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O.B. Okedere J.A. Sonibare B.S. Fakinle L.A. Jimoda

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O. B. Okedere
*College of Science, Engineering and Technology, Osun State University, Osogbo, Nigeria*
J. A. Sonibare and B.S. Fakinle
*Environmental Engineering Research Laboratory, Department of Chemical Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria, and*
L.A. Jimoda
*Department of Chemical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria*



## Abstract

**Purpose** – The aim of this paper is to provide basic information on the types of particulate cyclones separators used in the chemical and process industries, their principles of operation and factors affecting their performance.

**Design/methodology/approach** – A general review of the types of particle cleaning cyclones used in the chemical and process industries was carried out and the principles guiding their operation and performance discussed. Information which could aid the choice of cyclone for new applications is also discussed.

**Findings** – It was concluded that the choice of cyclone for any application is associated with a trade-off between two contrasting performance indicators (collection efficiency and pressure drop). Adequate and accurate data gathering is essential right from the design stage for smooth operation of cyclone.

**Originality/value** – The paper highlights the general principle of operation of cyclone separators and the factors that affect their performance.

**Keywords** Cyclone collector, Air pollution, Particulate matter, Collection efficiency, Pressure drop, Tangential entry, Axial entry, Chemical industries

**Paper type** Research paper

## 1. Introduction

The present drive for cleaner environment and sustainable development necessitate the use of various gas cleaning devices to minimize pollutant load being released directly into the environment. An equipment that has found wide application in particulate control is cyclone separator (Bahrami *et al.*, 2008). Its simple design, low maintenance costs and adaptability to wide range of operating conditions makes it one of the most widely used particle removal devices (Ogawa, 1997). By using suitable materials and method of construction, cyclones may be adapted for use in extreme operating conditions such as high temperature, high pressure and corrosive environments (Jianyi and Mingxian, 2003).

Cyclone separators are important equipment in most chemical and process industries. They are essentially useful in applications involving milling technologies for coal fueled boilers in power plants (Zhao, 2006) and in the fluid catalytic cracking unit of petroleum industry for recycling of catalyst back into the process and preventing its emission to the atmosphere (Fassani and Goldstein, 2000). Other areas of applications include cement industry, detergent industry, flour mills and powder

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making industry, brewery, steel recycling plants, tobacco industry to mention but a few. Recently, efforts have been made to incorporate cyclone in automobiles as air pre-filter (Karagoz *et al.*, 2010).

A typical cyclone separator (Figure 1) consists of inlet, cylinder, cone, collector, vortex finder tube and exit opening. Characteristically, a particle laden gas enters near the top and the flow is conditioned spirally downward partly due to cyclone shape and mode of entry. Centrifugal and inertial force make the particles to spread outward, make collision with the cyclone wall and then slide down to settle at the bottom of the cyclone where a rotary valve prevents re-entrainment. The gas flow reverse its downward spiral and goes upward in a smaller inner spiral leading to the exit of the cleaned air through a vortex finder (Wang *et al.*, 2004).

## 2. Cyclone classification

Cyclones are generally classified according to their gas inlet and dust discharge design, gas handling capacity and dust removal efficiency and their arrangement.

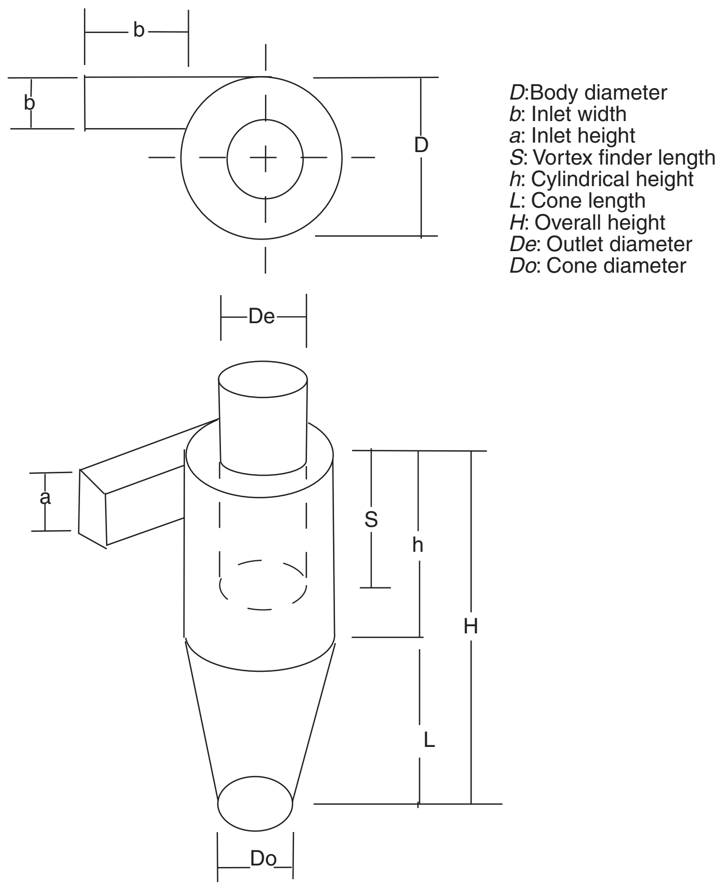


**Figure 1.**
A typical cyclone separator

**Source:** Lee *et al*. (2003)

*2.1 Classification gas inlet and dust discharge configuration*

Based on gas inlet and outlet configurations, cyclone can be classified traditionally as involute or vane axial types. The only difference between the two is the method of introducing the gas into the cylindrical shell in order to impact sufficient spinning motion. In simple involute type cyclones (Figure 1), the circular motion is attained by tangential gas inlet. The rectangular involute inlet passage has its inner wall tangential to the cylinder and the inlet is designed to blend gradually over a 180° involute. In vane axial entry cyclone, the cyclonic motion is imparted to the axially descending dirty gas by a ring of vanes. In either case, the operation depends on the tendency (inertial) to move in a straight line when the direction of the gas stream is changed. The centrifugal force due to a high rate of spin flings the dust particles to the outer wall of the cylinder and cone. The particles then slide down the wall into the storage hopper. The cleaned air reverses its downward spiral and forms a smaller ascending spiral. A vortex finder tube extending downward into the cylinder aids in directing the inner vortex out of the device. The dust collected is trapped in a collection bin at the base of the cyclone where a rotary valve prevents re-entrainment.

*2.2 Classification by gas handling capacity and collection efficiency*

When classified by gas handling and collection efficiency, cyclones are divided into two types: high efficiency and high through put (conventional) cyclones (Chermisinoff, 1993). For high-efficiency cyclones, the inlet is higher thereby imparting a higher centrifugal force. They are generally $<1$ ft in diameter and have long cones. Heavy particles reach the wall with much smaller angular movement whereas lighter ones travel through much greater angles to reach the wall thereby requiring longer cones (Chermisinoff, 1993). When collection efficiency (80-95 percent) is a primary consideration in cyclone selection, the high-efficiency single cyclone is commonly used. A unit of this type is usually smaller in diameter than the conventional cyclone, providing a greater separating force for the same velocity and shorter distance for particles to migrate before reaching the cyclone walls. These units may be used singly or arranged in parallel or in series. When arranged in parallel, they have the advantage of handling larger gas volumes at increased efficiency for the same power consumption. In parallel, they also have the ability to reduce headroom space requirements below that of single cyclone handling the same gas volumes by varying the number of units in operation (Wark and Warner, 1976). High through put cyclones on the other hand are generally larger with moderate efficiency and they can handle larger flow rates. A comparison of collection efficiencies of the two classifications revealed that for $<5$, 5-20, 20-40 μm and $>40$ μm particle, efficiencies were $<90$, 50-80, 80-95, 95-99 percent, respectively, for high-efficiency cyclone while 50-80, 80-95, 95-99 and 95-99 percent, respectively, were obtained for the same particle sizes mentioned above (Stern, 1977).

*2.3 Classification by arrangement*

Cyclones can be arranged in series or parallel (Chermisinoff, 1993). When very large gas volumes must be handled and high collection efficiencies are needed, a multiple of small diameter cyclones are usually nested together in parallel to form a multi-cyclone. A unit of this type consists of large number tubes that have a common gas inlet and outlet in the chamber. The gas enters the tube through axial inlet vanes and that imparts a circular motion. Due to limited gas handling capacity of each tube, large numbers of tubes are mounted in a single collector (Buonicore and David, 1992;

EPIN, 2000). The arrangement of tubes as well as the diameters affects the overall collection efficiency of a multi-cyclone. There is a small pressure drop in the incoming gas stream for each row of tubes it must pass. A decreasing length of outlet tube may be used to compensate for this, thereby producing an organ pipe arrangement. Alternatively, tubes can be arranged in groups, each with its own outlet plenum and space in between the groups which allows even and unimpeded gas flow to all tubes (Buonicore and David, 1992). The collection efficiency for a small diameter cyclone or collection of tubes can be quite high with dusts that are 5 μm or larger (Tomany, 1975). Series arrangement is used when high separation efficiency and higher flow rates of carrier gas are encountered or when it is required to protect a smaller higher efficiency cyclone from large abrasive particles.

## 3. Performance of cyclone separators

The most important parameters in cyclone operation are pressure drop and collection efficiency. While efficiency measures the cleaning action of cyclone, pressure drop is a measure of power required to drive the cyclone fan.

### *3.1 Pressure drop*

The pressure drop is given by the difference between static pressure at the cyclone entrance and the exit gas (Fassani and Goldstein, 2000). According to Wang *et al.* (2004), in the evaluation of cyclone design, pressure drop is a primary consideration because it is directly proportional to the energy requirement. Under any circumstance the knowledge of pressure drop through the cyclone is essential in designing a fan system. A differential pressure gauge may be used to measure gas pressure drop between the inlet and the outlet tubes of the cyclone separator (Ji *et al.*, 2008). The static pressure at the inlet cross-section is uniformly distributed because there is no swirling motion. But the static pressure at the outlet wall is quite different from its cross-sectional average due to the strong swirling flow. The dynamic pressure stored in the swirling motion can be significant. The estimation of static pressure downstream of a cyclone, hence the pressure drop becomes more complicated and difficult. A reliable pressure drop model must account for local loss and frictional loss (along the distance). The local loss includes an expansion loss at the cyclone inlet and contraction loss at the entrance of the outlet tube while frictional loss includes swirling loss due to friction between the gas flow and the cyclone wall and a dissipation loss of gas dynamic energy. Various models for predicting pressure drop have been developed. Caplan (1968) defined the power which must be expended in the cyclone system to overcome this pressure drop as:

$$W = Q\Delta P \tag{1}$$

$$Q = abV_{\mathrm{i}} \tag{2}$$

where $W$ is the power expended (Nm/s); $Q$ is the volumetric flow rate through the cyclone (m$^3$/s); $\Delta P$ is the pressure drop across the cyclone (N/m$^2$); $a \times b$ is the inlet area(m$^2$); and $V_{\mathrm{i}}$ is the inlet velocity (m/s).

For simple cyclones, pressure drop ranges from 1.25 to 5 mbar, while high-efficiency cyclone may experience losses of 5-12 mbar. Typical velocities and flow rates are in the range 15-20 m/s and 0.25-0.5 m$^3$/s.

One of the simplest pressure drop equation which correlates reasonably well was developed by Shehered and Lapple (Mycock *et al.*, 1995). This expressed pressure drop as the number of inlet velocity heads and is given as:

$$\Delta P = 0.033\rho_f V_i^2 N_H \tag{3}$$

where $\Delta P$ is the pressure drop (w.g.); $\rho_f$ is the fluid density (lb/ft$^3$); $V_i$ is the inlet velocity (ft/s) and $N_H$ is the number of velocity head:

$$N_H = k(ab)/D_e^2 \tag{4}$$

where $k$ is an empirical constant with a value of 16 for tangential inlet cyclones and 7.5 for one with inlet vane; $a$ is the inlet height (m); $b$ is the inlet width (m) and $D$e is the dust outlet diameter (m). Pressure drop is a function of square of inlet velocity, hence, too high velocity will cause excessive pressure drop.

Mukhopadhyay *et al.* (2007) gave a mathematical equation relating pressure drop to cyclone geometrical and operating parameters:

$$\Delta P = \frac{C\rho Q^2}{2D_e^2 BH} \tag{5}$$

The constant $C$ is defined by the following equation:

$$C = \frac{4.62D_e}{D_2}\left[\left(\frac{D_2}{D_e}\right)^{2n} - 1\right]\left[\left(\frac{1-n}{n}\right) + f\left(\frac{D^2}{D_e}\right)^{2n}\right] \tag{6}$$

where $n = 0.5$, $f = 2$; $D$ is the cyclone body diameter (m); $B$ is the inlet width (m); $H$ is the inlet height (m); $\rho$ is the particle density (kg/m$^3$); and $D_e$ is the exit duct diameter (m).

Dirgo *et al.* (1991) reported that pressure drop in a cyclone is related to the head of liquid in the manometer whose legs are placed across the inlet and exit of the cyclone separator by the following equation:

$$\Delta P = \frac{\Delta H V_i^2 \rho_{gas}}{2g\rho_{liquid}} \tag{7}$$

where $\Delta P$ is the pressure drop across the cyclone (N/m$^2$), $\Delta H$ is the dimensionless head of liquid column, $V_i$ is the inlet gas velocity (m/s) and $\rho_{gas}$ (kg/m$^3$) and $\rho_{liquid}$ (kg/m$^3$) are the gas and liquid densities, respectively, and $g$ is the acceleration due to gravity (m/s$^2$). The dimensionless head of liquid in the manometer was given by Dirgo *et al.* (1991) as:

$$\Delta H = \frac{20ab}{D_e^2}\left[\frac{S/D}{(H/D)(h/D)(D_o/D)}\right]^{0.33} \tag{8}$$

where $a$ and $b$ are inlet height and width, respectively, (m); $D_e$ is the exit duct diameter (m); $S$ is the length of vortex finder (m); $D$ is the cyclone body diameter (m); $H$ is the overall cyclone height (m); $h$ is the cylindrical height of cyclone (m), and $D_o$ is the cone tip diameter (m).

Both Shepherd and Lapple and Dirgo model are applicable for the pressure drop prediction at various flow rates under room temperature condition. One major drawback is that most of their procedures are empirical and suitable only for pure gases and not very satisfactory in generality. Additionally, the pressure drop of a cyclone under the condition high-temperature gases is of importance which these models do not address.

*3.2 Collection efficiency*

Efficiency is a measure of the extent to which the cyclone is able to clean the dust laden gas entering it. An approximate value of efficiency of cyclone may be ascertained from the ratio of centrifugal force to the drag force on the particle (Wark and Warner, 1976):

$$\eta = \frac{V_p \rho_p d_p^2}{R \mu_O} \tag{9}$$

where $V_p$ is the particle velocity (m/s); $\rho_p$ is the particle density (kg/m$^3$); $d_p$ is the particle diameter (m); $R$ is the radius of rotation in the cyclone (m) and $\mu_o$ is the viscosity (Ns/m$^2$).

The overall collection efficiency can be obtained when mass of solids collected by the cyclone in a time interval is divided by the mass flow rate of incoming solids (Fassani and Goldstein, 2000). It is equal to the ratio of the particle concentration difference between the inlet and outlet of the cyclone separator to the inlet particle concentration (Ji *et al.*, 2008) and is mathematically defined as:

$$\eta = \frac{C_i - C_O}{C_i} \tag{10}$$

where $\eta$ is efficiency (percent); $C_i$ is the inlet particle concentration (kg/m$^3$); and $C_o$ is the outlet particle concentration (kg/m$^3$).

Traditionally, cyclone separators were used in the industry as pre-screening devices to separate coarse particles (diameter $>10\,\mu$m). This is due to the fact that most cyclones used in the industry are large cyclones with body diameters $>10$ cm. Experimental work from several researchers has shown that small cyclones (body diameter $<5$ cm) may be used for fine particles with high collection efficiencies (Kim and Lee, 1990). It is sometimes desirable to know the collection efficiency of a cyclone for a specific particle size because that will indicate the performance of cyclone for that specific size and the kind of application where it can be deployed; such efficiency is referred to as grade efficiency or fractional efficiency. The grade efficiency curve could be achieved by comparison of particle size distribution between the inlet and outlet of the cyclone separator. The grade efficiencies of small particles ($<10\,\mu$m) in diameter vary with particle concentration. Ji *et al.* (2008) comparing the grade efficiencies of $3\,\mu$m particles at 5 and 1,000 mg/m$^3$ reported grade efficiencies of 71 and 96 percent, respectively. It approaches 100 percent for particles $>10\,\mu$m in diameter.

## 4. Factors affecting performance of cyclone

*4.1 Inlet gas velocity*

Inlet gas velocity of the cyclone is the variable with the greatest strong influence on its efficiency (Bahrami *et al.*, 2008). Apart from increasing the centrifugal force, an increase in gas velocity also increases the effective collection area in the cyclone and both factors result in appreciable improvement in collection efficiency

(Hoffman *et al.*, 1995). Similarly, the pressure drop undergone by dust laden gas traversing the cyclone has been known to increase with increase in the inlet gas velocity.

*4.2 Viscosity*

Due to increase of drag force, high viscosity leads to high cut-off diameter and consequently low efficiency. Bohnet *et al.* (1997) investigated the effect of viscosity and reported that efficiency of cyclone decreases with increasing viscosity. Avci and Karagoz (2003) in their study of the effect of viscosity on efficiency reported that high viscosity leads to low Reynold's number, high fractional resistance and low acceleration and thus low efficiency.

*4.3 Temperature*

Alexander (1949) found that the vortex exponent decreased with an increase in temperature. Patterson and Munz (1996) also confirmed the reduction of the tangential velocity with the rise of the temperature especially in the high-temperature range. Therefore, the inertial separation potential of the cyclone was subsequently reduced. Jianyi and Mingxian (2003) investigated the influence of operating temperature on cyclone performance. By making use of a 300 mm diameter tangential volute – inlet and reverse flow cyclone with air heated up to 973 K, the overall collection efficiency and fractional collection efficiency of the cyclone were measured as a function of inlet velocities and operating temperature. It was reported that for a given inlet velocity, both overall collection efficiency and fractional collection efficiency decrease with an increase in temperature.

*4.4 Particulate loading/concentration*

Particulate loading refers to the mass of dust present in the dust laden gas when compared with volume of gas carrying it. Both pressure drop and efficiency of cyclone are affected by solid loading (Fassani and Goldstein, 2000). A reduction in pressure drop with increase in particulate loading have been reported by quite a number of authors which include Shepherd and Lapple (1939) and Yu *et al.* (1978). However, both overall collection efficiency and grade efficiency were reported to have increased with increase in particle loading (Ji *et al.*, 2008).

*4.5 Geometry*

Geometrical consideration has to do with other factors other than particle characteristics and operating conditions. They are factors that relate directly to the cyclone configuration and they include: shape of inlet, diameter and height of cylindrical section, size of cone and length of vortex finder. Geometrical factors have been found to markedly influence cyclone collection efficiency and pressure drop. Kim *et al.* compared the efficiencies of single inlet and double inlet cyclones in which clean air was introduced. Their results showed that the efficiency of double inlet cyclone was 5-15 percent greater than that of a single inlet. Zhao (2006) showed that the efficiency of converging symmetrical spiral inlet (CSSI) design was greater than that of conventional tangential single inlet (CTSI) design when both were subjected to the same condition. Martignoni *et al.* (2007) compared the effect of cyclone geometry through creation of symmetrical inlet and volute scroll outlet design with single tangential inlet and reported that the new design improved cyclone performance parameters significantly. While it is true that considerable efforts have gone into studying the effect of geometry on cyclone performance, there are still contrasting views about the contribution of cone inclination which determines the cone size (tip diameter). The effects of the cone tip diameter have been neglected or taken in negligible order by most of the researchers. The cone is often assumed to deliver collected particles only. Bryant *et al.* (1983) observed that if vortex touched the cone wall, particle re-entrainment occurred and efficiency decreased. Lately, Avci and Karagoz (2003) stated the cone is very important from the point of view of acceleration, swirl number and pressure losses. More efforts are certainly required in this area.

## 5. Trade-off

The design of cyclone separator represents a compromise between collection efficiency and pressure drop (Flagan and Seinfeld, 1998). Pressure drop is a function of the square of inlet velocity, so too high a velocity will cause excessive pressure drop. On the other hand, too low a velocity would cause a low efficiency. A very high inlet velocity would decrease the collection efficiency because of increased turbulence and saltation/re-entrainment of particles. Generally it is found that the optimum operating velocity is around 18 m/s. However, the range of practicable cyclone inlet velocity is around 15-30 m/s (Shepherd and Lapple, 1939). In cyclone separators, the desire to minimize the pressure drop is unfortunately in conflict with the wish to maximize the separation efficiency. Any measure to increase the separation efficiency is normally coupled with considerable increases in pressure drop.

Several studies have been done in order to improve the performance of cyclone separators, i.e. increasing efficiency and decreasing the pressure drop. Xiang *et al.* (2001) have analyzed the effects of the dimensions of the conical part of the cyclone and the input speed upon the performance of the cyclone separators. In addition, Mi-Soo Shin *et al.* (2005) studied and analyzed the effects of the dimensions of the vortex finder on the performance of the device using numerical and experimental methods. Also, Chuah *et al.* (2006) have studied the effects of conical part dimensions of the cyclone on its performance. However, these studies have focussed on the effects of one or two geometrical dimensions of the cyclone on efficiency and pressure drop, a single objective function was used. Nevertheless, optimization efforts required to resolve the dichotomy presented by the design of cyclone should involve maximization of the overall collection efficiency and minimization of the pressure drop. In their work titled "Optimization of cyclone separators using genetic algorithm", Pishbin and Moghiman (2010), provided an all encompassing method of optimizing efficiency and pressure drop. The approach involved the use of genetic algorithm to model and optimize non-linear objective functions.

Trade-off is extremely important, since it illustrates a basic dichotomy or contradiction in cyclone design; high efficiency is desirable while high-pressure drop means more energy (cost) is required to power the fan. A compromise must be made between collection efficiency and pressure loss. In general, high efficiency is associated with high-pressure loss.

## 6. Conclusion

Particulate cyclone has been looked into in an introductory manner with its main concept discussed. It has been shown that cyclone separators are of utmost importance in industrial cleaning of dust laden gases prior to their release into the environment. Various factors that affect the performance of cyclone separator were critically reviewed and were shown to be very important in cyclone design. It was also stated that the choice of cyclone for any application is associated with a trade-off between two contrasting performance indicators. Adequate and accurate data gathering on particle properties (size, density, agglomeration and hygroscopic tendencies, etc.); operating conditions (temperature, humidity, pressure, flow rate, etc.) and structural limitations (material of construction, space requirement, etc.) are essential right from the design stage for smooth operation of cyclone. More efforts are required in the optimization of cyclones to resolve the dichotomy generated by collection efficiency and pressure drop and the use of genetic algorithm could provide the lead way.

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## About the authors

O.B. Okedere has BSc. and MSc. in Chemical Engineering from Obafemi Awolowo University Ile-Ife, Nigeria in 2004 and 2011, respectively. He is currently on his PhD program in the same department. He is an assistant lecturer at the College of Science, Engineering and Technology, Osun State University Osogbo, Nigeria. He can be contacted at: tunjiokedere@gmail.com

J.A. Sonibare received his PhD in chemical engineering from Obafemi Awolowo University Ile-Ife, Nigeria in 2005. He is an associate professor in the same department with over 18 years experience in teaching and research. Presently, Dr Sonibare has 45 publications in scientific journals and over 230 technical reports resulting from his activities as a Consultant on Air Quality and Life Cycle Analysis. He is a certified engineer. J.A. Sonibare is the corresponding author and can be contacted at: asonibar@yahoo.com or asonibar@oau.edu.ng

B.S. Fakinle has BSc. from Lagos State University, Nigeria and MSc. in chemical engineering from Obafemi Awolowo University Ile-Ife, Nigeria in 2011. He is currently a PhD student and research assistant in the Environmental Engineering Research Laboratory, Obafemi Awolowo University, Ile-Ife, Nigeria. He can be contacted at: xdales@yahoo.com

L.A. Jimoda received his PhD in chemical engineering from Obafemi Awolowo University Ile-Ife, Nigeria in 2010. He is a senior lecturer at the Department of Chemical Engineering, Ladoke Akintola University, Ogbomoso, Nigeria.