CONTROL TECHNIQUES FOR PARTICLES

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Contents

Summary

The controlling the emission of particulate matter from industrial and domestic sources is important in protecting the quality of air. Types of equipment used to control particulate emissions are gravity settlers, mechanical collectors (cyclones), electrostatic precipitators (ESPs), fabric filters (baghouses), and scrubbers. Operating principles, design, theory for control efficiencies and pressure drop, and suitable applications of these particulate control devices are presented respectively.

Mechanical collectors and ESPs work by driving the particles to a solid wall where they form agglomerates that can be removed. These devices have similar equations of collection efficiency. Filters and scrubbers divide the flow and collect particles using "target" (fiber or droplet). They have different theoretical equations from wall collection devices and from each other.

Cyclones are found most use when dust is coarse, dust loading is high, or high efficiency is not a critical factor. For batch processes or processes in which the volumetric flow rate is variable, baghouses have an inherent advantage. Principal applications for ESPs are the removal of particles from large, steady volumetric flow rates of gas. Applications of wet scrubbers include where the contaminant cannot be removed easily in a dry form, where soluble or wettable particulates are present, and where the dry particulate may ignite or explode.

The on-going researches on particulate collectors focus on theory and mechanisms of particulate collection, improvement of the performance of existing particulate collectors, and development of new particulate collecting devices. One area that has recently received some attention is hybrid systems—equipment that in some cases can operate both at higher efficiency and more economically than conventional devices. Tighter regulations and a greater concern for environmental control by society have placed increased emphasis on the development and application of these systems.

1. Introduction

If waste reduction is not possible, either by processes or material change, waste particulate materials must be removed from the processes air stream. The devices that capture dust, mists, and other solid and liquid particles in gas stream are named as particulate matter (PM) collectors. There are many kinds of particulate collectors available on the market, which utilize a number of different principles for accomplishing removal of particles from a gas stream.

In order to remove suspended particles from gas stream, the gas must be passed through a zone in which the particles come under the influence of some kind of force (or forces) causing them to be diverted from the flow direction of the stream. They must remain under the influence of the collecting force(s) sufficient length of time to be diverted to contact some collecting surface where they are removed from the stream.

The differences between those devices result mainly from the nature of the force that is applied to a particle in order to collect it and the collecting surface. According to the mechanisms being used, the particulate control devices can be classified as mechanical collectors, filters, electrostatic precipitators, and wet scrubbers.

Mechanical collectors separate suspended particles from gas by causing the gas stream to change direction while the particles, because of their inertia, tend to continue in their original direction and be separated from the gas. There are numerous types of mechanical collectors, including baffle-type separators, chip trap separators, louvered-type separators and cyclones. Cyclones, where the gas is forced to spin in a vortex through a tube, are the most common type of inertial separators.

Fabric filters (baghouses) remove the dust from dust-laden gas by passing the gas through a filtration medium, normally a fabric. The cleaned gas emerges from one side of the medium while the dust is collected on the other side. Subsequently the collected dust is removed from the fabric. Different collector designs, fabric types, configurations and a variety of cleaning methods provide numerous combinations.

Electrostatic precipitation is the most popular method in use for removing fine solids and liquids from gas streams. There are three fundamental steps in the electrostatic precipitation process, namely, charging the particles suspended in the gas stream, collecting the charged particles, and removal of the collected particles into an external receptacle. Charging is accomplished by applying a high dc voltage to an electrode system. Precipitators may be single stage or two-stage in which the charging and collecting fields are formed independently. Also, the gas stream may flow through tubular collecting electrodes or between parallel plates. The parallel-plate single–stage precipitator is very common.

Wet scrubbers collect particles by contacting the dirty gas stream with liquid drops. Most fine particles will adhere to a liquid drop if they contact it. Then when the gas stream passes through a cheap, simple cyclone, the drops and adhered fine particles will be collected. This is the basis of almost all scrubbers for particulate control.
The several collectors in common use are shown in Table 1. Of these collectors,

mechanical collectors, baghouses and dry ESPs are “dry” collectors, so named because they capture the particulate in the dry state. Similarly, wet ESPs and wet scrubbers are termed “wet” collectors.

Collector		Primary collecting forces	Collecting surface
Mechanical collectors	Gravity settling chamber	Gravitational	Plane
	Momentum	Gravitational and inertial	Plane or cylindrical
	Cyclone	Centrifugal	Cylindrical
Filters	Media	Inertial, diffusional, direct interception and electrostatic	Cylindrical fiber or granular
	Fabric	Direct interception	Layer of particles irregular
Electrostatic precipitator		Electrostatic	Plane or cylindrical
Scrubber		Inertial, diffusional and direct interception	Spherical or irregular targets
Thermal collector		Thermophpresis	Plane
Impinger		Inertial target collectors	Plane

Table 1: Particulate collectors in common use

2. Cyclones

Cyclones are widely used for the collection of medium-sized and coarse particles. Their relatively simple construction and absence of moving parts mean that both the capital and the maintenance costs are lower than that for fabric filters and electrostatic precipitators. However, the efficiency is not so high, and inertial separators are usually used as precleaners upstream of other devices, to reduce the dust loading and to remove larger, abrasive particles.

2.1 Dimensions of Cyclones

Cyclones are usually designed with geometric similarity such that the ratios of the dimensions remain constant at different diameters, and these dimensions can be expressed in terms of the body diameter, D_0 (Figure 1). Six sets of values for these dimension ratios are shown in Table 2. The principal differences are that high-efficiency cyclones have smaller values of W_i whereas high-throughput cyclones have larger values of W_i and of D_e.

Dimensions	Cyclone type					
	High efficiency		Conventional		High Throughput	
	(1)	(2)	(3)	(4)	(5)	(6)
Body diameter D_0/D_0	1.0	1.0	1.0	1.0	1.0	1.0
Height of inlet H/D_0	0.5	0.44	0.5	0.5	0.75	0.8
Width of inlet W_i/D_0	0.2	0.21	0.25	0.25	0.375	0.35
Diameter of gas exit D_e/D_0	0.5	0.4	0.5	0.5	0.75	0.75
Length of vortex finder	0.5	0.5	0.62	0.6	0.875	0.85

S/D_0			5			
Length of body H_1/D_0	1.5	1.4	2.0	1.75	1.5	1.7
Length of cone H_2/D_0	2.5	2.5	2.0	2.0	2.5	2.0
Length of dust outlet D_d/D_0	0.375	0.4	0.25	0.4	0.375	0.4

Table 2: Dimensions of cyclones

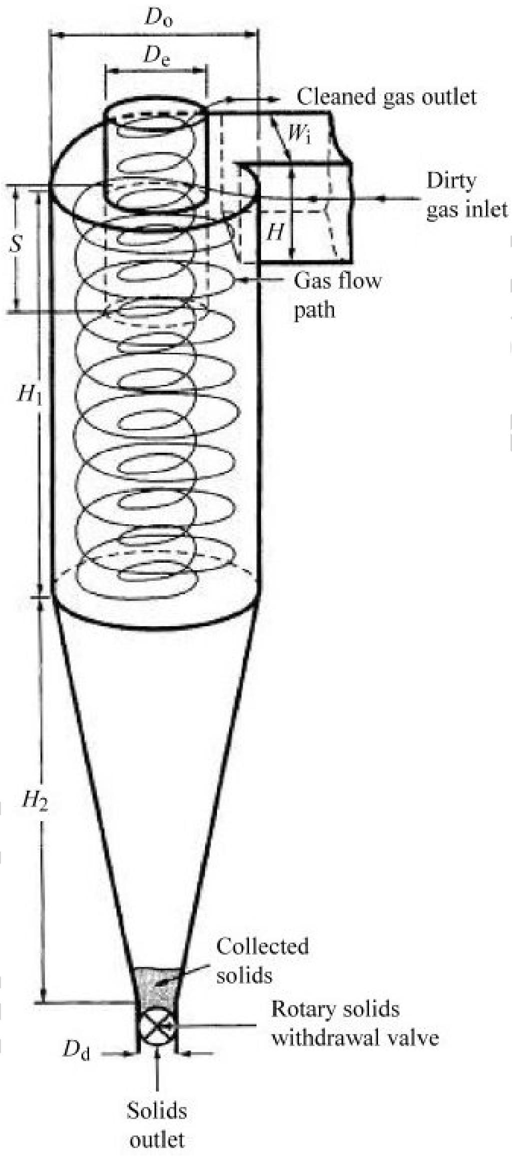

Figure 1: Schematic of a cyclone separator

2.2. Collection Efficiency of Cyclones

Collection efficiency of cyclone is a strong function of particle size and increases with increasing particle size. Determination of the overall efficiency requires knowledge of the particle size distribution of the dust particles. Collection efficiencies for each size range are then weighted accordingly and the values summed.

2.2.1. Laminar Model

Only the outer helix contributes to collection, particles that get into the inner helix, which flows upward to the gas outlet, escape uncollected. The inlet stream has a height W_i in the radial direction, so that the maximum distance any particle must move to reach the wall is W_i. The length of the flow path is $N_e \pi D_0$, where N_e is the number of turns that the gas makes traversing the outer helix of the cyclone, before it enters the inner helix. N_e can be estimated from cyclone dimensions since it depends on the height of one turn of the vortex and the length of cyclone:

$$N_e \cong \frac{1}{H}(H_1 + \frac{H_2}{2}) \tag{1}$$

To be collected, the particles must reach the outer wall before the gas leaves the outer vortex. The time is gas residence time, which depends on gas inlet velocity, radius of cyclone, and number of turns in the vortex. The maximum value of the distance to be traveled is the length from the inner edge of the inlet to the outer wall. Assuming laminar flow, an expression is derived that relates the collection efficiency to the cyclone parameters and operating conditions:

$$\eta = \frac{\pi N_e \rho_p d_p^{\ 2} \upsilon_g}{9 \mu W_i} \tag{2}$$

whereρ_p is the particle density, d_p is the particle diameter, υ_g is gas velocity, μ is gas viscosity.

This model predicts a finite value of particle diameter above which collection efficiency is 100% ("critical size"), whereas experimental evidence shows that efficiency approaches 100% asymptotically with increasing diameter.

$$d_{pcrit} = \left[\frac{9 \mu W_i}{\pi N_e \rho_p \upsilon_g}\right]^{0.5} \tag{3}$$

2.2.2. Back-mixing Model

The laminar flow model has limitations, as gas flow in a cyclone is not simply laminar. Nor is it fully turbulent, because the boundary layer has a significant depth. Considering the back-mixing of uncontrolled particles and determining an average residence time for the gas in the cyclone, the collection efficiency can be commonly expressed by following equation:

$$\eta = 1 - \exp\left[-A d_p^{\ B}\right] \tag{4}$$

where A is a coefficient and B an exponent.

2.2.3. Cut Diameter Approach

The concept of a cut size, d_{p50}, is defined as the size of particle that is collected with 50% efficiency. The value is a characteristic of the control device and operating conditions, not of the size range of the dust particles. The value of the cut size is calculated from equation (3) by setting efficiency equal to 50% and solving for d_p.

$$d_{\mathrm{p50}} = \left[\frac{9\mu W_{\mathrm{i}}}{2\pi N_{\mathrm{e}} \rho_{\mathrm{p}} \upsilon_{\mathrm{g}}} \right]^{0.5} \tag{5}$$

A number of equations have been proposed to describe the relationship between cyclone efficiency and particle size. The following equation is the simplest one.

$$\eta_j = \frac{{d_{\mathrm{p}j}}^2}{{d_{\mathrm{p}j}}^2 + {d_{\mathrm{p50}}}^2} \tag{6}$$

where η_{jj} is fractional efficiency in range j, d_{pj} is particle diameter in range j.

2.3. Pressure Drop of Cyclones

Pressure drop is an important parameter because it relates directly to operating costs. A number of methods have been proposed to estimate the total pressure drop in the flow of gas through a conventional tangential inlet cyclone. Unfortunately there has not been a definitive study to determine the best to use. However, most methods agree that the pressure drop across a cyclone is proportional to the square of the gas flow velocity,

$$\Delta P = \frac{1}{2} \xi \rho_{\mathrm{g}} \upsilon_{\mathrm{g}}^2 \tag{7}$$

where ξ is coefficient of drag force, which can be calculated by following equation:

$$\xi = \zeta \frac{HW_{\mathrm{i}}}{{D_{\mathrm{e}}}^2} \tag{8}$$

where ζ is an empirical constant with a value of 16 for a tangential inlet cyclone and 7.5 for one with an inlet vane.

Therefore, too high a velocity would cause excessive pressure drop. On the other hand, too low a velocity would cause a low efficiency. A very high velocity would also actually decrease efficiency because of increased turbulence and saltation/reentrainment of particles. Generally the best operating velocity is around 10~25 m/s.

2.4. Applications of Cyclones

Cyclone dust collectors must be properly designed and operated to boost separation efficiencies significantly. Improvement can be realized by maximizing the effect of several major and minor natural forces, namely the mass, drag and secondary forces. Also, the properties of the carrying gas, particulates and shape of the cyclone should be specified correctly. Moreover, one should ensure that the duct and material-discharge system are correctly designed, and that any changes in the nature of the carrier gas and particulate materials are accounted for during collection.

Because of their simplicity of construction and lack of moving parts, cyclones can be fabricated of a variety of materials, including ceramic, or lined with various materials. They are applicable over a broad range of temperatures from below ambient to above 866K. Cyclones can also be used at high gas pressures. Generally, the only criterion for good performance is the requirement for proportionate increase in power input to maintain separation velocities. The collector is not sensitive to the inlet concentration, and in fact, the efficiency can increase with increasing particle concentration because of particle interactions. Cyclones find most use when operating under the following situations: where dust is coarse, where dust loading is above 100 g/m^3, where high efficiency is not a critical factor.

Multiple-cyclone collectors are high-efficiency devices that consist of a number of small-diameter cyclones operating in parallel with a common gas inlet and outlet. The flow pattern differs from a conventional cyclone in that instead of bringing the gas in at the side to initiate the swirling action is then imparted by a stationary vane positioned in the path if the incoming gas. The diameters of collecting tubes usually range from 15 to 30 cm. Properly designed units can have a collecting efficiency as high as 90% for particulates in the 5-10 μm range. The most serious problems encountered with these systems involve plugging and flow equalization.

3. Fabric Filters

A unit of fabric filters consists of one or more isolated compartments containing rows of fabric bags in the form of round, flat, or shaped tubes, or pleated cartridges. Particle-laden gas passes up along the surface of the bags then radially through the fabric. Particles are retained on the upstream face of the bags, and the cleaned gas stream is vented to the atmosphere. The filter is operated cyclically, alternating between relatively long periods of filtering and short periods of cleaning. During cleaning, dust that has accumulated on the bags is removed from the fabric surface and deposited in a hopper for subsequent disposal. Fabric filters collect particles with sizes ranging from submicron to several hundred microns in diameter at efficiencies generally in excess of 99% or 99.9%. The layer of dust, or dust cake, collected on the fabric is primarily responsible for such high efficiency. The cake is a barrier with tortuous pores that trap particles as they travel through the cake. Baghouses are manufactured to handle airflows ranging from 0.5×10^{-3} m^3/s to several thousand m^3/s. Developments in fabric technology enable baghouses to cope with temperatures up to 430K, and to resist corrosive, acidic, and alkaline gases. Dust concentrations handled can range from very light, as is the case in atmospheric air, to very heavy for pneumatic conveying.

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