STUDY OF DESIGN OF CYCLONE SEPARATOR UNDER COLLECTION EFFICIENCY AND AIR DENSITY EFFECT

Radhe Shyam Verma[1], Prakash Kumar Sen[2], Shailendra Kumar Bohidar[3]

[1]*Student, Mechanical Engineering, Kirodimal Institute of Technology, Raigarh, (India)*

[2]*Student of M. Tech. Manufacturing Management, BITS Pilani*

[3]*Ph.D. Research Scholar, Kalinga University, Raipur*

ABSTRACTS

In this paper we are study of collection efficiency of cyclone separator and air density effect on cyclone separator. Cyclonic separation is a method of removing particulates from on air, gas or liquid stream, without the use of filters, through vortex separation. Rotational effects and gravity are used to separate mixtures of solids and fluids. The method can also be used to separate fine droplets of liquid from a gaseous stream. The collection or separation efficiency is most properly defined for a given particles size. As mentioned, fractional efficiency is defined as the fraction of particles of a given size collected in the cyclone, compared to those of that size going into the cyclone. The cyclone, because of its simplicity and low operating cost, is probably the most widely used dust collector in industry. With the growing concern for the environmental effects of particulate pollution, it becomes increasingly important to be able to optimize the design of pollution control systems. As a result, many studies have been made to characterize cyclone performance as affected by design and operational parameters. Unfortunately, there is no information available on the effect of air density on the cyclone inlet design velocity, and consequently on its performance. Experience shows that collection efficiency of cyclone separator increase with increasing particle mean diameter and density, increasing gas tangential velocity, decreasing cyclone diameter, increasing cyclone length, extraction of gas along with solids through the cyclone legs.

Keywords: Cyclone Separator, Air Density, Collection Efficiency, Pressure Drop, Performance, Solid, Liquid Particles and Gas Substant

I. INTRODUCTION

Cyclones, as the most cost-effective air pollution device for particulate matter removal, have been studied for decades. Although many procedures for calculating collection efficiency have been developed, current design practice either emphasizes past experience rather than an analytical design procedure, or cannot accurately predict cyclone collection efficiency.

In the literature, theories to predict cyclone efficiency have been reported for many years. As it is mentioned before, Lapple (1951) developed a theory (also known as CCD) for cut-point (d_{50}) based upon a force balance and representation of residence time with the air stream number of turns within a cyclone. The Lapple model is easy to use, but it cannot accurately predict cyclone collection efficiency. In 1972, Leith and Licht presented another theory (back-mixing) for the study of cyclone collection efficiency. Their back-mixing theory suggests that the turbulent mixing of uncollected particles in any plane perpendicular to the cyclone axis produces a uniform uncollected dust concentration through any horizontal cross section of a cyclone. Based upon this theory, they developed a model to predict efficiency for any size particles. It has been reported that the Leith and Licht model for efficiency appears to work best compared with other theories in the literature (Leith and Mehta, 1973). However, this model has not been tested with experimental data and it involves variables and dimensionless parameters not easily accounted for in practical applications.[1]

Stairmand (1951) and Barth (1956) first developed the "static particle theory" for the analysis of cyclone collection efficiency in the 50's. Since then, this static particle theory based upon a force balance analysis has been adopted by many other researchers in their theoretical analyses for characterizing cyclone performance. Basically the "static particle theory" suggested that force balance on a particle yields a critical particle, which has 50% chance to be collected and 50% chance to penetrate the cyclone. The diameter of the critical particle is d_{50}. The critically sized particle (d_{50}) is smaller than the smallest particle, which is collected, and larger than the largest particle that penetrates the cyclone. The critical particle with diameter of d_{50} is theoretically suspended in the outer vortex forever due to the force balance.[2]

The cyclone, because of its simplicity and low operating cost, is probably the most widely used dust collector in industry. With the growing concern for the environmental effects of particulate pollution, it becomes increasingly important to be able to optimize the design of pollution control systems. As a result, many studies have been made to characterize cyclone performance as affected by design and operational parameters. Unfortunately, there is no information available on the effect of air density on the cyclone inlet design velocity, and consequently on its performance.[2]

The cyclone design procedure outlined in Cooper and Alley (1994) is perceived as a standard method and has been considered by some engineers to be acceptable. However, this design process, hereafter referred to as the classical cyclone design (CCD) process, does not consider the cyclone inlet velocity in developing cyclone dimensions. Previous research at Texas A&M University (TAMU) (Parnell, 1990) indicated that the efficiency of a cyclone increased, and emission concentration decreased, with increasing inlet velocity. But at relatively high inlet velocities, the cyclone efficiency actually began to decrease. A dramatic increase in emission concentration has been observed at velocities higher than a certain threshold level (Parnell, 1996). The level at which the inlet velocities were too high and caused increased emissions was different for each cyclone design. The Texas A&M cyclone design (TCD) process specifies the "ideal" cyclone inlet velocities (design velocities) for different cyclone designs for optimum cyclone performance. The design inlet velocities for 1D3D, 2D2D, and 1D2D cyclones are 16 m/s ±2 m/s (3200 ft/min ±400 ft/min), 15 m/s ±2 m/s (3000 ft/min ±400 ft/min), and 12 m/s ±2 m/s (2400 ft/min ±400 ft/min), respectively. The TCD process allows an engineer to design the cyclone using a cyclone inlet velocity specific for the type of cyclone being considered. However, there is one problem with the CCD and TCD cyclone design processes. None of these cyclone design methods specify whether the cyclone design velocity should be based on the standard air density or actual air density.[3]

A design velocity of 16 m/s (3200 ft/min) based on standard air density (1.20 kg/dscm or 0.075 lb/dscf) would be 19 m/s (3700 ft/min) based on actual air density (1.04 kg/dscm or 0.065 lb/dscf). If the TAMU design process were to be used, then the 19 m/s (3700 ft/min) design velocity would be outside the acceptable range of inlet velocities for 1D3D cyclones (16 m/s ±2 m/s). Which is correct? Should cyclones be designed based on standard air density or actual air density?

It was hypothesized that cyclone performance and pressure drop would be affected by varying air density. The goal of this research was to quantify the air density effects on cyclone performance, and ultimately, to recommend a cyclone design philosophy based on either actual or standard air density.[3]

II. COLLECTION MECHANISM IN THE OUTER VORTEX

2.1 Particle Motion in the Outer Vortex

Study of the particle collection mechanism in the outer vortex is a way to understand the relationship between the cyclone performance characteristics and the design and operating parameters. The first step in this study is to characterize the particle motion in the outer vortex. In the study of particle motion and trajectory in the outer vortex, the following assumptions were made:-[5]

- Particle is spherical. For irregular non-spherical particles, their Stokes' diameters (also known as ESD) are used for analysis
- The relative velocity between the air stream and particle does not change the fluid pattern, i.e. the air stream velocity profile in the outer vortex.
- Particle motion is not influenced by the neighboring particles.
- The particle tangential velocity is the same as the air stream tangential velocity. In other words, the particle does not "slip" tangentially.
- Particle R_e <1, the drag force on a particle is given by Stokes Law.
- Force balance on a particle yields 50% collection probability on this particle.
- Particle moves from the interface of inner vortex and outer vortex towards the cyclone wall, once the particle hits the wall, it will be collected .

The analysis of particle motion in the outer vortex is conducted in a cylindrical coordinate system. When the air stream brings a particle with diameter d_p and density ρ_p into the cyclone outer vortex, centrifugal force acting on the particle generates a radial acceleration. The relative velocity between the particle and air stream generates a different path for the particle and air stream. Figure 15 shows the trend of a particle path and air stream path when the particle is moving in the outer vortex[6]

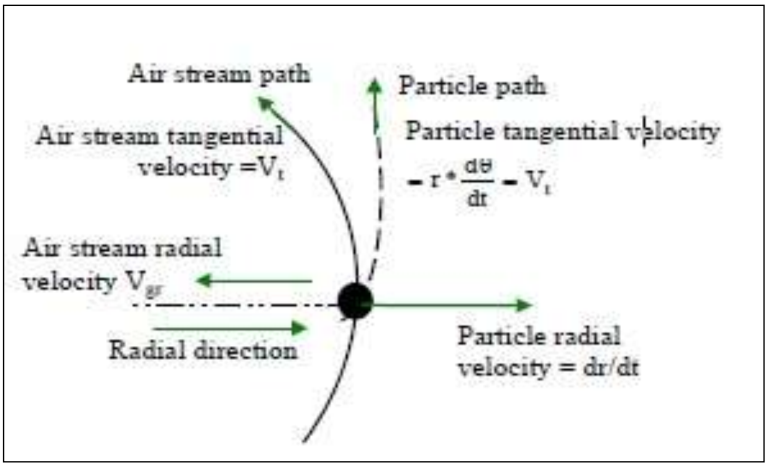

Fig (1) Paths of a Particle and Air Stream in The Outer Vortex

III. FORCE ACTING ON PARTICLES

The particle motion in the cyclone outer vortex can be determined by Newton's law as follows:

$$m_p * \frac{d\vec{V}_p}{dt} = \sum \vec{F}$$

3.1 Gravity Force (F_G)

The impact of gravity force on the particle motion is in the form of particle terminal settling velocity (V_{TS}). Based on the definition of particle terminal settling velocity (Hinds, 1999), the drag force of the air on a particle (F_{DG}) is exactly equal and opposite to the force of gravity when the particle is released in air and quickly reaches its terminal settling velocity, such as,[4]

$$F_{DG} = F_G = mg$$

In this equation, F_{DG} is the gas resistance force to the particle motion caused by gravity. It can be determined by the Stokes law as:[4]

$$F_{DG} = 3\pi * \mu * V_{TS} * d_p$$

Combining equations, a particle terminal settling velocity is obtained as follows:

$$V_{TS} = \frac{\rho_p * d_p^2 * g}{18\mu}$$

In this equation, particle density (ρ_p) is in kg/m^3; g is the acceleration of gravity in m/s^2; μ is gas viscosity in Pa.S; d_p is the particle diameter in m and V_{TS} is the particle terminal gravity settling velocity in m/s. Since particles of interest in the air quality research are less than or equal to 100 µm; as a result, the particle settling velocity caused by gravity is negligible compared to the particle traveling velocity in the outer vortex ($V_{TS} << V_p$). Therefore the impact of gravity force on particle motion is negligible.[4]

3.2 Centrifugal Force (F_C)

Centrifugal force is the force acting on the particle in the radial direction for the particle separation. It is determined by:-

$$F_C = m\vec{a}_r = \frac{\pi * d_p^3 * \rho_p}{6} * \left[\frac{d^2 r}{dt^2} - r\left(\frac{d\theta}{dt}\right)^2\right]$$

3.3 Drag Force (F_D)

Along the radial direction, there is another force, which is the gas resistance force to the particle motion caused by centrifugal force. It was assumed that the particle Reynolds number is less than one ($R_e<1$), which means Stokes' law, applies. As a result, the drag force on a spherical particle is:-[6]

$$F_D = 3\pi\mu d_p * (V_{pr} - V_{gr}) = 3\pi\mu d_p * \left(\frac{dr}{dt} - V_{gr}\right)$$

IV. FORCES BALANCE DIFFERENTIAL EQUATION

As mentioned above, in the cyclone outer vortex fluid field, there are only two forces (centrifugal force F_C & drag force F_D) acting on the particle in the radial direction. When $F_C > F_D$, the particle moves towards the cyclone wall to be collected. Whereas, when $F_C < F_D$, the particle will move to the inner vortex and then to penetrate the cyclone. The force balance ($F_C = F_D$) gives a particle a 50% chance to penetrate and 50% chance to be collected. The force balance differential equation can be set up by:-

$$\left[\frac{d^2 r}{dt^2} - r\left(\frac{d\theta}{dt}\right)^2\right] + \frac{18\mu}{\rho_p * d_p^2} * \left(\frac{dr}{dt} - V_{gr}\right) = 0$$

V. PARTICLE COLLECTION PROBABILITY DISTRIBUTION IN THE OUTER VERTEX

Based on the above analyses, d_{50} distribution defines the critical separation diameter (d_{50}) at the any point P(r, z) in the outer vortex. At the point P(r, z), if the particle diameter $d > d_{50}$, the particle will move to the wall and be collected, whereas if the particle diameter $d < d_{50}$, the particle will move to the inner vortex and penetrate. For a given inlet particle size distribution, the ratio of all the particles larger than d_{50} to the total inlet particles is the particle collection probability at the point P(r, z). If it is assumed that the inlet particle size distribution is a lognormal distribution with mass median diameter (MMD) and geometric standard deviation (GSD), then can be used to determine the particle collection probability at any point P(r, z) in the outer vortex.[8]

$$F(d) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}d_p \ln(GSD)} \exp\left[-\frac{(\ln(d_p) - \ln(MMD))^2}{2(\ln(GSD))^2}\right] dd_p$$

$$P(d) = \int_{d_{50}}^{\infty} \frac{1}{\sqrt{2\pi}d_p \ln(GSD)} \exp\left[-\frac{(\ln(d_p) - \ln(MMD))^2}{2(\ln(GSD))^2}\right] dd_p$$

The particle collection probability distribution (equation 68) is in fact the particle collection rate distribution in the outer vortex. It is also the collected concentration distribution in the outer vortex.

VI. THEORETICAL MODEL FOR CYCLONE OVERALL EFFICIENCY

The particle collection probability distribution in the outer vortex in which d_{50} is the critical separation diameter in the space. When the critical diameter on the interface is used, the integration yields the cyclone total collection efficiency. In other words, with d_{50} = cut-point is the theoretical model for calculating cyclone overall efficiency.[5]

VII. METHOD FOR STUDY ABOUT AIR DENSITY EFFECT

Cyclone airflow rate and inlet velocity change with air density. In this research, tests were conducted to evaluate 1D3D and 2D2D cyclone emission concentrations and pressure drops with two sets of inlet design velocities: one set based on actual airflow rate, and the other set based on dry standard airflow rate. All the tests were conducted at Amarillo, Texas, where the altitude is 1128 m (3700 ft) and consequently the air density is relatively low (1.04 kg per dry standard cubic meter). During the tests, barometric pressure, air temperature, and relative humidity were monitored by a digital weather station.[8]

VIII. CYCLONES

In the agricultural processing industry, 2D2D and 1D3D cyclones have been used for particulate matter control for many years. In this research, only fine dust and 1D3D and 2D2D cyclones were used to conduct experiments. Both 1D3D and 2D2D cyclones used in this research were 15 cm (6 in.) in diameter.

IX. TESTING MATERIALS

Fly ash, cornstarch, screened manure dust, and regular manure dust were used as test materials in this research ("screened manure dust" refers to cattle feedyard dust that has been passed through a screen with 100 µm openings, and "regular manure dust" refers to manure dust from the same source as the screened manure dust with the larger than 100 µm PM included). The particle densities of fly ash, cornstarch, and manure dust were 2.7 g/cm^3, 1.5 g/cm^3, and 1.8 g/cm^3, respectively. Emission concentrations for specific cyclone designs were directly related to the fine dust inlet loadings and the particle size distributions of inlet particulate matter. Tests were conducted with inlet concentrations of the dust at 1 and 2 g/m^3. A Coulter Counter Multisizer 3 (CCM) (Coulter Electronics, 2002) was used to analyze PSD's of inlet dust and emitted dust on the filters. The CCM is an electronic particle sizer that operates on a resistance principle to measure PSD in electrolyte liquid suspensions (Hinds, 1999). Figures 16 to 19 show the CCM PSD's of the four inlet PM. Mass median diameter and geometric standard deviation are two parameters that characterize PSD's. The MMD is the aerodynamic equivalent diameter such that 50% of PM mass is larger or smaller than this diameter. The GSD is defined by the following equation (Cooper and Alley, 1994).[9]

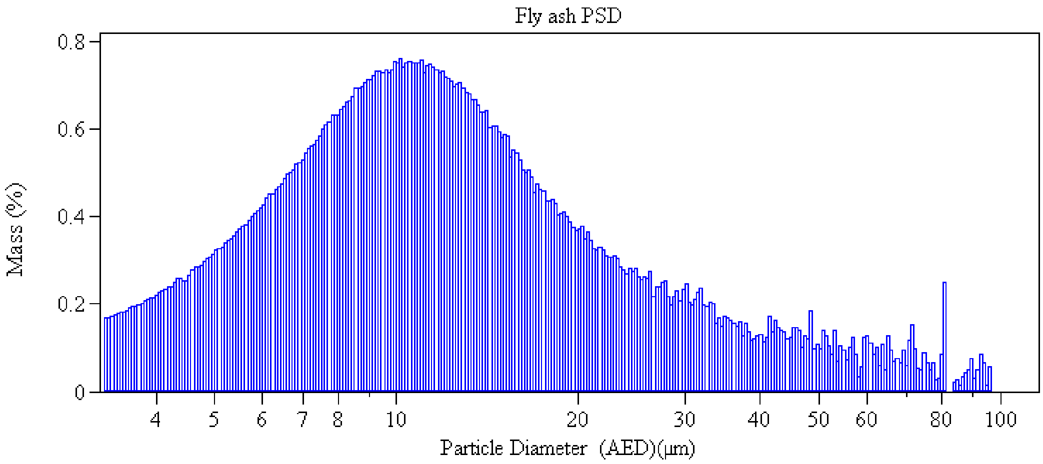

Fig (2) PSD for Fly Ash (MMD = 11.34 Mm, GSD = 1.82)

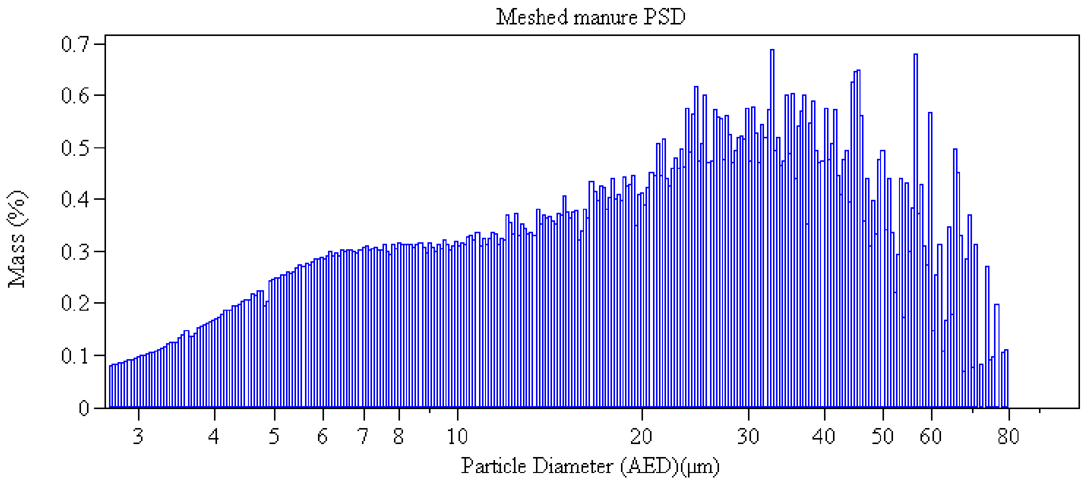

Fig (3) PSD for Screened Manure Dust (MMD = 20.81 Mm, GSD = 3.04)

X. TESTING SYSTEM

The testing system was a pull system shown in fig (4). The blowers pull the air from the feeding mechanism directly into a pipe and then to the cyclone. A collection hopper was connected to the bottom of the cyclone dust outlet to store the dust collected by the cyclone. Cleaned air flowed out of the cyclone through the outletconveying duct to a filter holder. The filter captured all the dust emitted from the cyclone, and clean air flowed through an orifice meter and the blowers and was discharged into the testing room. The designed airflow rate was maintained by monitoring the pressure drop across the orifice meter during the test. The equipment used in the testing system. The relationship between flow rate and pressure drop across the orifice meter.[8]

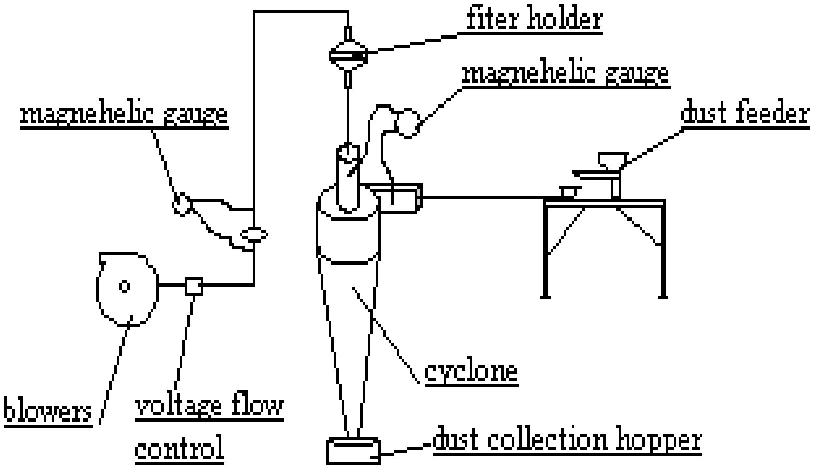

Fig (4) Cyclone Testing System

Testing time was 3 min for each test, and the system was cleaned between tests. The filters were conditioned in an environmental chamber for 24 h at 25°C and 46% relative humidity, as specified by EPA, and weighed with a microbalance (range: 0 to 101 mg, accuracy: ±0.1 mg) that was located in the environmental chamber before and after testing to determine total penetrating weights. The airflow rates of the testing system were determined by using the TCD design velocity the airflow rate and cyclone inlet velocity used to calculate cyclone airflow rates and inlet velocities based on actual or standard conditions.

The same testing system was used to measure cyclone pressure drops at two inlet velocity treatments. In order to accurately measure the static pressure drop across the cyclones, the static pressure taps were inserted into the air stream such that the static pressure sensing position was in the direction of airflow. The pressure drop measurement was conducted without any dust feeding.

XI. TEST RESULTS AND DISCUSSION

The average emission concentrations for the tests conducted on the 1D3D and 2D2D cyclones. The null hypothesis for the 1D3D cyclone design was that there was no difference in emission concentrations for inlet velocities of 16 actual m/s (3200 afpm) versus 16 standard m/s (3200 sfpm or 3800 afpm); at an air density of 1.02 kg/m^3 (0.0635 lb/ft^3), the 16 standard m/s (3200 sfpm) velocity corresponds to 19 actual m/s (3800 afpm). For comparison purposes, all the emission concentrations were converted from mg per actual cubic meter (mg/acm) into mg per dry standard cubic meter (mg/dscm).[8]

The statistical analyses indicated that the cyclone emission concentrations were highly dependent on cyclone design, inlet loading rates, PSDs of inlet PM, as well as air density. The following observations were noted:

1. For the fly ash tests, the average emission concentrations were significantly higher for both 1D3D and 2D2D cyclones for inlet velocities of 16 and 15 actual m/s (3200 and 3000 afpm) compared to 16 and 15 standard m/s (3200 and 3000 sfpm). For an air density of 1.02 kg/m^3 (0.0635 lb/ft^3), 16 standard m/s (3200

sfpm) is equivalent to 19 actual m/s (3800 afpm), and 19 m/s (3800 afpm) is outside of the TCD ideal design velocity range of 16 ±2 m/s (3200 ±400 fpm) for the 1D3D cyclones. One would assume that higher emissions would occur at 19 m/s (3800 afpm). However, the measured data did not support this assumption. Experimental results indicate that the optimum design velocity for the 1D3D cyclone is 16 standard m/s (3200 sfpm), not 16 actual m/s (3200 afpm). The same observations were made for the 2D2D cyclone. With an air density of 1.01 kg/m^3 (0.063 lb/ft^3), 15 standard m/s (3000 sfpm) inlet velocity is equivalent to 18 actual m/s (3600 afpm), and 18 actual m/s (3600 afpm) is also outside of the TCD ideal design velocity range of 15 ±2 m/s (3000 ±400 fpm) for the 2D2D cyclones. Again, the experimental data indicate that the optimum design velocity for the 2D2D cyclone should be 15 standard m/s (3000 sfpm), not 15 actual m/s (3000 afpm).

2. For agricultural dust with larger MMD, such as cornstarch and manure dust, the trend of decreasing emission concentration for 1D3D and 2D2D cyclones was observed when the inlet design velocity was based on standard air density. However, the differences in the emission concentrations for inlet velocities based on actual versus standard air densities were not statistically significant.
3. The results from both 1D3D and 2D2D cyclones also indicate that higher inlet loading rates increased the differences in the emission concentration with different inlet velocity treatments. This implies that the effect of air density is increased as cyclone inlet loadings increase.

XI. CONCLUSION

Particle motion in the cyclone outer vortex was analyzed in this paper to establish the force balance differential equation. Barth's "static particle" theory combined with the force balance equation was applied in the theoretical analyses for the models of cyclone cut-point and collection probability distribution in the cyclone outer vortex. Cyclone cut-points for different dusts were traced from measured cyclone overall collection efficiencies and the theoretical model for the cyclone overall efficiency calculation. The theoretical predictions of cut-points for 1D3D and 2D2D cyclones with fly ash are 4.85 μm and 5.25 μm. Based upon the theoretical study in this chapter the following main observations are obtained:-

1. The traced cut-points indicate that cyclone cut-point is the function of dust PSD (MMD and GSD).
2. Theoretical d_{50} model (Barth model) needs to be corrected for PSD
3. The cut-point correction factors (K) for 1D3D and 2D2D cyclone were developed through regression fits from theoretically traced cut-points and experimental cut-points.
4. The corrected d_{50} is more sensitive to GSD than to MMD.
5. The theoretical overall efficiency model developed in this research can be used for cyclone total efficiency calculation with the corrected d_{50} and PSD. No fractional efficiency curves are needed for calculating total efficiency

The performance of 1D3D and 2D2D cyclones is highly dependent on the inlet air velocity and air density. Proposed cyclone design inlet velocities are:

• 16 m/s ± 2 m/s (3200 ft/min ± 400 ft/min) with air density at standard condition for 1D3D cyclones.
• 15 m/s ± 2 m/s (3000 ft/min ± 400 ft/min) with air density at standard condition for 2D2D cyclones.
• 12 m/s ± 2 m/s (2400 ft/min ± 400 ft/min) with air density at standard condition for 1D2D cyclones.

It is important to consider the air density effect on the cyclone performance in the design of cyclone abatement systems. TCD ideal design velocity for 1D3D, 2D2D, and 1D2D cyclones should be the ideal inlet velocity of standard air, not the ideal inlet velocity of actual air. In designing cyclone abatement systems, the proposed design velocity should be the basis for sizing the cyclone and determining the cyclone pressure drop. The recommended sizes for 1D3D, 2D2D, and 1D2D cyclones are reported in this paper.

REFERANCES

1. Alexander, R. M. K. ~1949!. ''Fundamentals of cyclone design and operation.'' Proc. Aust. Inst. Min. Met. (New Ser.), 152/3, 202
2. Casal, J., and Martinez-Benet, J. M. ~1983!. ''A better way to calculate cyclone pressure drop.'' Chem. Eng., 90~3!, 99–100.
3. Leith, D., and Licht, W. ~1972!. ''The collection efficiency of cyclone type particle collectors.'' AIChE Symp. Ser., 68~126!, 196–206. Licht, William ~1988!. Air pollution control engineering, Marcel Dekker, New York.
4. Economopoulou, A. A., and Economopoulos, A. P. ~2001!. ''Method for estimating size-specific particulate emission inventories.'' J. Environ. Eng., 127~12! 1139–1148.
5. Mothes, H., and Loffler, M. ~1988!. ''Prediction of particle removal in cyclone separators.'' Int. Chem. Eng., 28~2!, 231–240
6. Salcedo, R. L. ~1993!. ''Collection efficiencies and particle size distributions from sampling cyclones—Comparison of recent theories with experimental data.'' Can. J. Chem. Eng., 71, 20–27.
7. Kalen, B., and Zenz, F. A. ~1974!. ''Theoretical-empirical approach to saltation velocity in cyclone design.'' AIChE Symp. Ser., 70~137!, 388. Koch, W. H., and Licht, W. ~1977!. ''New design approach boosts cyclone efficiency.'' Chem. Eng., 84~24!, 80.
8. Shepherd, C. B., and Lapple, C. E. ~1939!. ''Flow pattern and pressure drop in cyclone dust collectors.'' Ind. Eng. Chem., 31, 972
9. Koch, W. H., and Licht, W. ~1977!. ''New design approach boosts cyclone efficiency.'' Chem. Eng., 84~24!, 80.