Electrostatically Enhanced Cyclone Separators

P. W. DIETZ

General Electric Company, Corporate Research and Development, Schenectady, NY 12301 (U.S.A.)

(Received June 19, 1981)

SUMMARY

The separative performance of a cyclone can be enhanced if electrical forces are employed to supplement the inertial forces. By precharging the particles and applying a radial electric field within the cyclone, collection efficiency is improved. In the present paper, a model is developed for such an electrostatically augmented cyclone. The model assumes that turbulence promotes complete radial mixing within each of three regions: the entrance region, the downflow region and the core (or upflow) region. Based on this model, an analytic expression for the collection efficiency of cyclone separators is developed.

INTRODUCTION

Cyclone separators (see Fig. 1) provide a simple, inexpensive means for removing relatively fine particles from gas streams. Although this level of performance has been adequate for many applications, the increasing emphasis on environmental protection is dictating that finer and finer particles must be removed. To meet this challenge, improvements in cyclone efficiency are required.

One potential technique for enhancing cyclone performance is to augment the inertial separative force in the cyclone with electrostatic forces (the device is termed an 'electrocyclone'). A simple cut-size analysis demonstrates the significant improvements in efficiency that can be achieved in an electrocyclone [1]. These improvements in performance have also been observed experimentally. In 1962, Petrol1 and Langhammer [2] demonstrated that electrostatic forces can be employed to significantly enhance the collection performance of a conventional, reverse-flow cyclone. They achieved a reduction in penetration of 28% through the addition of a simple high voltage electrode structure. Similar performance improvements have been achieved by Reif [3-5] in axial flow cyclones. Yet, in spite of these successes, this technology has not been implemented. However, as pollution control standards become increasingly stringent, such improvements cannot be ignored and, indeed, must be pursued.

Further experimental support for the importance of electrostatic forces in cyclones...
was recently obtained by Giles [6]. Even in the absence of an applied electric field, Giles found that the cyclone efficiency could be enhanced if the particles were electrically charged. Also, in contradiction to conventional cyclone theory, the efficiency increased as the flow rate was reduced, as predicted by Soo [7].

In the present paper, an analytic model is developed for the electrostatically enhanced cyclone separator. Electrostatic forces are incorporated into the three-region model recently proposed for flow within the cyclone [8].

ELECTROCYCLONE MODEL

The most efficient algorithm for developing a model for collection in an electrocyclone would be to include the electrical forces in an existing cyclone model. However, classical cyclone models do not lend themselves to such an approach. The commonly employed theories of both Stairmand [9] and Lapple [10] are based on empirical curves for a specific cyclone configuration. Derived scaling laws are then employed to modify these curves for variations in cyclone size, flow rate, etc. Thus, one approach to modeling the electrocyclone would be to develop a comparable data base for such an empirical curve. However, such a data base would be applicable only to the specific configurations tested.

Fortunately, two recent theoretical treatments of cyclone separators do allow direct incorporation of electrical forces: Leith and Licht [11] and Dietz [8]. Because Dietz's approach more accurately models geometric effects, it will be employed here. This simple, three-region model incorporates the following features.

- includes cyclone geometry,
- recognizes the importance of turbulent mixing,
- provides for a distribution of gas-residence times,
- does not assume the core and annular region are well mixed, yet
- allows exchange of particles between the core and annular region.

In the three-region model, the cyclone is conceptually separated into the following regions (see Fig. 1):

(1) the outer annulus of the cyclone in which the gas velocity is essentially downward (regions 1 and 2), and
(2) the core of the cyclone in which the gas velocity is essentially upward (region 3).

For analytic convenience, the downflow region is further subdivided into the region above the exhaust tube (1) and the region below it (2).

To simplify the analysis, the conventional cyclone geometry (see Fig. 1) has been modified to a right circular cylinder (Fig. 2). The cyclone radius \( R_c \) and exit tube radius \( R_t \) are unchanged. The engagement length of the modified cyclone \( D \) is equal to the average engagement length:

\[
D = s - \frac{a}{2}
\]  

where \( s \) is the actual engagement length of the cyclone and \( a \) is the axial extent of the inlet. The length of the model cyclone is equal to the actual length of the cyclone below the outlet duct unless the natural turning length of the vortex is less than this length. In this case, the effective cyclone length is given by [12]

\[
e_0 = 7.3R_t \left( \frac{R_c^2}{ab} \right)^{1/3}
\]

In each region, turbulent mixing is assumed to maintain uniform radial concentration profiles. Thus, conservation of particles in each region requires that
\[ Q_{\omega} \frac{dn_1}{dz} = -2\pi R_d \Gamma_\omega(z) \quad \text{Region 1 (2)} \]

\[ \frac{d}{dz} \left[ Q_\nu(z)n_3 \right] = -2\pi R_\nu \Gamma_\omega(z) - 2\pi R_\nu(z) \Gamma_\nu(z) \quad \text{Region 2 (3)} \]

\[ - \frac{d}{dz} \left[ Q_\nu(z)n_3 \right] = 2\pi R_\nu(z) \Gamma_\nu(z) \quad \text{Region 3 (4)} \]

where \( Q_\nu(z) \) is the axial volume flow rate (equal to the total volume flow rate of the cyclone in region 1), \( \Gamma_\omega(z) \) is the particle flux to the cyclone wall, \( R_\nu(z) \) is the radius of the core region and \( \Gamma_\nu(z) \) is the flux of particles from the annular region to the core region (2 → 3). Because eqns. (2) - (4) are expressed in terms of particle fluxes, they are identical to those proposed by Dietz [8]. To compute these particle fluxes in the electrocyclone, the electrostatic force must obviously be included.

The radial particle velocity \( U_{pw} \) at the cyclone wall (where the radial gas velocity is zero) can be directly computed from a balance between the drag forces (assume Stokes' drag) and the sum of the inertial plus electrical forces.

\[ 6\pi \mu R_p U_{pw}(z) = \frac{4\pi \rho_p R^3 U_{\text{tw}}^2}{3R_c} + qE_w \quad (5) \]

where \( \mu \) is the gas viscosity, \( R_p \) is the particle radius, \( U_{\text{tw}}(z) \) is the tangential gas velocity, \( \rho_p \) is the mass density of the particle, \( q \) is the charge on the particle, and \( E_w \) is the electric field at the cyclone wall. Because Stokes' drag is assumed, the enhancement in collection efficiencies that results from high dust loadings will not be reflected in this model. The electric field is imposed by applying a high voltage to the exit duct and an electrode structure within the cyclone (see Fig. 1). The depicted electrode configuration is hypothetical and, in practice, may be far from that which is actually employed. For instance, the electrode could be a single axial rod contained entirely within the viscous core region. For the present analysis, this electrode structure simply imposes a Laplacian radial electric field. The flow is assumed to be unaffected by its presence.

\[ U_{pw}(z) = \frac{2\rho_p R^2 U_{\text{tw}}^2}{9\mu R_c} + bE_w \quad (6) \]

where \( b \) is the particle mobility \((b = q/6\pi \mu R_p)\). The particle flux is given by

\[ \Gamma_w = n(z)U_{pw} \quad (7) \]

This expression for the particle flux to the wall assumes that all particles that hit the wall are collected. Thus, both particle bounce and re-entrainment are neglected. Although these assumptions are valid for most conventional reverse flow cyclones, the application of an electric field may alter the particle–wall interaction. In electrostatic precipitators, conducting particles tend to bounce away from the wall to become re-entrained. On the other hand, semi-insulating particles tend to adhere more tightly to the electrode in the presence of a corona current. (Consequently, the application of a corona electrode within the cyclone may reduce re-entrainment and thus further improve cyclone performance.) Rather than model these new particle–wall interactions, both mechanical and electrical re-entrainment mechanisms will be neglected and all of the particles that hit the wall will be assumed to be collected.

At the boundary between the core and annular regions, the mechanisms responsible for the particle flux are more complex. Following the approach developed by Dietz [8], the particle flux between the core and annular regions is assumed to be composed of two components. The radial gas velocity carries particles from the annular region to the core and, at the same time, the centrifugal force plus the electrostatic force act to propel particles from the core into the annular region with velocity \( U_{pv} \). Thus, the particle flux is

\[ \Gamma_\nu = n_2 U_{\nu} - n_3 U_{pv} \quad (8) \]

Now, the velocity of particles thrown from the core into the annulus can again be computed from a balance between forces (the radial velocity is neglected since it is included in the transport from the annulus to the core). Thus

\[ U_{pv}(z) = \frac{2\rho_p R^2 U_{\text{tw}}^2}{9\mu R_c} + bE_\nu \quad (9) \]

where \( E_\nu \) is the electric field at the boundary of the vortex. In the limit of negligible space charge, the electric field is given by \( E_\nu = E_w(R_c/R_\nu) \). To complete the model, it is only necessary to specify the flow pattern within the cyclone. The simple picture proposed by
Dietz incorporates many elements of the actual physical system:

the radial velocity into the core region is constant:

$$U_r(z) = U_r0 = \frac{Q_v0}{2\pi R_v \ell}$$

(10)

thus, the axial flow rate is given by

$$Q_v(z) = Q_v0(1 - z/R)$$

(11)

the tangential velocity does not vary axially [9].

the radial dependence of the tangential velocity is given by a modified form of the free vortex in an inviscid fluid [12, 13]:

$$U_t(r) = U_{tw}(r_c/r)^m$$

(12)

where $m$ is between 0.5 and 1.0, and

the radius of the core region (which separates upflow from downflow) is equal to that of the exit tube [13, 14]:

$$R_c = R_t$$

(13)

(The radius of the maximum separative region is somewhat smaller than the exit tube [9].)

With the model thus completed, eqns. (2) - (4) become a set of coupled, non-constant coefficient, ordinary differential equations. Since the electrical effects enter only through the boundary conditions, the general analytic solutions obtained previously are applicable. Matching these boundary conditions and computing efficiency gives

$$\eta = 1 - \frac{n_0(z = 0)}{n_0}$$

(14)

$$= 1 - K_0 + (K_1^2 + K_2)^{1/2} e^{-\mu \left(\frac{-2\pi R_c U_{pv} d}{Q_v}\right)}$$

(15)

where

$$K_0 = \frac{R_c U_{pv} + R_v U_{r} + R_c U_{pv}}{2R_v U_{pv}}$$

(16)

$$K_1 = \frac{R_v U_{pv} - R_c U_{r} - R_c U_{pv}}{2R_v U_{pv}}$$

(17)

and

$$K_2 = \frac{R_c U_{pv}}{R_v U_{pv}}$$

(18)

DISCUSSION

In the preceding section, an analytic model was developed for the collection of fine particles in an electrostatically enhanced cyclone. To employ this model to investigate the effects of the electric fields on collection performance and scaling, it is necessary to specify a specific cyclone configuration. For this purpose, a Stairmand ‘high-efficiency’ design [9] has been selected (see Table 1). With this information, eqn. (15) can be employed to compute grade-efficiency curves for each configuration. However, for comparison between various cyclone sizes and flow rates only the cut-sizes (the cut-size $d_{pc}$ is defined such that $\eta(d_{pc}) = 0.5$) will be compared.

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions of Stairmand ‘high-efficiency’ cyclone [10]</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$1.0R_e$</td>
</tr>
<tr>
<td>$b$</td>
<td>$0.4R_e$</td>
</tr>
<tr>
<td>$R_v$</td>
<td>$0.5R_e$</td>
</tr>
<tr>
<td>$S$</td>
<td>$1.0R_c$</td>
</tr>
<tr>
<td>$h$</td>
<td>$5.0R_c$</td>
</tr>
<tr>
<td>$H$</td>
<td>$8.0R_e$</td>
</tr>
</tbody>
</table>

Tangential velocity at design point 15 m/sec

For a cyclone diameter of 0.75 m (30 in.), the cut-size has been computed as a function of inlet velocity (see Fig. 3). In the absence of electrostatic augmentation, the computed cut-size decreases with increasing inlet velocity. For reference, Stairmand’s [9] predicted cut-size is also presented on this graph. (It should be noted that at the rated flow, Stairmand predicts a cut-size of 3.5 µm as compared with the 4.5 µm computed here. However, Stairmand’s computation is based on the total cyclone length rather than the effective vortex turning length. If the total length is used in the present model, comparable cut sizes are predicted (3.5 µm as against 3.7 µm).)

To compute the electrically enhanced performance of the cyclone, it is necessary to specify the electrical parameters. The entering particles are assumed to be charged to their
saturation value, $q_{sat}$, in an electric field $E_c$ [15]:

$$q_{sat} = 12\pi \varepsilon_0 R_p^2 E_c$$

Both the charging field and the maximum imposed electric field within the cyclone are assumed to be

$$E_c = E_{max} = 5 \times 10^5 \text{ V/m}$$

(the breakdown strength of air under standard conditions is $3 \times 10^6 \text{ V/m}$; however, field strengths above $1 \times 10^6 \text{ V/m}$ are difficult to achieve in practical systems).

With these parameters specified, the cut-size of an electrostatically augmented cyclone can be computed (see Fig. 3). At low flow rates, electrostatic forces are important and a significant enhancement of the collection efficiency is predicted (for this cyclone, Stairmand’s design flow rate is in this regime). In fact, in this range, increasing the flow rate results in an increase in the cut-size!

At higher flow rates, the inertial forces dominate and the cut-size of the cyclone is essentially unaffected by the presence of the electrostatic forces.

At the design flow rate (inlet tangential velocity of 15 m/sec), the cut-size of the Stairmand cyclone increases with increasing size (see Fig. 4). Since the tangential velocity is limited by practical considerations such as erosion, particle bounce and re-entrainment, the size of conventional cyclones is constrained. By contrast, the cut-size of an electrocyclone asymptotically approaches a constant value (for a fixed inlet velocity). Thus, as predicted by the simple cut-size
analysis [1], increasing the cyclone size (beyond a certain point) results in no degradation in performance for an electrostatically enhanced cyclone!

CONCLUSION

A model has been developed for the collection of fine particles in an electrostatically augmented cyclone. This model is an extension of Dietz's model for conventional, reverse-flow cyclones and, consequently, variations in cyclone geometry can be studied. Both turbulent mixing and variations in gas residence time have also been included in the model. Two important assumptions have been incorporated in the model. First, the fluid mechanics of the vortex are assumed to be unaffected by the electrode structure. If these effects are important, the only viable approach may be to electrify the outlet duct to avoid adding further electrodes. The second assumption necessary to complete the model is that all particles reaching the wall are collected. Of course, such an assumption is applicable to most droplet collectors. However, for solid particles, the limitations imposed by this assumption will need to be tested. As an aside, it should be noted that re-entrainment can set an upper limit on the tangential velocities in conventional cyclones and that this mechanism is neglected in most cyclone analyses.

The model developed in this paper clearly demonstrates the potential of the electrocyclone for particulate pollution control. Large efficiency increases can be obtained. And, most importantly, the model predicts that large electrocyclones can be as effective as small cyclones in removing fine particles!

ACKNOWLEDGEMENT

This work was performed by Corporate Research and Development of the General Electric Company under DOE Contract No. EX-76-C-01-2357 to the Company's Energy Systems Program Department.

REFERENCES

1 P. W. Dietz, 2nd Symp. on the Transfer and Utilization of Particulate Control Technology, Denver, July 1979, Session Q1.
8 P. W. Dietz, submitted to AIChE J.
10 C. E. Lapple, Chem. Eng., 58 (May 1951) 144.