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Evolution of Industrial Particulate Cyclone Design - A Review

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ABSTRACT

Industrial particulate cyclones have over the years been considered to be first stage low efficiency collectors for particulates. Particulate emission from process industries has continued to be a source of concern to environmental stakeholders due to the associated human and environmental health impacts of air borne particulate. This had driven researches on the improvement of cyclone designs. Present day cyclones have high collection efficiency even for small particles and their applications have expanded markedly to industries outside the process industries. The major constraint in cyclone design remains the need for trade-off between collection efficiency and pressure drop which are the two most important performance characteristics. This review provides information on the evolution of the theory of industrial particulate cyclone design; its classifications and operational characteristics, merits and drawbacks, the current state of knowledge and their industrial applications.

Keywords: Collection Efficiency, Cyclone, Particulate, Pressure Drop.

1. INTRODUCTION

The process industry is a huge industry which generates massive benefits all over the world. In these industries, primary raw materials in the form of ores are converted either into finished goods for the end users or intermediate products which may serve as raw materials for other industrial processes. They are usually associated with enormous energy and raw material consumption. A few examples of process industries include those for cement production, petroleum refining and petrochemicals, food and household products processing, thermal plants for electricity generation among many others. As beneficial as these industries are, they also constitute principal sources of anthropogenic air pollution leading to reduction of air quality (Okedere *et al.*, 2021). Depending on the industry, the pollutants may include greenhouse gases which are of great significance in global atmospheric climate discourse (Okedere and Oyelami, 2021). Others include criteria air pollutants such as Carbon Monoxide (CO), Oxides of Nitrogen (NO_x), Oxides of Sulphur, Hydrocarbons (HC), Volatile Organic Compounds (VOCs) and Particulate Matters (PMs) (Fakinle *et al.*, 2020; Adesanmi *et al.*, 2021). These criteria air pollutants are of serious concern because they have been reported to cause various degrees of damage to the environment and human health (Sonibare, 2010).

Among these criteria air pollutants, PMs are the most investigated and the term PMs generally refers to solid particles, mixture of solids and liquid droplets that are suspended in air (aerosols). Anthropogenic sources of particulates include combustion of fuels (gasoline, diesel, coal or biomass), construction sites, landfills, animal house, wastes burning, and industrial sources among others. They range from very small particles to bigger ones that can be seen with naked eye such as soots and smokes. They are usually classified on the basis of their aerodynamic diameters commonly expressed in micro metres (μm). PM_{10} particles which are also regarded as coarse or inhalable particles refer to PMs with aerodynamic diameters of less than or equal to 10 μm (Kan *et al.*, 2007; Moreno-Rios *et al.*, 2022). They can pass through the human respiratory system. $PM_{2.5}$ particles on the other hand are regarded as fine particles and have aerodynamic diameter of 2.5 μm and below. These have the ability to go deeper into the lungs. Yet, there are those categories that are smaller than $PM_{2.5}$ which are regarded as ultrafine particles. They are represented as $PM_{0.1}$ and have aerodynamic diameters less than or equal to 0.1 µm (Kan *et al.*, 2007; Moreno-Rios *et al.*, 2022).

The PM_{10} and $PM_{2.5}$ have received tremendous research attention notably because of their ubiquitous sources and their hazardous nature (Burki, 2019). They exert toxic properties either as a result of their intrinsic composition or by providing adsorbing surfaces for conveyance of other harming pollutants into the human body. They also exert toxic properties based on their sizes which allow them to penetrate deep into the human body. The extent of their toxicity is related to the degree of penetration into the body which is a function of their aerodynamic diameters (Adesanmi *et al.*, 2021). Reports on the deleterious effects of PMs abound in the literature. They have been reported to cause irritation to the eye, nose, throats and the lungs (Kappos *et al.*, 2004; Heal *et al.*, 2012; Kumar *et al.*, 2021). Other harmful health effects of particulates include coughing, sneezing, and shortness of breath and aggravation of disease conditions in patients with respiratory and cardiovascular diseases (Guo *et al.*, 2019; Yang *et al.*, 2019; Yang *et al.*, 2020).

Apart from direct impacts on human health, particulates can be transported over a long distance by atmospheric dispersion processes (Okedere *et al.*, 2017). They may be washed down either by dry or wet deposition processes thereby settling on the ground or water bodies and depending on their intrinsic composition or materials adsorbed to their surfaces, they may cause acidity, nutrient imbalance or depletion and changes in biodiversity in the receiving media. Damage to vegetations and agricultural crops have also been reported as negative effects of particulate pollution. Other environmental health hazards associated with PM pollution are visibility reduction with major consequences on the aviation industry as well as defacing of sculptural and art works of cultural and historical significance (Okedere and Oyelami, 2021).

The aforementioned human and environmental health impacts of particulates have necessitated the need to reduce their emissions from industrial sources. Various control devices are used in the process industries for control of particulate emissions depending on varieties of factors which are sometimes conflicting (Okedere *et al.*, 2013). Some of these factors include: the type of industry, concentration of the pollutant, carrier gas characteristics, process factors (flow rate, temperature, allowable pressure drop, and desired efficiency), health and safety considerations and constructional factors (space and strength of materials) (Fassani and Goldstein, 2000; Bahrami *et al.*, 2008; Ji *et al.*, 2008).

The present review examines the cyclone separator, an important industrial particulate matter emission control device in the process industry. Attempt is made at presenting the evolution of its design theories, classifications, operational characteristics, challenges in operating it and the current state of knowledge on the device.

2. CYCLONE SEPARATORS: CLASSIFICATIONS, PRINCIPLE OF OPERATIONS AND PERFORMANCE INDICATORS

Cyclone separators function as initial and inexpensive devices that are used in the process industry for separation of PMs from PM laden streams (Wang *et al.*, 2003). The absence of moving, smart or sensitive components as well as filter medium ensures reduced maintenance demands, pressure drop and consequently the operating cost. They can also handle removal of wide variety of PMs including powders, metal chips, mists and others which may be toxic or abrasive. While reverse flow tangential entry cyclones are very popular, the mode of entry of the PM laden stream can also be perpendicular or from the side. After entering, the gas laden PM is subjected to a swirling motion due to the shape of the cyclone and the particles are separated by a combination of centrifugal and inertia forces which cause them to be thrown against the cyclone wall and get settled in the hopper by gravity. The relatively lean air passes out through the inert vortex and depending on the extent of cleaning required (removal efficiency), the lean air may be passed through series of cyclones before eventual discharge into the environment.

The classification of PM cyclone separator can be on the basis of inlet configurations and mode of entry of the PM laden gas giving rise to reverse and axial flow entry cyclones. In reverse flow, the gas stream enters tangentially into the cyclone while in axial flow; the mode of entry is straight through the cycle. Due to design considerations, reverse flow configurations are more popular in the process industries. PM cyclones are also classified as high efficiency or high throughput on the basis of their body sizes. High efficiency cyclone designs target long bodies with small openings while reduced pressure drop is sacrificed. The high-rate designs on the other hand tend to have shorter bodies and wider openings; hence, large volume of gas streams can be handled at reduced pressure drop but low collection efficiencies. Typical tangential entry cyclone is shown in Figure 1 as adopted from the work of Okedere *et al.* (2013).

The performance of cyclone separators depends on a number of factors which include the inlet air velocity, volumetric flow rate, dust loading, minimum filtered particle size and density, efficiency of collection, flow resistance (pressure drop) and device properties such as all smoothness, body diameters, height to length ratio among many others. The most important performance indices of a cyclone separator are the pressure drop and collection efficiency. While collection efficiency is a measure of the smallest particle size that can be collected with good efficiency, the pressure drop is a measure of the amount of power required. Hence, several research efforts aimed at improving the performance of a cyclone separator usually target increase in efficiency of collection while minimizing pressure drop. Oftentimes, there is a trade-off between the two opposing factors.

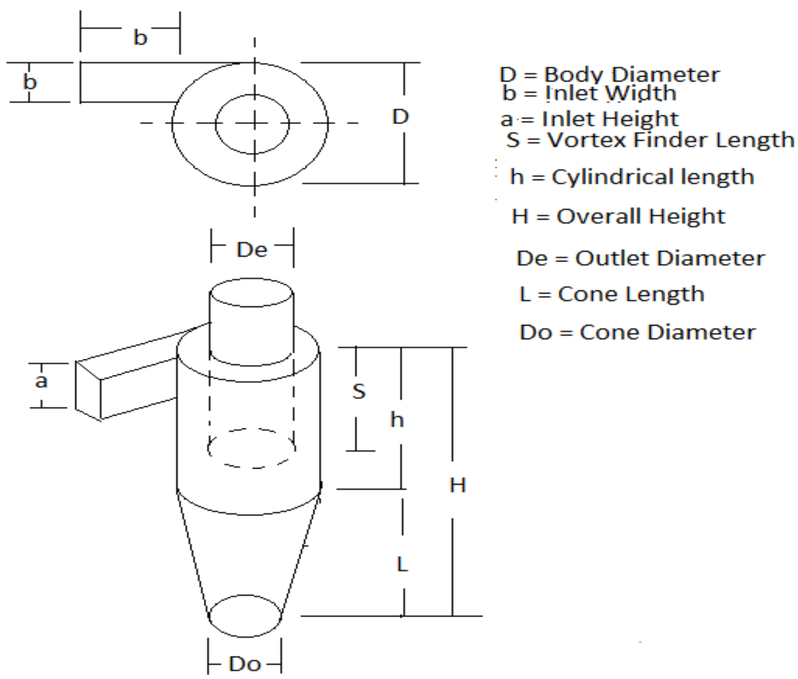

Figure 1: A Typical Tangential Entry Particulate Cyclone Separator (Okedere *et al.*, 2013)

3. REVIEW OF DESIGN THEORIES OF PARTICULATE CYCLONE SEPARATOR

The theory of PM cyclone separator design had begun as far back as the 1950s when the Classical Cyclone Design (CCD) theory popularly regarded as Lapple model was developed (Muhammad *et al.*, 2016). Although, there have been improvements over this model, it continues to provide the basis for understanding cyclone design. The CCD design procedures are usually expressed in terms of number of effective turns (N_t), the cut-point (d_p), fractional efficiency (η_i), overall efficiency (η_o) and pressure drop (ΔP) which are represented as Equations 1 to 6.

$$N_t = \frac{1}{H_i}\left[L_b + \frac{Z}{2}\right] \quad (1)$$

$$d_p = \left[\frac{9\mu W}{\pi N_t V(\rho_1 - \rho_2)}\right]^{\frac{1}{2}} \quad (2)$$

$$n_i = \left[\frac{1}{1+\left(d_{pi}/d_{pc}\right)^2}\right] \quad (3)$$

$$\eta_O = \sum \frac{n_i m_i}{M} \quad (4)$$

$$H_V = K\frac{WH_i}{D^2} \quad (5)$$

$$\Delta P = \frac{1}{2}\rho g v^2 H_v \quad (6)$$

Where: Hi = inlet duct height (m)
Lb = length of cyclone (m)
Z= vertical height of the conic section (m)
d_p = particle diameter (m)
W = inlet duct width (m)
ρ = particle density (kg/m^3)
V = terminal velocity (m/s)
μ = air viscosity (kg/m.s)
n_i = efficiency of collection of particles in the ith size range
dpj = the characteristic diameter of the ith particle

The CCD assumes that there is an in-depth knowledge of the flow conditions, particle concentration and its size distribution and cyclone type. While the CCD of cyclone provides the foundational understanding required, certain drawbacks have been reported in the equations that led to the overall efficiency and pressure drop. The major limitation of the CCD technique includes non-inclusion of gas stream inlet velocity in the dimension parameters of the cyclone (Parnell, 1996). It has also been reported that the approach does not represent accurate value of the number of turns. The parameters affect the accuracy of the fractional efficiency and by extension the overall efficiency of the cyclone (Kaspar *et al.*, 1993). The pressure drop value which is a representation of energy consumption was also reported to have inherent inaccuracies (Leith and Mehta, 1973).

A reliable response to the observed limitations of the CCD cyclone design theory was the Texas A&M Design (TCD) approach (Parnell, 1996). In this design approach, the determination of optimum inlet velocities for the various cyclone designs is crucial and for highest efficiency, design should be based on inlet velocities of dry standard air. Associating a specific inlet velocity with a particular cyclone design allows the determination of the cyclone body diameter (D_c) from the flow rate (Q) and inlet velocity (V_i) using Equation 7. Equation 8 calculates the standard flow rate (Q_{std}) of air on the bases of actual air density (ρ_{act}) and standard density (ρ_{std}) while Equation 9 is used for the determination of the pressure drop (ΔP) from inlet velocity pressure (VP_i) and outlet velocity pressure (VP_o). The dimensionless parameter K is empirically determined and is constant for a particulate cyclone design (Wang *et al.*, 2003).

$$D_C = \sqrt{\frac{8Q}{V_i}} \quad (7)$$

$$Q_{std} = Q_{act} \times \frac{\rho_{act}}{\rho_{std}} \quad (8)$$

$$\Delta P = K \times (VP_i - VP_o) \quad (9)$$

Apart from this, several other efforts have been made towards improving the performance of cyclone separator. In their study on collection efficiency and pressure drop of cyclone using cornstarch as test particles, Faulkner and Shaw (2006) reported that the emphasis on narrow window of flow rate that is associated with TCD may not be very critical as efficiency up 99% was obtained irrespective of inlet velocities.

4. SOME INDUSTRIAL APPLICATIONS OF CYCLONES

Cyclones separators have wide applications in the chemical process industries. Their scopes of applications include milling technologies for coal boilers (Zhao, 2006); beneficiation of fine particles in mineral and coal processing (Bahrami *et al.*, 2018); recovery and recycling of solid catalyst in the Fluid Catalytic Cracking Unit (FCCU) of the petroleum refineries (Selalame *et al.*, 2022); removal of sawdust particles from air stream in the wood processing industry (Muhammad *et al.*, 2016) and in the hoods of professional kitchens where they are applied to separate oil and grease from gas streams (Muhammad *et al.*, 2016). Other important areas of relevance of cyclone separator are the powder, cement, detergent, food, brewery and steel processing industries. In these industries, cyclones are used as end of pipe treatment for particle laden gas streams prior to release into the environment (Okedere *et al.*, 2013). The usability of a cyclone separator as air pre-filter in automobiles have been demonstrated by Karagoz *et al.* (2010) and Sakin *et al.* (2017). Presently, they have found application in environmental researches where they are used to classify $PM_{2.5}$ and PM_{10} (Mohammed *et al.*, 2019).

5. CONCLUSION

A short review on the evolution of cyclone theory had been undertaken. While cyclone design theory has its root in the classical cyclone design approach, present day cyclone design has made some remarkable improvements over the classical theories. Two important performance yardsticks of cyclone performance are collection efficiency and pressure drop. Most design efforts involve trade-off between these two performance indicators. While increased efficiency is desirable, the amount of fan power required will have effect on the overall operating cost of the equipment and is thus considered very important. Presently, decisions on cyclone design are usually based on the specific area of application and targeted goals of the cyclones. The reverse flow tangential entry cyclone design has been favoured above other designs.

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