Gas Cyclones

CONTENTS

NOMENCLATURE

c	dust concentration
c^*	see explanatory text for Eq.(5) and Eq.(7)
D	cylindrical section diameter
E_T	total cyclone efficiency
E_T^*	see explanatory text for Eq.(5)
Eu	Euler number defined in Eq.(1)
Eu_c	resistance coefficient with clean air
K	height of rectangular inlet
k	empirical constant in Eq.(8)
L	width of rectangular inlet
M	diameter of gas outlet pipe
Q	gas flowrate
Stk_{50}	Stokes number defined in Eq.(6)
$Stk^o{}_{50}$	Stokes number at very low dust loading
$Stk^*{}_{50}$	see explanatory text for Eq.(7)
v	characteristic velocity defined in Eq.(2)
x_{50}	cut size (50% point on grade efficiency curve)
α	empirical coefficient in Eq.(4)
β	empirical exponent in Eq.(4)
Δp	static pressure drop
μ	gas viscosity
ρ	gas density

ρ_s solids density

INTRODUCTION

The gas cyclone is a flow device in which the inlet gas is brought tangentially into a cylindrical body. A strong vortex is created inside the cyclone and any particles in the flow, if they are denser than the carrier gas, are subjected to centrifugal forces. These forces move the particles radially outwards, towards the inside cyclone surface onto which the solids deposit.

There are two basic types of gas cyclones depending on the direction in which the clean gas leaves the cyclone: the reverse flow cyclone and the uniflow or "straight through" cyclone. In the uniflow cyclone, the gas enters at one end of the cylindrical body and it leaves at the other end; this type has limited use in industry and will not be discussed further. The reverse flow cyclone is by far the most commonly used type and its principle of operation is shown in Figure 1.

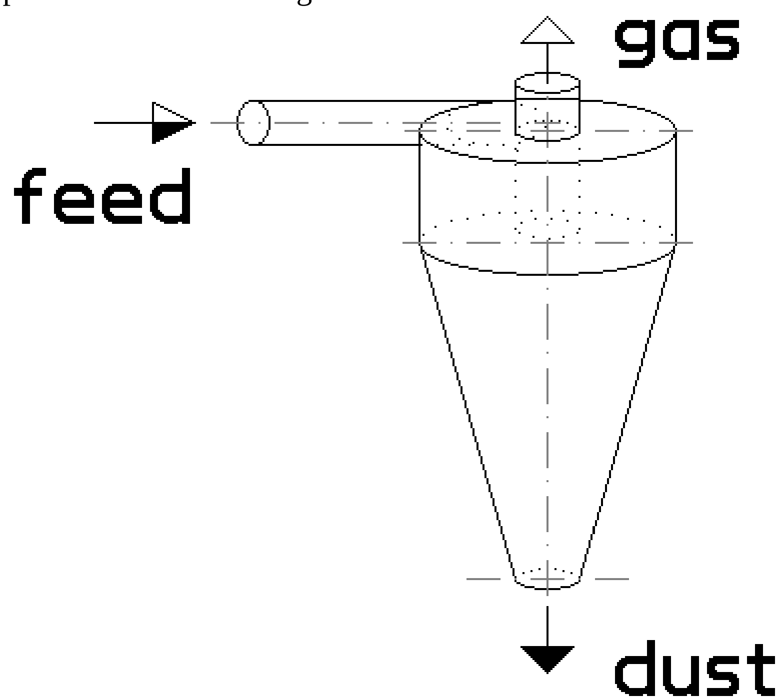

Figure 1: Schematic diagram of a gas cyclone

The body of the reverse flow cyclone consists of a cylindrical section joined to a conical section. The clean gas outlet is through a central pipe at the same end of the cyclone as the tangential inlet. The gas outlet pipe extends some distance axially into the body, through the top lid. The discharge of the separated dust is through a central orifice in the apex of the conical section.

There are four different types of inlet used in gas cyclones (Fig.2): tangential, axial, helical or spiral. Each inlet type has its advantages and applications but, from the fundamental point of view, they all create a confined vortex flow which reverses its axial direction in the conical section, as shown in Figure 3. The incoming gas spins in the outer vortex and moves downwards. In the apex, the axial direction is reversed and the gas moves upwards in the inner vortex and leaves through the gas outlet pipe.

The tangential velocity is the largest component of the gas velocity in the cyclone; it leads to large centrifugal forces on the particles in the flow. The main axial flow in the cyclone is downward on the larger radii and upward near the centre. There is also a small radial velocity component, radially inward, which transfers some of the gas from the outer vortex into the inner vortex, throughout the length of the cyclone body.

Particles present in the swirling gas migrate towards the inside wall and separate into the boundary layer flow at the wall. As the main bulk flow near the wall is in the downward direction, the boundary layer flow is also downward and the separated dust layer is carried down into the apex and out through the dust discharge orifice. It is, therefore, not gravity but the gas flow that is responsible for dust discharge from a gas cyclone. Gravity has little effect on the separation process in gas cyclones except when very coarse dusts are separated in large cyclones. It also follows from this that the cyclone orientation with respect to gravity plays a minor role except for large cyclones which should be installed with their axis in a vertical or near-vertical direction.

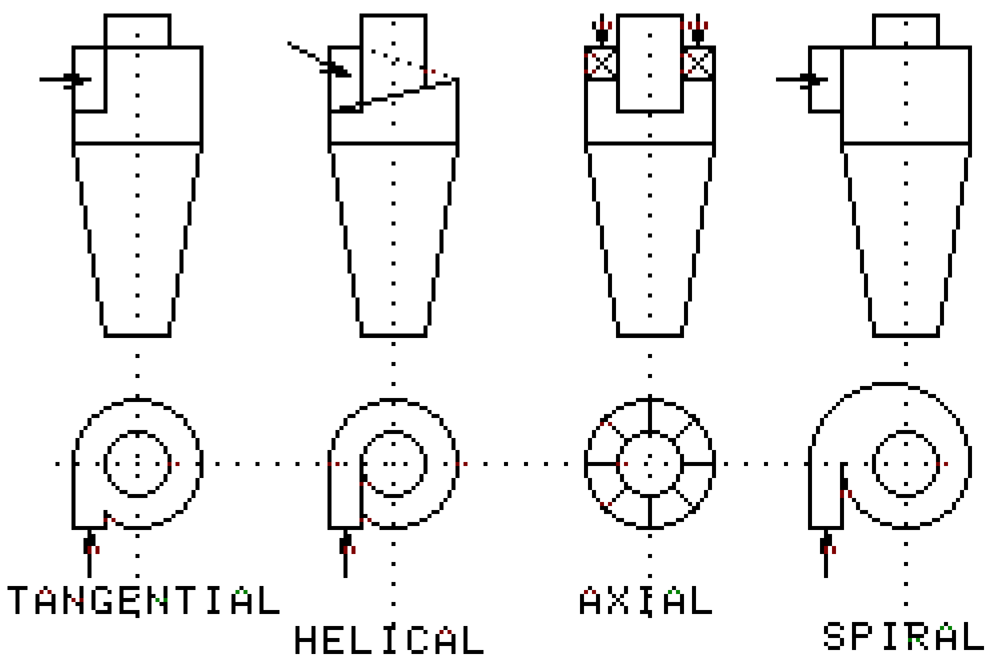

Figure 2: Types of inlet

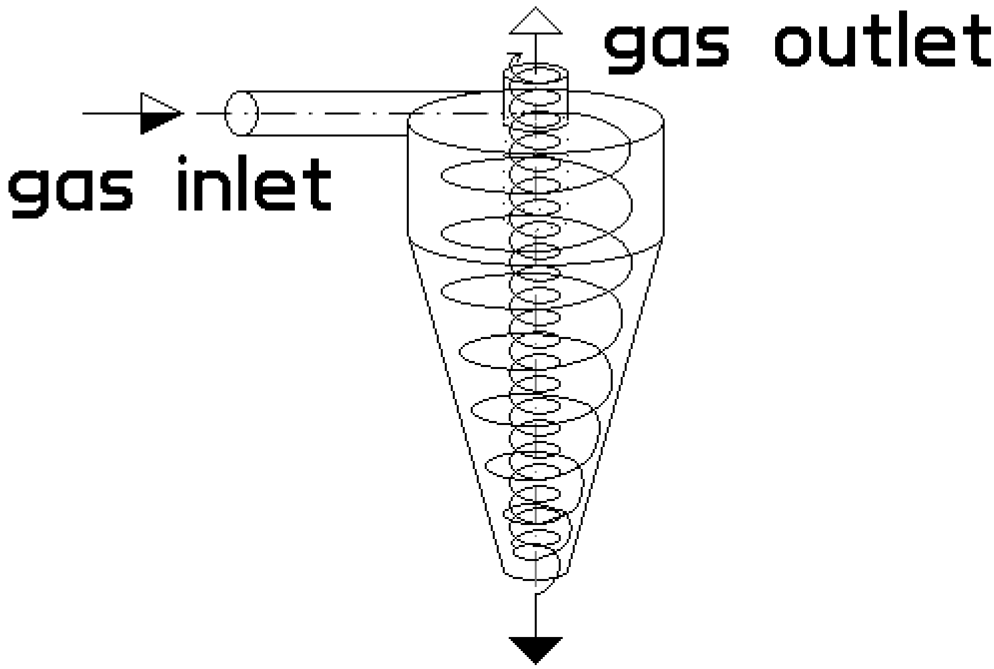

Figure 3: Gas flow in a gas cyclone

As the vortex reaches very far into the apex, it is advisable not to place any restriction or valve there. It is better to leave the dust outlet clear and use a discharge hopper or "disengagement chamber" underneath the cyclone (Fig.4), with the necessary valve on the hopper outlet. There is evidence of the vortex reaching even into the hopper itself and it is therefore recommended, in order to avoid particle re-entrainment, not to allow any accumulation of dust in the hopper if possible, and certainly not within about one cyclone diameter below the dust discharge orifice.

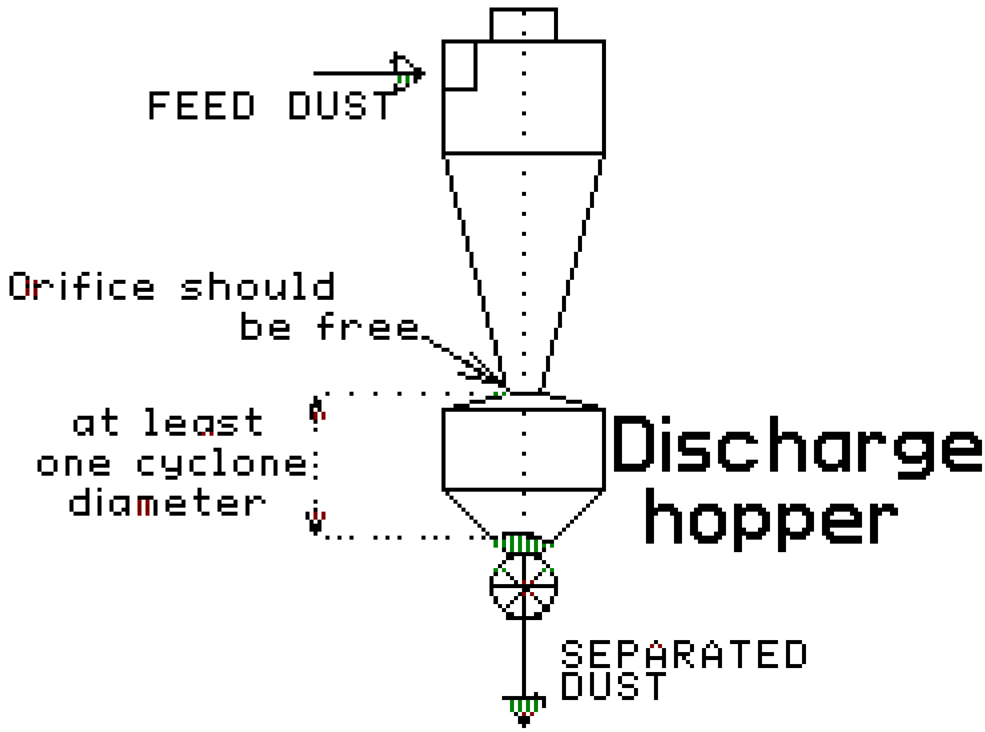

Figure 4: Dust discharge from gas cyclones

Inward leakage of air into the discharge hopper reduces cyclone efficiency, whilst any outward leakage marginally improves it. As the latter case leads to pollution and loss of product, it is best to keep the hopper and the discharge valve air-tight whether the pressure inside is positive or negative.

CHARACTERISTICS OF GAS CYCLONES

The main performance characteristics of gas cyclones are the pressure drop - flowrate relationship and the separation efficiency. These are conveniently described by two dimensionless groups, the Euler number Eu and the Stokes number Stk_{50}, to be defined in this Section. These numbers are constant for a family of geometrically similar cyclones and, unlike with some other separators, they are independent of the Reynolds number and therefore independent of the flow conditions (within the recommended range of operation, see later). Both Eu and Stk_{50} are affected by the dust loading (i.e. feed dust concentration) but the effect is usually taken as being negligible up to the concentrations of about one gram per cubic metre.

Flow Characteristics

The static pressure drop Δp measured between the inlet and the gas outlet of a cyclone is usually proportional to the square of gas flowrate Q. This means that the resistance coefficient defined as the Euler number, Eu, in equation (1) is practically constant for a given cyclone geometry or "design" and independent of the cyclone body diameter:

$$\mathrm{Eu} = \frac{\Delta p}{(\rho v^2/2)} \tag{1}$$

where ρ is gas density and v is a characteristic velocity defined below. In terms of its physical significance, Eu represents a ratio of pressure forces to inertial forces acting on a fluid element.

The characteristic velocity v can be defined for gas cyclones in various ways but the simplest and most appropriate definition is based on the cross-section of the cylindrical body of the cyclone, so that:

$$v = \frac{4Q}{\pi D^2} \tag{2}$$

where Q is the gas flowrate and D is the cyclone inside diameter.

The two other alternatives to the definition of characteristic velocity, the average inlet or outlet velocities, are not recommended because neither of them would lead to sensible comparison of different designs; it can be argued that the cyclone body diameter is the most important dimension, determining the manufacturing costs, the space occupied, headroom etc.

As an example to demonstrate the superiority of the definition of body characteristic velocity in Eq.(2) , consider two cyclones, identical in diameter and all other dimensions except in their inlet and gas outlet diameters. One has large inlet and small gas outlet whilst the other has a small inlet and large gas outlet: the relative size of the two openings may be such as to result in an identical pressure drop - flowrate relationship for both cyclones. Using the body velocity defined in Eq.(2) , the resistance coefficient Eu in Eq.(1) would be the same for both cyclones; this is to be expected as the cyclones are of the same size and give identical flowrates for the same pressure drops. If, however, either the inlet or the gas outlet velocities are used (and some authors still insist on using those), the resistance coefficients thus obtained would be very much different for the two cyclones, thus apparently favouring strongly (and wrongly) one of the two designs depending on which of the two alternative definitions of v is used.

Note that Eu is sometimes quoted in terms of the total pressure drop rather than static pressure drop as it is used here. The difference between the two is small because the gas velocities in the input and output are comparable and the kinetic energy of the incoming gas can therefore be assumed to be fully recovered. Static pressure drop is much more convenient to measure and for constant geometry the small difference does not matter anyway because the ratio of the two velocities is fixed.

The resistance coefficient Eu is generally not affected by operating conditions if the dust loadings are low: there is no universal top limit but 1 g/cu.m is probably about right. For operation under such concentrations, therefore, Eu can be simply tested with clean air at ambient conditions and experimental values of Eu for many known or commercial geometries are available in the literature [1]. When test data are not available for a given design, the next best alternative is to use a theoretical expression to predict the value of the coefficient.

Leith and Mehta [2] reviewed the available correlations and found the expressions by Barth, Stairmand, and Shepherd and Lapple to give the best predictions out of five different equations, when tested with twelve known geometries of known cyclones. They selected the correlation due to Shepherd and Lapple [3] as best because it was simple and yet it gave results as good as those produced by the other two, more complicated expressions. The Shepherd and Lapple equation is given below (for inlets without vanes) and the notation for cyclone dimensions used in the equation is given in the nomenclature.

$$Eu = \pi^2 \cdot (D/L) \cdot (D/K) \cdot (D/M)^2 \qquad (3)$$

The resistance coefficient Eu, whether predicted by Eq.(3) or measured with clean air, is known to be reduced by the presence of a significant amount of solids. This is because the static pressure drop is largely due to the centrifugal static head and that in turn depends on the distribution of the tangential velocities in the cyclone. The latter are modified by the presence of the solids, turbulence is dampened, and the resulting effect is the reduction in resistance to flow; this is opposite to what happens in pneumatic conveying in pipes where the resistance is increased due to the additional friction between the solids and the pipe walls. The reduction in resistance only takes place up to a certain dust loading, above which Eu starts to rise: the increased friction due to particles then takes over and becomes dominant.

The correlations available in the literature for the effect of dust loading on the resistance coefficient are necessarily empirical: the most acceptable one is quoted by Smolik [4] and it can be expressed in the following form:

$$Eu = Eu_c \cdot (1 - \alpha c^{\beta}) \qquad (4)$$

where Eu corresponds to dust concentration c (g/cu.m), Eu_c is the resistance coefficient with clean air and α and β are empirical coefficients which according to Smolik depend on the dust: he quotes $\alpha = 0.02$ and $\beta = 0.6$, supposedly obtained with coal dust. The value of the exponent β (which controls the rate of decline in Eu with dust concentration) in particular is bound to depend on the size distribution and density of the feed solids because turbulence damping is known to be affected by those variables.

Note that Eq.(4) must be quoted together with a top limit of applicability in feed concentration c, above which a rise in Eu will take place. If applied above the limit, Eq. (4) would predict Eu=0 or negative and that would of course be a nonsense.

Efficiency of Separation

The overall separation efficiency of cyclones is sometimes called total efficiency E_T and it is simply the solids recovery by mass. It depends on the operating conditions and on the feed size distribution of the solids: the latter effect is taken care of by using the concept of grade efficiency as described below.

One of the important operating variables affecting total efficiency is the dust loading: generally, high dust loadings lead to higher recoveries due to particle enlargement through aggregation of particles. This is because dust particle collision rates increase with the square of particle concentration. Aggregation depends on the nature of the dust, namely its surface properties, and also on the carrier gas: humidity for example has been known to affect aggregation. The effects of aggregation are usually not observed below about 5 g/cu.m. When designing cyclones for higher dust loadings, predictions are first carried out assuming low loading and the resulting efficiencies are then upgraded using empirical charts or equations. One such equation is widely quoted in the literature (unspecified dust) and attributed to Caplan [5] as follows:

$$\frac{1-E_T^*}{1-E_T} = \left(\frac{c}{c^*}\right)^{0.182} \qquad (5)$$

where E_T^*, c^* and E_T, c are the corresponding pairs, one (say the first pair with a star *) representing the test conditions (or predicted values) at low concentrations, and the other the values expected at a given high loading c. A similar correction, in the form of a graph, was published by Zenz [6] for cracking catalysts but the two do not coincide.

In order to describe the separation efficiency in a form independent of the feed size distribution, the recovery is measured and expressed as a function of particle size (Fig.5). It is then called the "grade" efficiency and it increases from zero for ultra-fine particles to 100% for very coarse particles. The particle size recovered at 50% efficiency is referred to as the "cut" size x_{50} and it can be understood as equivalent to the aperture size of an ideal screen that would give the same separation performance as the cyclone. The total solids recovery in a particular case then depends on the grade efficiency (or cut size) which characterizes the cyclone operated under given conditions, and on the size, density, shape, concentration and dispersion of the particles (i.e. the characteristics of the feed aerial suspension). The concept of cut size is useful where the efficiency of a cyclone is to be expressed as a single number independent of the solids size distribution, such as in scale-up calculations.

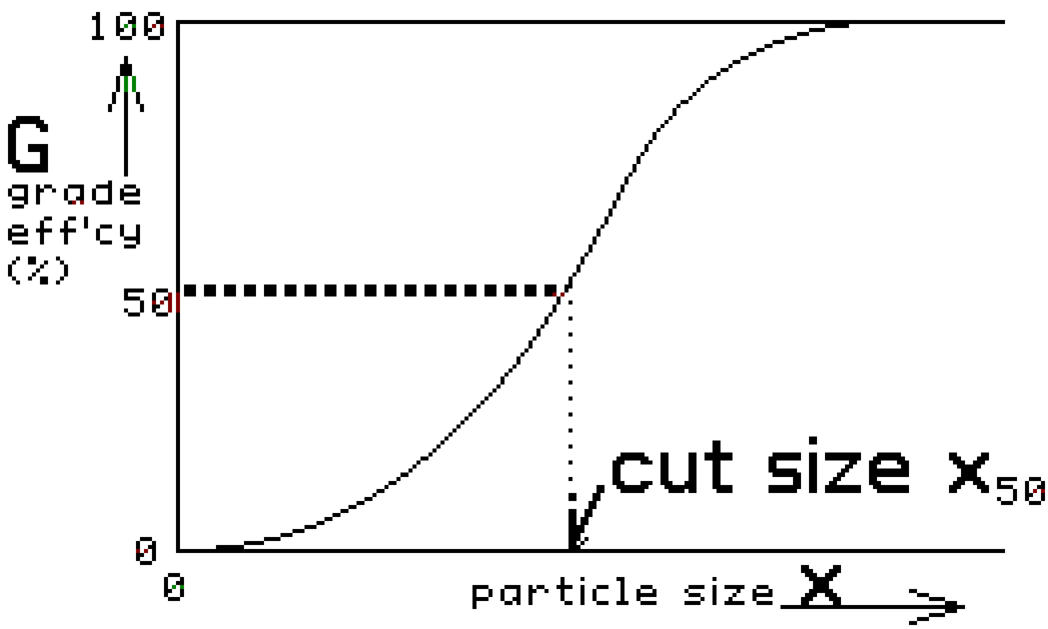

Figure 5: Grade efficiency curve of a gas cyclone

Such scale-up is based on a second dimensionless group which characterizes the separation performance of a family of geometrically similar cyclones. It is the Stokes number Stk_{50} defined as:

$$Stk_{50} = x_{50}^2 \cdot \rho_s \cdot v/(18 \cdot \mu \cdot D) \qquad (6)$$

where μ is gas viscosity, ρ_s is solids density, v is defined by Eq.(2) and x_{50} is the cut size (equiprobable size). The physical significance of Stk_{50} is that it is a ratio of the centrifugal force (less buoyancy) to the drag force, both acting on a particle of size x_{50}. For large, industrial-sized cyclones, this dimensionless group, like the Euler number defined previously, is independent of Reynolds number. With small diameter cyclones, however, say less than 100mm chnages in Reynolds number may affect both Eu and Stk_{50}.

As can be seen from Eq.(6) , the separation efficiency is described there only by the cut size x_{50} and no regard is given to the steepness of the grade efficiency curve. If the whole grade efficiency curve is required in design or performance calculations, it may be generated around the given cut size using plots or analytical functions of a generalized grade efficiency function available from the literature or from previously measured data. The knowledge of the exact form of the grade efficiency is usually not critical in solid-gas separation applications because only total mass recovery is of interest and this is not much affected by the shape of the curve. Consequently, very little is known how the shape of the grade efficiency curve is affected by operating pressure drop, cyclone size or design, and feed solids concentration.

In powder classification applications, however, including the case of de-gritting, the shape of the curve determines the amount of the "misplaced" material, such as the amount of grit reporting to the gas outlet.

Coming back to Stokes number Stk_{50} defined in Eq.(6) , this is usually constant for a given cyclone design (i.e. a set of geometric proportions relative to cyclone diameter D), when the cyclone is used to separate granular material at feed concentrations of less than about 5 g/m^3. Like in the case of Euler number, Stokes number for a particular geometry can also be predicted theoretically from cyclone proportions but this is less reliable than in the case of Eu. There is little point in listing here the available correlations for Stk_{50}; they are given in **1**. In short, there are three groups of theories, the centrifugal sedimentation model, the centrifugal elutriation model and the turbulent sedimentation model with complete lateral mixing. The former two give generally pessimistic predictions while the last one has been shown to be closest to experimentally determined values but on the optimistic side.

The second way of accounting for the concentration effect on efficiency is via the cut size and the dimensionless group which includes the cut size, the Stokes number Stk_{50}. According to Matsen [7], the cut size of a gas cyclone is inversely proportional to the dust concentration to the power of 0.2. In terms of Stk_{50}, this is written as:

$$\frac{Stk_{50}^{*}}{Stk_{50}} = \left(\frac{c}{c^{*}}\right)^{0.4} \qquad (7)$$

where the starred values represent the tested or predicted values at low dust loadings and the unstarred are the values expected at a high loading. The effect is not expected to apply at loadings below 5 g/m^3.

Note that the values of dust concentrations c in the above equation may be in any consistent units (as they are in a ratio).

The third method, recently proposed [8] and also empirical, is based on another expression for Stk_{50} as follows:

$$Stk_{50} = Stk_{50}^{0} - kc \qquad (8)$$

where Stk^{o}_{50} is measured at a very low dust loading, c is dust loading as a fraction by volume and k is an empirical constant. Limits of validity have to be quoted with this equation.

Note that for the purpose of testing of cyclones for the grade efficiency or the cut size, particle size x is best measured as the equivalent Stokes' diameter by sedimentation or elutriation methods. This equivalence is based on the assumption that, if a spherical particle and an irregularly- shaped particle settle at the same velocity (in gravity or centrifugal fields), they will separate at the same efficiency. This assumption does not hold for flat or needle-shaped particles which assume different orientation in a cyclone than under gravity or centrifugal settling. Problems are also encountered when the particles undergo the separation process in an agglomerated state and the agglomerates are subsequently re-dispersed into single particles before particle size analysis.

Recommended range of operation

One of the most important characteristics of gas cyclones is the way in which their efficiency is affected by pressure drop (or flowrate). Correctly designed and operated cyclones should operate at pressure drops within a recommended range, and this for most cyclone designs operated at ambient conditions is between 2 and 6 inches of water gauge (WG) (approximately from 500 to 1500 Pa). Within this range, the recovery increases with applied static pressure drop. At higher absolute pressures, the applicable limits increase to higher values and the equivalence is based on the same inlet velocity.

At pressure drops below the bottom limit, the cyclone represents little more than a settling chamber, giving low efficiency due to low velocities within it which may not be capable of generating a stable vortex. Above the top limit (the value of which depends very much on the cyclone design and can be as high as 15"WG i.e. 3740 Pa, depending particularly on what happens at and below the dust outlet orifice [9]), the mass recovery no longer increases with increasing pressure drop and it may actually decline; it is therefore wasteful to operate cyclones above this limit.

CYCLONE TYPES AND DESIGN FEATURES, CYCLONES IN SERIES

There is a whole host of different cyclone designs available today [1], and they are usually divided into two main groups according to their geometrical proportions relative to the body diameter: the "high efficiency" designs and the "high rate" designs. Note that only the reverse flow cyclone is considered here because that is the type used in the tests under consideration.

The so-called "high efficiency" cyclones are characterized by relatively small inlet and gas outlet orifices, and a long body, and they give high recoveries. The "high rate" designs give medium recoveries but offer low resistance to flow so that a unit of a given size will give much higher air capacity than a high efficiency design of the same body diameter. The high rate cyclones have large inlets and gas outlets, and are usually shorter. In order to prevent the incoming jet of air impinging on the gas outlet pipe, the inlet is spiral (wrap-round type) while the high efficiency units can (and often do) have a simple tangential entry.

It is interesting to find that, for well-designed cyclones, there is a direct correlation between Eu and Stk_{50}: high values of the resistance coefficient usually lead to low values of Stk_{50} (therefore low cut sizes and high efficiencies), and vice versa. This is shown in Fig.6 where the corresponding values of Eu and Stk_{50} are plotted for several commercial and other well-known designs [10]. The points are well scattered but a line can be drawn through them to show a general trend. The line drawn in Fig.6 can be described by the following approximate equation:

$$Eu = \left(\frac{12}{Stk_{50}}\right)^{\frac{1}{2}} \tag{9}$$

This equation may be used for estimates of cut size of unknown cyclone designs (of "reasonable" proportions) from the cyclone flow characteristics and it is intended for guidance only.

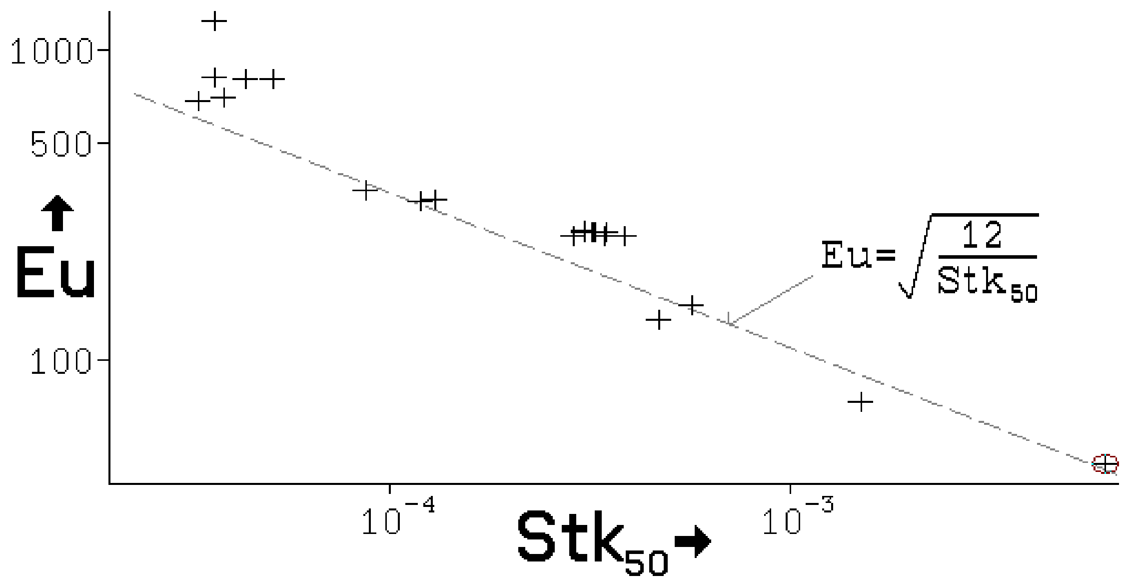

Figure 6: Experimental values of Eu and Stk_{50} for some commercial cyclone designs

Note that the scale-up of cyclones based on Eu and Stk_{50} works well not only for near-ambient conditions but it predicts the performance at high absolute pressures and high temperatures also reasonably well: this means that there is no effect of high pressures and temperatures other than that accounted for in the definitions of Eu and Stk_{50} on gas viscosity and density.

The most important reason for using cyclones in series, generally speaking, is that the solids recovery of a single cyclone does not carry on rising with applied pressure drop above a maximum. No more than two cyclones should be used, however, unless steps are taken that the cut size of the subsequent stages is progressively lower by "tightening up" on the design (primary stage of medium or low efficiency design and further stages of progressively more efficient design or smaller diameter). The first stage often has a high dust loading and the operating cut size is thus reduced by agglomeration; the second stage, if identical in design, may operate at greater cut size on account of it receiving much more dilute feed. This does not make good utilization of the second stage as its recovery is small: it's like using a fine screen followed by a coarse screen and design changes in the second stage should therefore ensure that its cut size is as small or smaller than that of the first stage.

Apart from the resulting gain in recovery, two-stage systems are also advantageous for separation of fragile, agglomerated or abrasive dusts in that the first stage is then designed to operate at low inlet velocity. A large diameter primary cyclone may be used to collect the grit which would plug or erode the high efficiency cyclone in the second stage. The two-stage systems also offer additional reliability in that if the primary cyclone plugs, the secondary still collects.

The series connection of cyclones is not always necessarily in the direction of the gas overflow: sometimes it is advantageous to draw off 5 to 15% of the gas flow through the dust outlet orifice and separate the concentrated aerial suspension in a small secondary cyclone. Such an arrangement does not improve the overall recovery of the plant, however, other than through the beneficial effect it has on the recovery in the first stage. An example of use is in the fluidized bed combustor of British Coal [11]. Several pressurized fluidized bed combustors under test worldwide, including the facility at Grimethorpe, use conventional series connections on overflow, however, with up to four stages [12,13,14].

Cyclones are also widely used in series connections with other gas cleaning devices such as filters, electrostatic precipitators or scrubbers, usually as pre-collectors, to reduce the load on the high efficiency units that follow.

THE EFFECTS OF HIGH PRESSURE AND TEMPERATURE

One of the advantages of cyclones is their suitability for use at high temperatures and pressures. Refractory-lined cyclones have been used for many years in hot gas applications and most recently, several experimental pressurized fluidized bed combustors (PFBC's) have employed cyclones for the cleaning of the combustion gases before their expansion to atmospheric pressure and dicharge.

It is difficult to make sweeping conclusions from the available range of tests of PFBC installations because the scatter in the results due to measurement errors is usually great and the feed size distribution of solids is never constant. Any measurements at the high pressures and temperatures used in the tests are much more difficult and subject to larger errors than under near-ambient conditions. Furthermore, the tests were in most cases primarily designed for the combustor and other associated equipment: the cyclone operating variables all changed almost in a random fashion from test to test and this obscures their correlation with the measured performance.

It is possible, however, to evaluate the cyclone performance using the well established dimensionless groups, which compound the operating variables and allow correlations in a more manageable form. Comparisons of the results with known relationships for cyclones operated at near-ambient conditions allowed the following conclusions to be drawn; those are of course subject to any systematic errors in the measurements or errors of the evaluation in the data supplied.

The effects of pressure and temperature can be divided into those on the resistance coefficient Eu, on the efficiency of separation (or the Stokes number) and on the recommended range of operation; these are dealt with separately in the following:

1. The resistance coefficient Eu does not seem to be affected by temperature or pressure at low dust loadings (less than 1 g/cu.m). The clean air value Eu, extrapolated from the test results, is quite close to the value measured at ambient conditions or predicted by Eq.(3) from the cyclone dimensions. Eq.(3) does not use all cyclone dimensions but it gives predictions at least as good than other more complicated expressions based on a fuller account of cyclone proportions. The effects of pressure and temperature are therefore quite predictable from the effect they have on gas density.

At higher loadings than 1 g/cu.m, Eu is reduced in a manner similar to that occurring at ambient conditions and Eq.(4) can be used to predict the change. The slope of change as described by exponent β in Eq.(4) was sometimes [8] found to be a little higher (0.7) than the value quoted in the literature (0.6) but this could be due to the nature of the solids rather than the effects of temperature and pressure; the real cause is impossible to be established without further tests.

2. The efficiency of separation is also affected by temperature and pressure. A fuller review of the relevant work can be found in our previous report [8]; only general conclusions are given here.

One problem that underlies all of the PFBC cyclone tests, including the IEA series [8], is that of aggregation and/or attrition on separation. This demonstrates itself in apparently flat grade efficiency curves (like in the case of the secondary and tertiary cyclones at Grimethorpe), with the dust in the gas outlet and the dust collected often being both of very similar size distributions.

The effects of aggregation and attrition have not yet been studied systematically and, until their fundamentals are properly investigated, predictions of gas cyclone performance at high pressures and temperatures will not be reliable. High temperatures may be conducive to aggregation or even sintering together of agglomerates, which may be broken on separation.

The use of a dimensionless group, the Stokes number Stk_{50}, has been necessary because the feed size distribution was changing from test to test. Only some cyclones showed a "cut size", the others suffered from aggregation and attrition, making scale-up correlations impossible. Also, the method of particle size analysis was not always relevant to the application and this might have led to incorrect data.

The effect of dust loading on Stk_{50} is once again more dominant than that of temperature or pressure: the data are very scattered but there are recognizable trends of Stk_{50} decreasing with increasing dust loading. The same is known to happen under near-ambient conditions. It seems, however, that the efficiency is somewhat reduced at high pressures and temperatures, over and above what is due to the increase in gas viscosity and density under such conditions. The reduction is not large, however, and the cut sizes measured are still within the order of magnitude of the values predicted from theory or ambient tests.

3. The range of recommended operation at higher absolute pressures moves to higher pressure drops. The actual drop in solids recovery at high inlet velocities has not yet been demonstrated in applications at high pressures and temperatures but it is likely to occur. The pressure drops corresponding to the recovery limit vary from 100 to 400 mmWG (10 to 40 mbar) for cyclones run at near ambient conditions and inlet velocities from 15 to 20 m/s are usually recommended. This range in pressure drops would correspond to pressure drops from 25 to 50 mbar at absolute pressure of 10 bar and temperature of 820 ºC if the conversion is on the basis of the same inlet velocity but only tests under the actual conditions can verify this.

OVERALL VERDICT: The effects of pressure and temperature on cyclone performance are broadly predictable from theory. In most PFBR tests they were over-shadowed by the effect of dust loading and obscured by experimental errors leading to very scattered data.

WORKED EXAMPLE: CYCLONE SELECTION AND SIZING

Determine the diameter of a gas cyclone and, if necessary, the number of cyclones to be operated in parallel, to treat 0.177 m^3/s of ambient air (viscosity is 18.25 x 10^{-6} Ns/m^2, density 1.2 kg/m^3) laden with solids of density 2500 kg/m^3 at a pressure drop of 1650 Pa and a cut size of 0.8 µm (to within 0.01 µm). The geometry to be used has Eu = 700 and Stk_{50} = 6.5 x 10^{-5}.

Solution

From the definition of the resistance coefficient Eu in equation (1) and the definition of v in equation (2), the cyclone diameter can be calculated directly as the only unknown:

$$D^2 = \frac{4Q}{\pi}\sqrt{\frac{\rho \ Eu}{2\ \Delta p}}$$

which gives D = 0.337m and, from the definition of Stk_{50} in equation (6), the cut size is

$$x_{50} = \sqrt{\frac{18\,\mu\,\pi\ \mathrm{Stk}_{50}\,D^3}{4\ \rho_s\ Q}}$$

which gives x_{50} = 1.2 μm.

This value is greater than the 0.8 μm required and the feed flow has to be divided into several smaller cyclones operated in parallel. The number of parallel cyclones can be found by repeating the above calculation but using the flowrate Q divided by 2,3,4 etc. until the cut size of 0.8 μm is obtained. Alternatively, the two equations used above can be solved simultaneously for D and N if Q/N is substituted for Q.

The former method yields the following results, from which the effect of cyclone size on the cut size can be clearly seen:

If the total feed flowrate is Q = 0.117 m^3/s, then for

2 cyclones in parallel: D = 238 mm and x_{50} = 1.01 μm

3 cyclones in parallel: D = 195 mm and x_{50} = 0.92 μm

4 cyclones in parallel: D = 169 mm and x_{50} = 0.85 μm

5 cyclones in parallel: D = 151 mm and x_{50} = 0.81 μm

Answer: 5 cyclones in parallel, each 151 mm in diameter, with a capacity of 0.177/5 = 0.0354 m^3/s each.

Note:

The scale-up procedure used above is based on an assumption that inertial separation is the predominant mechanism. It does not take into account the effects of particle agglomeration, electrostatic effects or dust re-entrainment from the bottom part of the cyclone and the discharge hopper. The effect of dust re-entrainment becomes important at higher pressure drops (i.e. higher velocities), usually around 1500 Pa for most cyclone geometries, when the rise of separation efficiency with pressure drop (predicted by the inertial theory) terminates. Under atmospheric conditions, there is, therefore, little point in operating (and designing) cyclones at pressure drops very much higher than 1500 Pa.

There is also a bottom limit of pressure drop, below which cyclones are little more than settling chambers, operating at very low efficiencies. This lower limit is arbitrarily set at about 500 Pa.

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