DUST CYCLONE RESEARCH IN THE 21ST CENTURY

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Abstract

Research to meet the demand for ever more efficient dust cyclones continues after some eighty years. Recent trends emphasize design optimization through computational fluid dynamics (CFD) and testing design subtleties not modeled by semi-empirical equations. Improvements to current best available control technology will need to be energy-neutral, or the emissions associated with producing additional electricity will offset any emission reductions at the gin.

Introduction

The cotton ginning industry continues to proactively respond to the 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 particulate emissions. Control technologies developed for or by the ginning industry are emulated by other industries. Collecting fine particulate, particles less than 2.5 microns ($PM_{2.5}$), became a legal issue when the U.S. Environmental Protection Agency (EPA) promulgated revisions to the particulate matter National Ambient Air Quality Standards (NAAQS) in 1997, regulating $PM_{2.5}$ for the first time. The EPA revised the NAAQS for $PM_{2.5}$ in 2006, establishing an annual threshold of 15 g m^{-3} and a (lower) 24 hr limit of 35 g m^{-3}. The EPA's final designation of 39 areas as nonattainment with 1997 NAAQS for $PM_{2.5}$ (EPA, 2007) resulted in 20 states being 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, in many cases by applying the region-wide ambient air quality standard as a property line limit. Currently, the ginning industry is documenting actual $PM_{2.5}$ emissions. It is probable that most, if not all, gins will be significantly under this limit without any further improvement to dust collection equipment. However, a review of the literature was undertaken to discover recent developments in particulate control so that the industry might be prepared, just in case a gin is required to further reduce their fine particulate emissions.

Cyclones are the particulate control of choice as they have no moving parts and low capital and maintenance costs. Other industries also use cyclones – for emissions control, product separation, process enhancement, heating, drying, source sampling and monitoring. They have even appeared in household vacuum cleaners. 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, over 100 recent manuscripts pertaining to gas-particle separation were collected and searched for transferable technology. Technology deemed impractical for handling fibers and large particles (typical in cotton gin airflows) was excluded.

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 increase or decrease together. Collection efficiency has been reported as what escapes (or more often, what does not) proportional to what was suspended in the incoming gas flow. As collection efficiency is strongly dependent on particle size, efficiency has frequently 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.

Designs

The shape of dust cyclones has not changed much since the electric motor was first married to a fan to create a pneumatic conveying system (sometime late in the 19th Century). 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 velocities, though with 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 one presents representative cyclone designs from the past century. Figure 1 illustrates these common cyclone designs. Differences in performance have been small since the Shepherd and Lapple "2D2D" design was introduced in 1939. In the late 1950's and 1960's the 2D2D design became popular in the ginning industry. USDA research identified operating parameters suitable for handling cotton gin trash with 2D2D cyclones (Baker and Stedronsky, 1967).

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

		Height (in Diameters)		
Author (date)	Efficiency	Cylinder	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

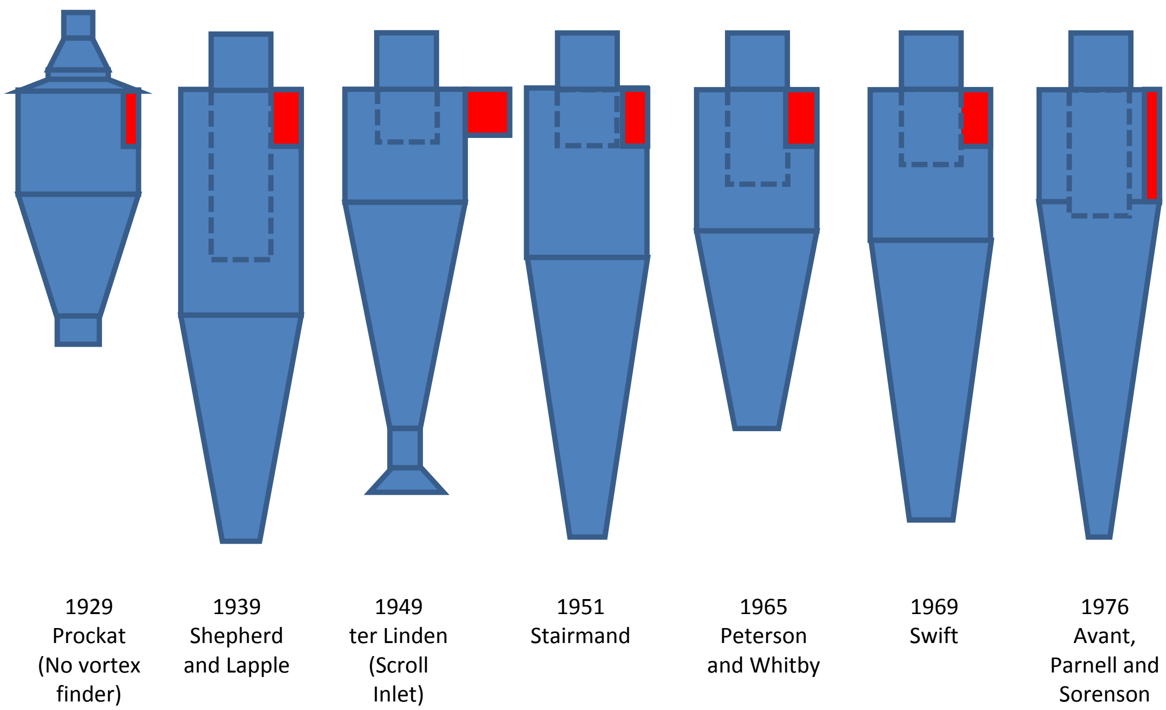

Figure 1. Representative dust cyclone designs.

Design Subtleties

The relative dimensions of the major elements of a cyclone have long been the focus of research. But subtle details can have just as large an influence on performance, even though many semi-empirical models ignore them. For example, seams and slight bends in the cyclone body can lower efficiency (Armijo et al., 1992). As another example, increasing the diameter of the cone bottom outlet has been shown to decrease pressure drop (Xiang et al., 2001) and increase efficiency (Baker and Hughs, 1999). Other changes to the dust outlet can have significant impact on collection efficacy, such as including expansion chambers (Obermair and Staudinger, 2001; Baker et al., 1997). The latter also documented the impact of a linear flight attached to the cone wall. Not only did pressure drop decrease, but by eliminating recirculation of collected particles collection efficiency increased. 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 abounded – and floundered – for as long as performance data has been collected (the earliest publications found were from the 1920's). Cyclone behavior models were at first based on semi-empirical algebraic equations. They 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 outward-acting apparent centripetal force caused by the inertia of a particle's mass is equal to the inward-acting drag force acting on the particle volume's surface. Apparent centripetal force is caused by rotation. 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 drag forces caused by rising gasses are 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). This 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 basic geometry and gas velocity, so they cannot account for other influences such as nuances in cyclone design or particulate size distribution.

Time-of-Flight Collection Models

Rather than just balancing apparent centripetal force and drag force acting on a particle, time-of-flight models consider a particle collected only if it is in the cyclone long enough for the centripetal force 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 result of the Leith and Licht model 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 included in the model by Li and Wang (1989). 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 ranges. 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. Cortes 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 presure 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 1940's and 1950's. Elsayed and Lacor (2010) used response surface methodology to find optimal values for each of seven geometric dimensions of a cyclone design, where the Muschelknautz and Kambrock (1970) equations estimated pressure drop and cutpoint. They claimed to have found a design having collection efficiency equal to the Stairmand cyclone, but with half the pressure drop. Salcedo and Candido (2001) used similar numerical optimization to explore novel geometries, testing two proprietary designs. Response surface methodology was also used 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 statistical models can not account for parameters that are not in the data sets.

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) 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) including 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 and Hughs, 2000). Strong inward velocities just under the vortex finder end – lip leakage – were also captured by CFD models (Peng et al., 2002). Grid cells were added to model turbulent flow patterns in the expansion chamber (product receiver or dust bin), an important cause 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 (Cortes and Gil, 2007; Peng et al., 2005). Yet despite the resource-intense investment being made by research groups around the world, 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, such as horizontal, vertical and spiral grooves in the cylinder surface (Kim et al., 2001), and turbulence-inducing "pressure drop sticks" (Wang et al., 2011). Other teams that have used CFD cyclone models include Gimbun et al. (2004), Hu et al. (2005), and Zhao and Su (2006).

Model Limitations

Cyclone performance models have been helpful for designing typical dust collection systems and 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 (Cortes 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 (Obermair and Staudinger, 2001; Holt et al., 1999) or vortex finder shape (Ogawa and Arakawa, 2006; Lim et al., 2004; Baker and Hughs, 1998), 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 (Baker and Stedronsky, 1967; Armijo et al., 1992). 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

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 using modern technology attempted to visualize and quantify vortex end attachment and progression (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 it is a significant factor in cyclone efficiency.

Future Work

In the future, compliance with environmental regulations will need to consider energy consumption in addition to current considerations since producing energy also has an environmental impact (Funk, 2010). Entering the second decade of the 21st century, cyclone research will continue to focus on collection efficiency, especially for finer particulates, but most likely 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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