections to the cylinder diameter. The cotton ginning industry lists the cylinder and cone heights respectively. Other industries list the cylinder and total heights. Table 1 presents representative cyclone designs from the past century. Fig. 1 illustrates these common cyclone designs.

Differences in performance have been small since the 2D2D design was introduced (Shepherd and Lapple, 1939).

Table 1. Some common dust cyclone designs, by year of first publication.

Author (date)	Height (in Cylinder Diameters)			
	Efficiency	Cylinder (Barrel)	Cone	Total
Prockat (1929)	Low	1	1	2
Shepherd and Lapple (1939)	High	2	2	4
ter Linden (1949)	High	1	2	3
Stairmand (1951)	High	1.5	2.5	4
Peterson and Whitby (1965)	High	1.33	1.84	3.17
Swift (1969)	High	1.4	2.5	3.9
Avant et al. (1976)	High	1	3	4

As the cotton harvest was mechanized in the late 1950s and throughout the 1960s, gins responded by adding material handling capacity and used the 2D2D design where cyclones were needed. USDA research identified operating parameters suitable for handling cotton gin trash with 2D2D cyclones (also called ‘Atomic Energy Commission small-diameter cyclones’) (Baker and Stedronsky, 1967b; Wesley, et al., 1972).

Research teams led by Calvin B. Parnell at Texas A&M University developed 1D3D and 1D2D cyclone designs for agriculture (Avant et al., 1976; Simpson and Parnell, 1994). Improvements to the 1D3D design developed by scientists and industry practitioners were validated at Federal labs (Hughes and Baker, 1998; Funk et al., 2000). Now considered the standard, these “fully enhanced” 1D3D cyclones are replacing older designs in the ginning industry. They have inlets half a diameter high by a quarter diameter wide with correspondingly shorter vortex finders (Baker and Hughes, 1999) and cone bottoms one third of a diameter across (Holt et al., 1999) with an expansion chamber (Funk et al., 2001) (Fig. 2).

Fabrication Details and Design Subtleties. Using proper materials and fabrication techniques is critical to achieving optimum cyclone efficiency. Irregularities in the cyclone body and cone, whether from chord breaking (instead of rolling) or from the properties of the metal itself (using ordinary sheet steel instead of lock-forming quality) can lower efficiency by introducing particle bounce, which leads to particle re-entrainment. Rough seams in the cyclone body or cone, and misalignment between them, can in the same way significantly reduce collection efficiency (Armijo et al., 1992; Whitelock et al., 2009).

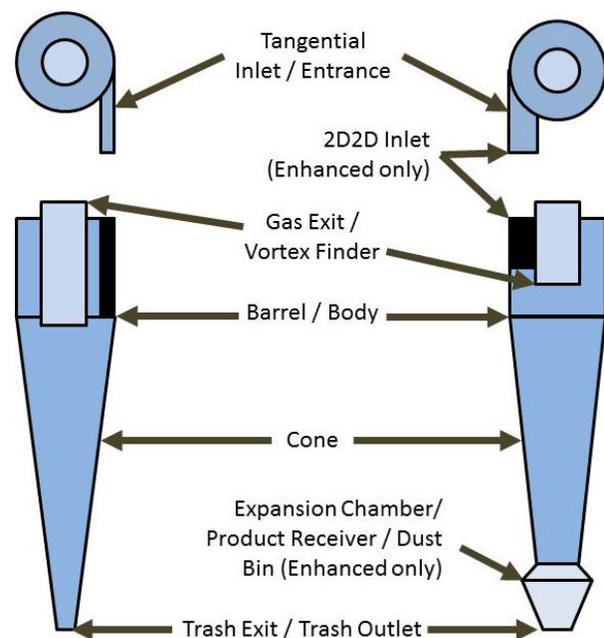


Figure 2. Dust cyclone components and vocabulary with top (plan) view above side (elevation) view; original 1D3D cyclone (left) and fully enhanced 1D3D (right) with shorter and wider inlet, shorter vortex finder, expansion chamber, and wider trash exit.

The relative dimensions of the major elements of a cyclone have long been the focus of research. However, small details can have just as large an influence on performance. For example, increasing the diameter of the cone bottom outlet has been shown to decrease pressure drop (Xiang et al., 2001) and increase mass efficiency (Baker and Hughes, 1999). Other changes to the dust outlet can have significant impact on collection efficiency, such as including expansion chambers (Baker et al., 1997; Holt et al., 1999; Obermair and Staudinger, 2001). The latter also documented the impact of a 2.5 cm (1 in) linear flight attached to the cone wall, running top to bottom on one side. Not only did

pressure drop decrease, but recirculation of collected particles – especially fibers – was eliminated. Overall collection efficiency decreased slightly. Linear flights are still occasionally used in the expansion chamber to reduce wear by inhibiting the circulation of abrasive particles, (Fig. 3). This practice is discouraged (J. Kelly Green, Texas Cotton Ginners Association, Personal Communication, 22 Oct. 2012).

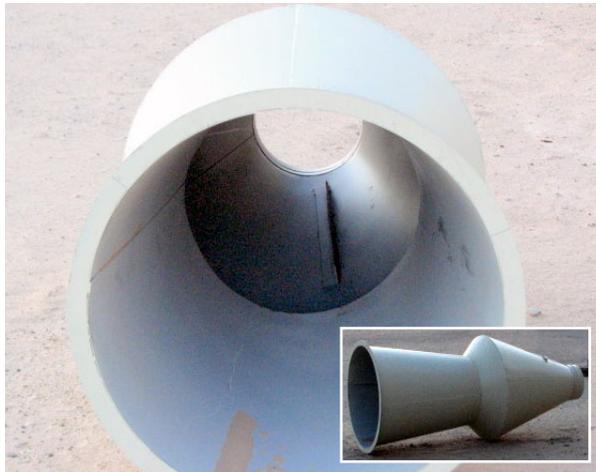


Figure 3. Photograph illustrating linear flight in expansion chamber. (Expansion chamber and bottom third of cone are fabricated in one piece separate from the rest of the cyclone to facilitate annual replacement, as local seed cotton has a high sand content.)

For a constant area, the shape of the inlet is important as well. Collection efficiency increases as the inlet becomes shorter and wider (Baker and Hughs, 1998), but only to the point that the inlet width aligns with the gas outlet tube, or vortex finder (Funk et al., 2001).

MODELS

Testing every conceivable design under every possible operating condition is infeasible. Experimenters have always sought trends in their data by which to make inferences within and extrapolations beyond it. Cyclone performance theories have been formulated and tested for as long as performance data has been collected. The earliest publication found was from more than eighty years ago (Prockat, 1929). Cyclone behavior models were at first based on semi-empirical algebraic equations. The equations were attempts to reconcile the physics of fluid mechanics and particle dynamics to actual observation. These equations were usually predictive within the range of the data they were based on, but rarely

beyond it due to airflow complexity and sensitivity to other influences such as subtle design changes or dust loading. The proliferation of computers has led to additional classes of models – those based on statistical analyses, and more recently, computational fluid dynamics (CFD) models that discretize the cyclone volume into a plurality of finite elements and sequentially solve equations describing mass, momentum and energy transfer through the boundaries of each element for a repeated series of small time increments. These categories are summarized with some of their strengths and weaknesses:

Balanced-Forces Collection Models. Balanced-forces or equilibrium-orbit models, assume that 50% collection efficiency (the cutpoint) occurs when the drag force acting on the particle's volume surface is just strong enough to hold the particle in a circular orbit. Drag force is caused by gas flow toward the center. This slow inward-moving or radial component of velocity is surprisingly uniform from the wall to a control surface projected from the vortex finder to the bottom, independent of elevation (ter Linden, 1949). This is the rotational equivalent to a particle suspended in air flowing up a flue; the particle will settle if gravitational attraction is greater, and will escape if the drag force caused by rising gasses is greater. Early models were published by Shepherd and Lapple (1939, 1940) and Lapple (1951). Stairmand (1951) developed a model which included corrections for wall friction and fluid viscosity, and accounted for designs with orientations other than vertical, those with internal vanes and even wetted wall designs. Barth (1956) used the settling velocity in still air to find drag, and considered the collection efficiency to be a function of the ratio of settling velocity to terminal settling velocity. Improvements were proposed by Dirgo and Leith (1985), who found an expression to replace Barth's figure relating collection efficiency to that ratio, and again by Iozia and Leith (1990), who proposed a logistic function that allows the inclusion of an empirical parameter after fitting data from 11 designs. Muschelknautz and Trefz (1992) expanded upon the Barth theory by including surface roughness and particle loading rate (the only algebraic model to include loading). Muschelknautz and Trefz's theory accurately predicts that larger particles will be collected more effectively as their ratio of mass to surface area is greater. These elegant approaches integrate a rational physical explanation with observations, and are predictive for standard designs and operating conditions within the data range of derivation. These models are based on

overall cyclone geometry and entrance gas velocity, so they cannot account for other influences such as nuances in cyclone design or particle size distribution.

Time-of-Flight Collection Models. Rather than just balancing inertia to drag force acting on a particle, time-of-flight models consider a particle collected only if it is in the cyclone long enough for inertia to bring the particle into contact with the wall. Leith and Licht (1972) assumed turbulence causes a uniform particle concentration, then calculated the radial distance a particle must travel to touch the wall. They were able to estimate collection efficiency for various cyclone designs with considerable accuracy. Clift et al. (1991) improved the Leith and Licht model prediction by changing the equation and the residence time assumption it depended on. Dietz (1981) divided the cyclone into sections and included terms for particle transport between them. Mothes and Löffler (1988) improved on the Dietz model by adding diffusion (turbulent dispersion) and re-entrainment. Particle re-entrainment and turbulent diffusion were also included in the model by Li and Wang (1989). Another improvement was to not assume uniformity, but include a term for the radial particle concentration gradient (Zhao, 2005). Both the balanced-forces and time-of-flight categories, and later models that combine these principles, are equally elegant in their simplicity and predictive over their specified range. Yet no model can predict the influence of an excluded parameter. If, for instance, the model does not include a term for particulate loading, its influence will be ignored.

Pressure Drop Models. Semi-empirical models have also been developed to predict pressure drop. Lissman (1930) provided a model based on tangential velocity. Shepherd and Lapple (1939) included the effect of dust loading on pressure drop. Stairmand (1949) included friction factor and exit loss along with several cyclone dimensions. Barth (1956) treated the exit tube (vortex finder) and the cyclone body separately. Cortés and Gil (2007) found the equations of Muschelknautz and Kambrock (1970) to be the most complete, accounting for geometry, friction, density ratio and the Froude number, adding that pressure drop decreases with solid loading to a point (ca. 200 to 700 g m⁻³), then increases. Correlating published, measured values for pressure drop to model predictions requires consistent treatment of the velocity component of total pressure; if the inlet and exit ducts have different areas then their gas velocities differ.

Statistical Models. Ramachandran et al. (1991) found published data for 98 cyclone designs and used statistical methods to derive a model for pressure drop based solely on cyclone dimensions (cylinder diameter, inlet height and width, exit tube diameter, exit tube protrusion, cylinder height, total height and bottom diameter). The statistical model predicted pressure drop better than the empirical models of the 1940s and 1950s. Elsayed and Lacor (2010) used response surface methodology to find optimal values for each of seven geometric dimensions of a cyclone design, using the Muschelknautz and Kambrock (1970) equations to estimate pressure drop and cutpoint. They claimed to have found a design having a collection efficiency equal to the Stairmand cyclone, but with half the pressure drop. Salcedo and Cândido (2001) used similar numerical optimization (a stochastic adaptive random search to solve a profit function) to explore novel geometries, developing a proprietary design claimed to have only 53% the emissions for the same pressure drop of a Stairmand (1951) cyclone. Response surface methodology was used elsewhere to find the natural vortex length (Qian and Zhang, 2005). Some weaknesses with these approaches are: their dependence upon extrapolations of semi-empirical models of limited accuracy even over the range of their derivation; their use of diverse data sets that may have inconsistent controls and interpretations; and the fact that a statistical model, like any other model, cannot account for parameters that are not included.

Finite Element Models. Stairmand (1951) observed that, “the flow pattern in even the simplest cyclone is complex and our understanding is still imperfect ...”, and many would agree that this is still true today. However, our understanding has increased greatly through the use of Computational Fluid Dynamics (CFD) numerical modeling to analyze cyclone flow. The use of CFD began with finite element grids constructed symmetrically about the vertical axis (Boysan et al., 1982) to keep the number of cells in a manageable range. As computational capacity has become less expensive, it has become feasible to include more sophisticated CFD models (full cyclone volume models now have tens of thousands of grid cells). Present models include two-phase flow, 3-D Reynolds Stress Models, and, more recently, particle-gas interaction equations.

As simplification has decreased, accuracy has increased. The abrupt directional change made by the gas stream as it completes its first revolution

in the cylinder section, a phenomenon ignored by semi-empirical models, was first observed using CFD modeling (Funk et al., 2001, Funk and Hughs, 2000). Strong inward velocities just under the vortex finder end (lip leakage) was also captured by CFD (Peng et al., 2002). Grid cells were added to model turbulent flow patterns in the expansion chamber (product receiver or dust bin), an important source of particle re-entrainment, with results confirmed by laser Doppler velocimetry (Hu et al., 2005).

The most impressive CFD models even show a spiral-shaped vortex (Derksen, 2003) with vortex tip instability; the swirling tip tends to attach to the wall of the cone bottom or dust outlet tube and progress around it (Peng et al., 2002; Cortés and Gil, 2007). Accounting for the effect of turbulence fluctuation on particle motion helps CFD models agree closely with experimental data (Zhao and Su, 2006). Yet despite the resource-intensive investment being made by research groups around the world [other teams using CFD for cyclone modeling are working in Brazil (Bernardo et al., 2006; Vegini et al., 2008); Malaysia (Gimbun et al., 2005a), and P.R.C.: Beijing (Hu et al., 2005) and Shanghai (Zhao and Su, 2006)], even CFD models do not always predict the energy cost and collection benefit accurately. Additionally, phenomenon of current research interest still cannot be modeled adequately. These innovations include horizontal, vertical and spiral grooves in the cylinder surface (Kim et al., 2001), and turbulence-inducing “pressure drop sticks” (Wang et al., 2001), among others.

Model Limitations. Cyclone performance models have been helpful for designing ‘typical’ dust collection systems, and for predicting trends in new design directions. But there will always be a need for lab and field testing to confirm performance. Models have two major limitations. First, they can only explain modeled variables. Dust cyclones are complex and their performance is influenced in statistically significant ways by a large number of parameters, the majority being omitted for simplicity or overlooked out of ignorance. Case in point: it has long been recognized that particulate loading attenuates swirl and turbulence, reducing pressure loss and increasing efficiency at levels up to about 500 g m⁻³, then having the opposite impact at higher levels (Cortés and Gil, 2007), but semi-empirical (and most CFD) models cannot account for this phenomenon. Other examples of parameters known to influence performance that are not included in most models include things like dust outlet geometry; (Holt et al.,

1999; Obermair and Staudinger, 2001); or vortex finder shape (Baker and Hughs, 1998; Lim, et al., 2004; Ogawa and Arakawa, 2006), even though they impact pressure drop and collection efficiency. In addition, models are only accurate over a limited dimensional range. Most semi-empirical models predict increasing collection efficiencies with increases in inlet velocity but do not usually include a term to account for surface imperfections known to have a deleterious effect; at higher velocities particles near the wall bounce and are re-entrained (Armijo et al., 1992; Baker and Stedronsky, 1967a; Koch and Licht, 1977). For reasons such as these, as well as those mentioned in the ‘Design Subtleties’ section, empirical experimentation remains important; model results must be validated experimentally.

EXPERIMENTS

Basic Research. Recent experiments with cyclones have investigated the influence of factors such as cyclone diameter, showing an inverse relationship to collection efficiency (Faulkner et al., 2007) and no change in cutpoint, but an increase in the slope of the fractional efficiency curve with increasing cyclone size (Faulkner et al., 2008). Experiments with cyclones in series showed a decreasing efficiency (expected due to the decrease in load and particle size) but also a decrease in cutpoint, even though successive cyclones had the same dimensions and operating parameters (Whitelock and Buser, 2007), confirming some semi-empirical model predictions as demonstrated with very small diameter cyclones earlier (Ray et al., 2000).

Another experiment used a strobe light for visualization and high-time-resolution pressure measurements to quantify vortex end attachment and progression. The vortex core rotated at about the same rate as the gas in the cyclone (Peng et al., 2005). Laser Doppler techniques were used to visualize swirl pattern in the cyclone and dust hopper (Hu et al., 2005), (Peng et al., 2002), and to look at dust agglomeration (Obermair et al., 2005), especially in the dust hopper, as agglomeration is a significant factor in cyclone efficiency.

Model Validation. Salcedo and Candido (2001) tested a new cyclone design, and the model used to develop it, to see if laboratory performance was accurately predicted. Laboratory-scale cyclone results were confirmed by stack sampling tests on a larger (pilot-scale) cyclone at a Portuguese chemical

factory. Emissions were reduced typically by 50% compared to a high efficiency cyclone at comparable pressure drops (Salcedo and Pinho, 2003).

CFD results for cyclones operating in series were confirmed at a cement plant in Brazil (Vegini et al., 2008). Two cyclone size/shapes operating at three temperatures (430 to 860°C) were replicated (redundant towers, or split-stream processing) and pressure drop and collection efficiency predictions were found to be accurate when using a multi-fluid concept to model the interaction between the gas and the particles. The model was sensitive to particle size and loading, showing promise as an accurate design tool.

Temperature and Pressure Experiments.

Collection efficiency as measured by cutpoint improved with pressure up to 2530 kPa and worsened with increases in temperature up to 693°C for 5 cm diameter cyclones at entrance velocities of 1.8, 2.6 and 5.2 m/s (Parker et al., 1981). Cyclone performance at temperatures up to 2000°C was quantified on 10 cm diameter cyclones in an experiment that unfortunately was confounded as gas flow rate and temperature were not independent (Patterson and Munz, 1989). Performance data (collection grade efficiency and pressure drop) for a non-standard shape (0.69D-1.88D) cyclone at temperatures from 20 to 800°C resulted in a useful data set and a new algebraic model (Bohnet, 1995). A fictitious fluid was used in a CFD model to separate the effects of density and viscosity on cyclone performance. Density significantly affected pressure drop, viscosity did not. Collection efficiency was proportional to the square of tangential velocity. Collection increased with pressure for the same inlet velocity because the gas tangential velocity was distributed differently at higher densities, with higher velocities near the outside wall at 6 and 12 atm. Collection efficiency decreased with increases in temperature for the same inlet velocity because of decreases in tangential velocity at 400 and 800°C (Shi et al., 2006).

AIR DENSITY AND ENTRANCE VELOCITY

The optimal entrance velocity for 1D3D and 2D2D cyclones was determined empirically (Mihal-ski et al., 1992). Environmental regulations require correcting sampled ambient air to standard conditions as defined by the US Environmental Protection Agency (EPA). EPA's standard temperature is 25°C and standard pressure is 760 mm Hg (EPA, 2001).

This correction is necessary from the standpoint of uniformly defining and fairly applying regulations across a range of elevations, climate zones and seasons. However, corrections to standard conditions should be avoided when establishing the proper operating conditions for or designing a dust cyclone. The collection efficiency of a dust cyclone is more sensitive to particle velocity than to air mass flow, and therefore should be sized and operated according to actual or local inlet velocity.

Consider the balanced-forces and time-of-flight collection models presented above. Moving particles normally have a tendency to travel in a straight line. Particles following a circular path inside a cyclone are therefore being acted upon by an external force. This 'centripetal' force is actually drag caused by the surrounding fluid (air) flowing radially towards the center of the cyclone. Drag force is governed by Stokes' Law:

$$F = 3\pi\mu d v_r \quad (1)$$

Where μ is the dynamic viscosity, d is the particle diameter and v_r is the velocity of the particle relative to the surrounding fluid (Cooper and Alley, 1994). In this relationship the only variable influenced by ambient air conditions is the dynamic viscosity. The impact of pressure is negligible and dynamic viscosity is primarily a function of temperature (Maxwell, 1866). Over a temperature range of from 0 to 200°C the dynamic viscosity of air varies from 1.72×10^{-5} to 2.57×10^{-5} (N s/m²), a difference of only 50% (Roberson and Crowe, 1980).

Particle inertia results in an apparent force (sometimes called centrifugal force), described by Newton's second law, which in the case of uniform circular motion is:

$$F = m v_t^2 / r \quad (2)$$

Where m is the particle's mass, v_t is its tangential velocity, and r is the radius of its circular path. In this relationship the only variable influenced by ambient air conditions is particle velocity. The initial tangential velocity of a particle is approximately equal to the entrance velocity of the air carrying it.

Particles escape being collected when drag force (1) is greater than inertia (2) and air carries the particle out of the cyclone. A particle is collected when drag force is too weak to maintain a circular orbit and the particle contacts the cyclone wall during the time it is in the cyclone volume. For a cyclone with a fixed mass flow rate, at an elevation of 1183 m (3880ft.) air density would be 15% lower than at sea level and entrance velocity would be 15% greater.

Drag forces would be equal, but the force required to keep a given particle traveling in a circular orbit would be 33% greater than at sea level. Thus it is important to design and adjust dust cyclones based on local air density.

FUTURE WORK

In the future, state implementation plans and local environmental regulations will need to consider the energy consumption of control devices and not just stack total emissions, as producing electricity to operate control devices results in pollution where that electricity is generated (Funk, 2010). Future cyclone research will continue to focus on collection effectiveness, especially for finer particulates, but will also focus on minimizing energy costs. As computing resources become less expensive and CFD modeling becomes more sophisticated, increasingly complex models will continue to contribute to our still imperfect understanding. Yet numerical simulation will always require validation trials that test cyclones under conditions and loads as near to the real world application as feasible. As methods for quantification of particulate emission particle size distributions become more affordable, the quality of the data collected in these future trials should further improve (Ray et al., 2000).

DISCLAIMER

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