SOME PRACTICAL ASPECTS OF PARTICLE DYNAMICS THEORY WHICH ARE USEFUL IN THE SELECTION OF GAS CLEARING DEVICES

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Abstract

Small particles can be removed from gases by only four means, inertial, diffusional, electrostatic and agglomerative means; some practical aspects of the theory describing these four ways of separation are presented. This is done by considering the design correlations currently used for predicting the collection efficiency of cyclones, venturi scrubbers, impingement devices and electrostatic precipatators. Some relative cost data is appended together with a selected bibliography on some gas scrubbers.

Introduction

The problem in gas clearing is to move the dust or mist particles from the stream to some collecting wall, and in practice this can be done in only four ways:

Inertial methods
Diffusional methods
Electrostatic methods
Agglomerative methods

A complete fundamental description of these methods has not been presented yet due to the extreme complexity of the situation; for example the drag coefficient (which appears in any force balance one might write down for a particle in motion) is not linear with respect to the particle Reynolds number and hence one cannot resolve particle trajectories into components[9] the effect of the suppression of turbulence in multiparticle situations on the drag forces is as yet unknown; particle diffusion in turbulent conditions is not fully understood; electrostatic effects, particle spin and so on are far from being quantitatively described.

Since a complete description is thus still beyond our reach we are obliged to use our present rather simple theory as a model of reality and to base our scale-up and extrapolation on the best version we can find of the relevant model.

It is the purpose of this paper to look at some of the particle dynamics models in the light of recent developments in the field. This will be done by discussing the design equations of a few common gas clearing devices. It is not to be inferred that these devices are the best available, they have simply been selected because between them they illustrate the most important practical formulae pertaining to small particle motion.

Cyclones

This is a pure inertial separating device, solid or liquid particles are thrown out to the walls of the vessel by centrifugal force as the gas spins through the cyclone. The efficiency of collection and hence its potential suitability for a given cleaning job could theoretically be predicted from a study of the trajectory of particles in a rotating field (see Figure 1), by finding out for any particular particle whether its terminal radial velocity will be high enough to move the particle from its position in the entering spinning gas at R_1 to the walls at R_2 within the residence time the particle will have in the cyclone. This problem in particle dynamics was first solved by Rosin, Ramler and Intelmann (16) in 1932 who proposed that the smallest particle X min that could reach the wall could be related to the cyclone design parameters by the formula.

$$X_{min} = 3\sqrt{\frac{\mu}{\pi \rho_S V_C}} \qquad \sqrt{S\left(1 - \frac{s}{d}\right)\frac{1}{N_t}}$$

(the meaning of all symbols is given in the table of nomenclature in the appendix)

Rosin's treatment assumed:
a "Swiss Roll" vortex for the particles
no particle interaction
no gravity effects and negligible bouyancy
a single inlet tangential velocity for all particles
no re-entrainment
no eddy flows

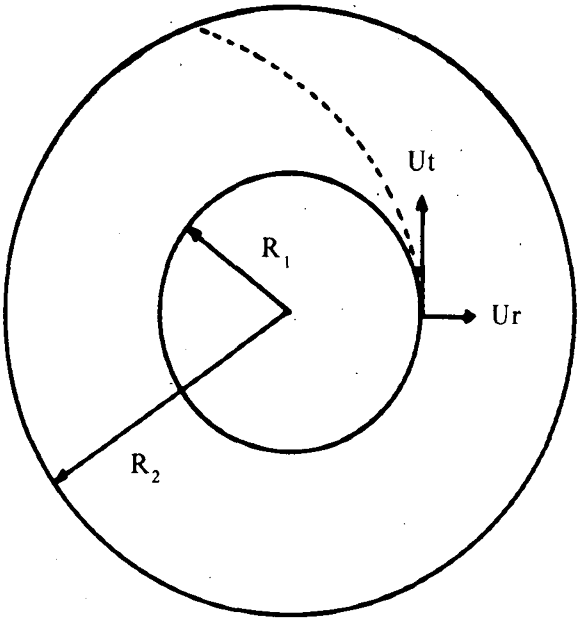

Figure 1. Trajectory of particles in a rotating Flow Field.

Clearly the Rosin model is an over simplification. Various refinements to this model have been made over the years but no single relationship has been proposed to embrace all the above factors.

One of the more recent refinements and that which is probably still of most use to the field engineer is due to Valentine (24) (former Professor fo Chemical Engineering at Natal). He incorporated the detailed flow measurements of TerLinden (23) into Rosin's treatment to give the formula:

$$X_{min} = \sqrt{\frac{18\mu d A_i}{\pi(\rho s - \rho)\, V_c\, D\, H}}$$

Although this is still an over simplification it does give us the correct information regarding the effects of the various factors on the collection efficiency.

It is convenient to describe the efficiency of any separator in terms of the grade efficiency. This can be defined as the efficiency with which a separating device removes a particular particle size. Figure 2 shows a typical grade efficiency curve for a well designed high gas rate cyclone separating a dust of density 2,5 gm/cm^3 from air (20). Using Valentine's formula one can translate this data to the system of interest. For example, for the removal of bagasse flyash of density 0,6 gm/cm^3 the abcissa of the grade efficiency curve should be moved to the right by a factor of

$$\sqrt{\frac{(\text{density of flyash - density of air})}{(\text{density of test powder - density of air})}}$$

i.e. 2,0.

TABLE I

Flyash Particle Size Analysis (3)

Size (micron)	Cumulative less than
500	99,94
420	99,32
250	97,26
149	90,88
105	84,05
74	78,59
53	67,84
35,1	57,89
28,8	54,20
17,1	44,76
11,4	31,07
6,9	19,67
4,3	11,28
2,5	4,07

The resulting curve is shown in Figure 3. This curve can now be compared with a typical flyash particle size analysis given in Table 1 (3) and it is clear that this particular cyclone design would be a poor solution to the air pollution problem resulting from flyash.

The efficiency of collection could be improved by modifications to the outlet pipe diameter or the diameter of the cyclone body etc and again Valentine's formula gives us a good rule of thumb method for estimating the effect.

An assessment of pressure drop is not as simple since the geometry of the cyclone has a profound effect. However if one is willing to stick to standard proportions (24,20) then the correlations of Lapple and Shepherd (18) are sufficiently accurate to give order of magnitude answers.

Target scrubbers

The venturi scrubber, dry target scrubbers, irrigated target (Peabody type) scrubbers depend principally on the inertial mechanism again. In this case it is the inertia of the dust/mist particles that carries the particles into collision with the target instead of swerving past it with the fluid. (In the case of the venturi scrubber, the targets are the water droplets injected into the throat of the device).

The principle is sketched in Figure 4 for a simple cylindrical target. The heavier particles will cross the streamlines and will impinge on the target. The fraction of particles contained within the streamtube AA in the sketch that strike the target gives us a measure of the target efficiency.

The calculation of target efficiency for simple shapes was first successfully performed by Sell in 1931 (17). He derived a set of equations of motion for a particle projected into a fluid moving uniformly in a given direction (see Figure 5). These he integrated to give the displacement (x,y) of the particle from the origin after a specified interval of time t:

$$x = \frac{mu}{k} \cos\alpha \left[\frac{kt}{m} - (1 - e^{-\frac{kt}{m}})\right] + \frac{V_o}{k}\beta(1 - e^{-\frac{kt}{m}})$$

$$Y = \frac{mu}{k} \sin\alpha \left[\frac{kt}{m} - (1 - e^{-\frac{kt}{m}})\right] + \frac{V_o}{k}\beta(1 - e^{-\frac{kt}{m}})$$

It is possible to solve these equations for the more complicated situation obtaining as the flow field bends and passes around an object by dividing the curved flow field into a large number of small regions assuming that in the small region the flow is essentially straight and solving the above equations in a stepwise manner.

The results of such laborious calculations have been displayed graphically in Johnstone and Roberts paper (8) in 1949 and also in modified forms in various texts (12,14) Figure 6 is a sketch of the general shape of the curve.

It is most instructive to examine these graphical results carefully. On the x axis the group being plotted is $\frac{mu}{kD_c}$

(D_c is the target size).For the case of fairly small particles which will probably be moving in Laminar or Stokian flow, the proportionally constant k can be replaced by $3\pi\mu D_p$ (D_p is the particle size) and the abcissa of the plot becomes

$$\frac{1}{18} \times \left(\frac{D_p^2 U P}{\mu D_c}\right)$$

The graph shows an increase in target efficiency with increase in this group. Hence one can roughly conclude that:

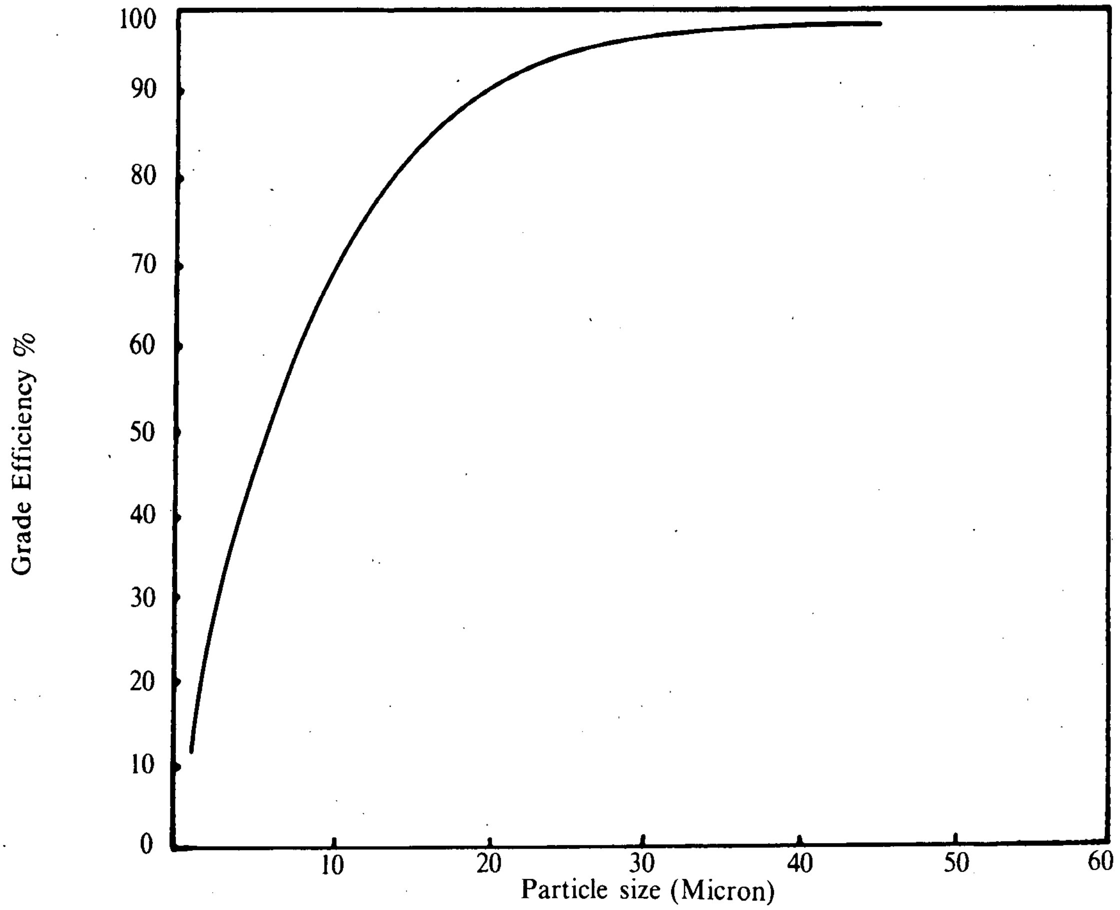

FIGURE 2 GRADE EFFICIENCY CURVE FOR A HIGH GAS RATE CYCLONE ([13]) — dust density 2,5 gm/cm^3

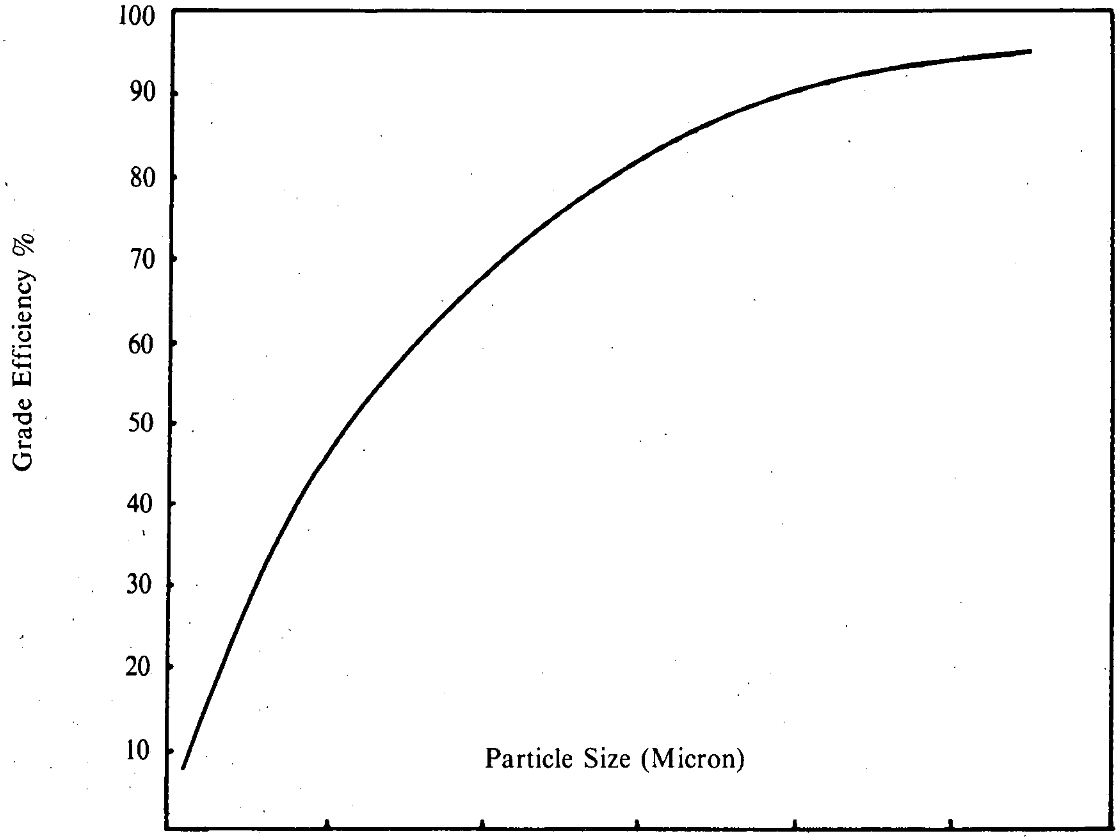

FIGURE 3 TRANSPOSED GRADE EFFICIENCY CURVE FOR A HIGH GAS RATE CYLONE — dust density 0,6 gm/cm^3.

1) Efficiency is proportional to D_p^2 (i.e. the square of the particle size)

2) Efficiency is proportional to $\frac{1}{D_c}$ (i.e. the reciprocal of the object size)

The first conclusion is perhaps quite obvious, one would expect that the larger the particle the more chance there is of it striking the target. Any means of agglomerating particles therby increasing the effective diameter Dp is clearly an important step.

The second conclusion is most suprising really, the smaller the target, the higher the target efficiency! The reason for this only really becomes apparent if one follows the whole mathematical argument leading to the results shown in Figure 6, however arguing heuristically, it is as a consequence of the reduced curvature in the streamlines approaching a small object as compared to the curvature for a large object.

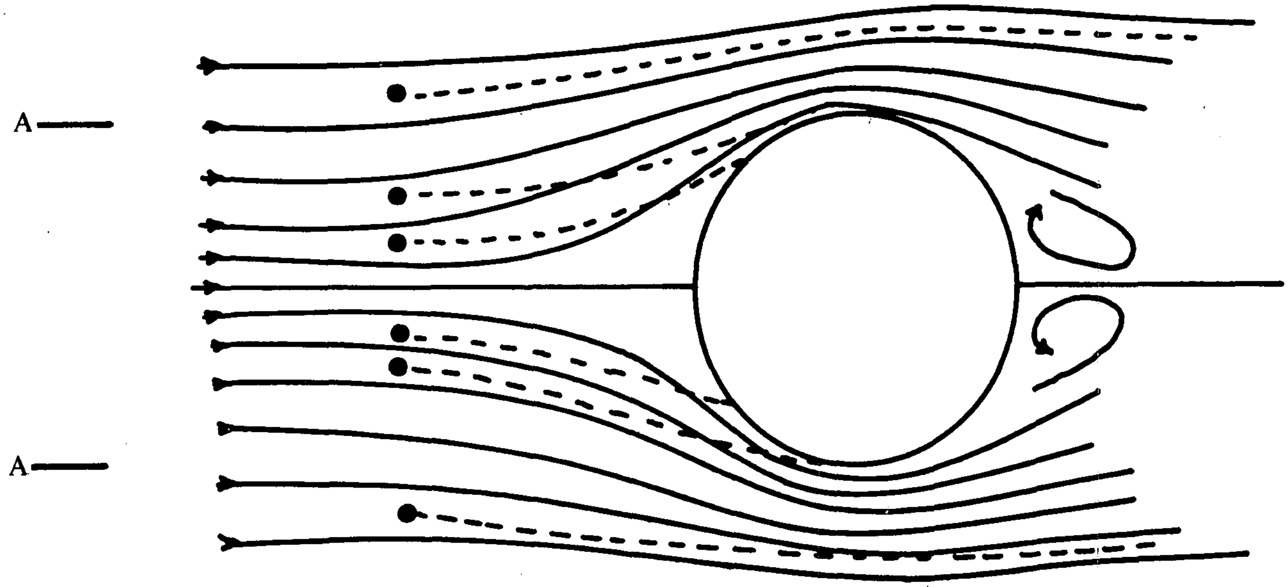

FIGURE 4: INERTIAL IMPACTION — Cylindrical Target.

Conclusion(2) has obviously got far reaching implications in scrubber design/selection when the scrubber relies on inertial impaction as a method of dust collection. Take for example a simple water spray chamber being used to scrub a dusty gas. The size of the dust particles Dp are generally beyond ones control, however a distinct improvement in collection efficiency can often be brought about by simply reducing the size of the water droplets D_C (one could achieve this by higher nozzle pressures for example). Of course there is always a limit beyond which any improvement such as this cannot go; in this case where the droplets are falling under gravity, then as one decreases the droplet size D_C, so one also decreases the relative velocity between the dust particles being carried in the gas and the falling droplet targets. An optimum droplet size can thus thus be calculated (19).

The efficiency of the venturi scrubber can also be discussed in the light of this analysis. High relative velocities (u) are achieved in the throat between the dusty gas stream and the injected water droplets. The relative velocities can be several times higher than obtainable in a simple water spray chamber if the throat and injection ports of the Venturi are well designed, hence with small Dc and large u, Sell's analysis correctly predicts high collection efficiency.

The cost of obtaining these high efficiencies is of course the increased pressure drop associated with Venturi scrubbers (19). Recent studies at Natal University (6) show that significant optmisation (costwise) can be achieved by careful selection of the inlet water pressure. Incidently these studies also show that particle diffusion is negligible in the venturi contrary to some opinions (21).

With very small particles or very large targets, Sell's classical analysis breaks down due to boundary layer effects, separation etc. Corrections have been proposed for these, notably by Albreich (1) but in principle they do not alter the kernel of the argument discussed above.

Electrostatic devices

The separating power of these devices can be described by an argument similar to that discussed above for cyclones, namely, will a given dust particle migrate sufficiently far under the influence of the electrostatic field during its residence time in the precipitator to reach the collecting electrodes? The answer to this depends on the following factors:

the susceptibility of the particle to become charged
the rate at which it migrates in the field
and the behaviour of the collected particles on the collecting electrode.

Only when the particle characteristics comply favourable with all three of these factors will an electrostatic precipitator be efficient.

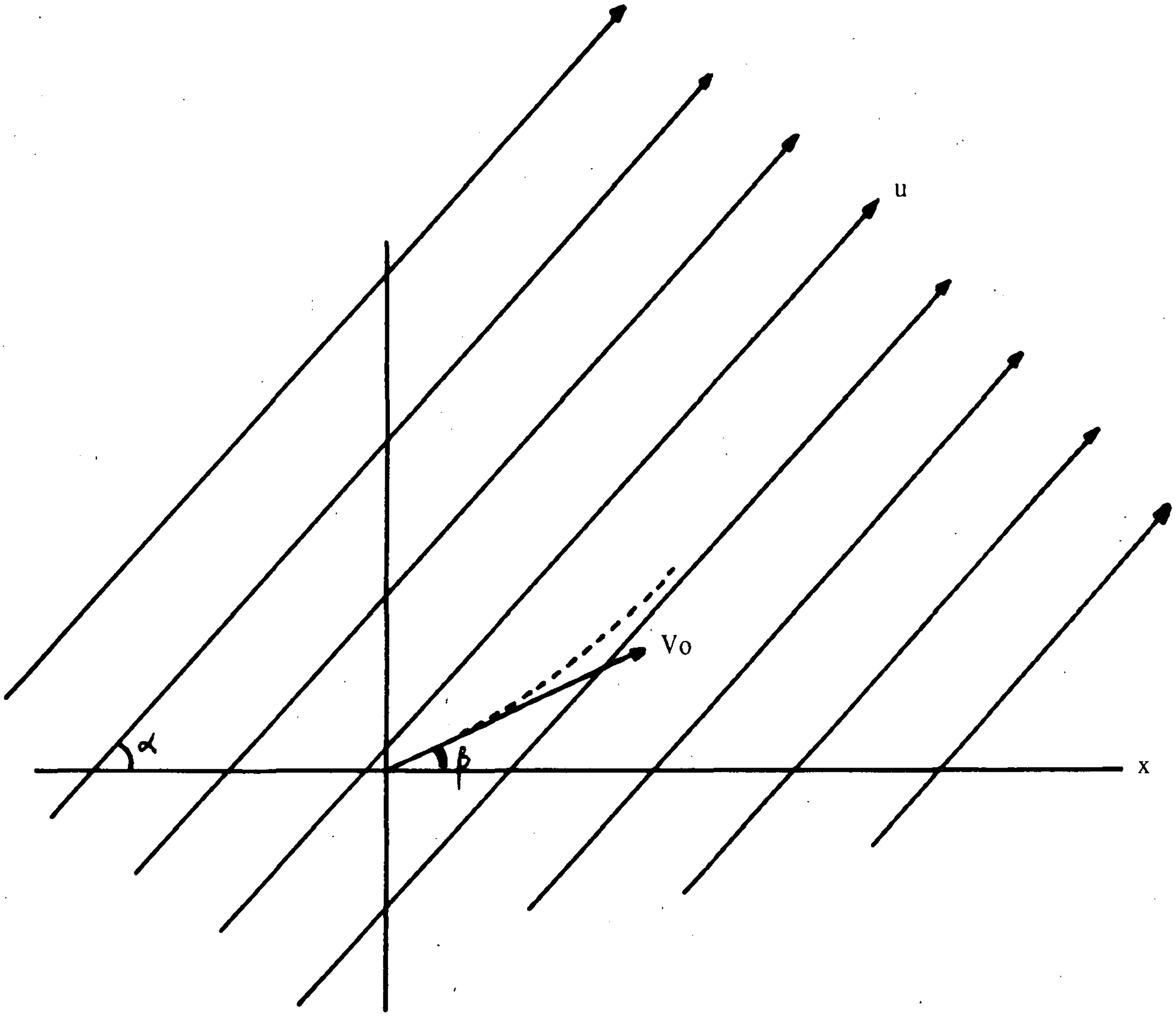

FIGURE 5: TRAJECTORY OF A PARTICLE PROJECTED INTO A MOVING FLUID

Particle charging

The rate of particle charging depends mainly on the electric field strength (E) associated with the corona discharge produced in the separator and the dielectric of the particle ( ). The effect of these two factors are conveniently described in Pautheniers equation (13)

$$q_t = \left[1 + 2\left(\frac{\epsilon - 1}{\epsilon + 2}\right)\right] \frac{E.\, D_p^2}{4} \left(\frac{\pi u' \eta \xi t}{1 + \pi u' \eta \xi t}\right)$$

The term containing t in this expression is often neglected in precipitator selection, the usual assumption being that the particle has achieved its limiting charge

$q_t \longrightarrow \infty$

However the published work of Lowe and Lucas (11) and also of Little (10) would suggest that this may be a considerable oversimplification in practice.

The field strength (E) in Pautheniers equation is well described at the present time, the corona discharge and the way this is modified by the mobility of the charged gas ions which are formed is an old problem in physics and is well described. Rose (15) for example quotes the following useful equations for two conventional designs.

$$E = \sqrt{\left(\frac{2i}{\mu_i'}\right)\left(1 + \frac{\epsilon Ar}{\epsilon + 2}\right)} \qquad \text{for wire/tube type}$$

$$E = \sqrt{\left(\frac{8iL}{\mu_i' w}\right)\left(1 + \frac{\epsilon Ar}{\epsilon + 2}\right)} \qquad \text{for wire/plate type}$$

Hence by measuring or estimating the dielectric of the particles and assuming limiting particle charge, one can obtain a fairly good idea of whether the particles will become reasonably well charged in the precipitator.

Migration

The original work of Deutsch ([4]) has for several decades been standard method of predicting the rate of migration to the electrodes. Coupled with an estimate of the particle charge and the critical dimensions of the precipitator, Deutsch produced his well known efficiency equations:

$$\zeta = 1 - \exp\left(- \frac{2w\,L'}{R\,Vg}\right) \quad \text{for wire/tube type}$$

$$\zeta = 1 - \exp\left(- \frac{w\,L'}{RVg}\right) \quad \text{for wire/plate type}$$

These are also known as the "exponential law" equations

The migration velocity or drift velocity w is given by Deutsch as:

$$w = \sqrt{\frac{2q\ CE}{C_d\ A_\rho}}$$

However it is well known ([22,15,2]) this is really just a fudge factor and that real drift velocities are much different from the above relation. Nevertheless the concept of drift velocity is an easy one to grasp and for years electrostatic precipitator vendors have been quoting w. Precisely how they calculate it is a closely guarded secret.

Recently some fundamental work on improving Deutsch's formula for drift velocity has been published, the most notable work being due to Williams and Jackson ([27]) and Cooperman ([2]). The important concept introduced by these workers is that in addition to the migration towards the collector electrode, one has to account for back diffusion of the particles due to turbulence. A direct comparison between these recent publications and the Deutsch treatment is not easy, the essential message is that Deutsch's correlation is over-optimistic under tubulent conditions.

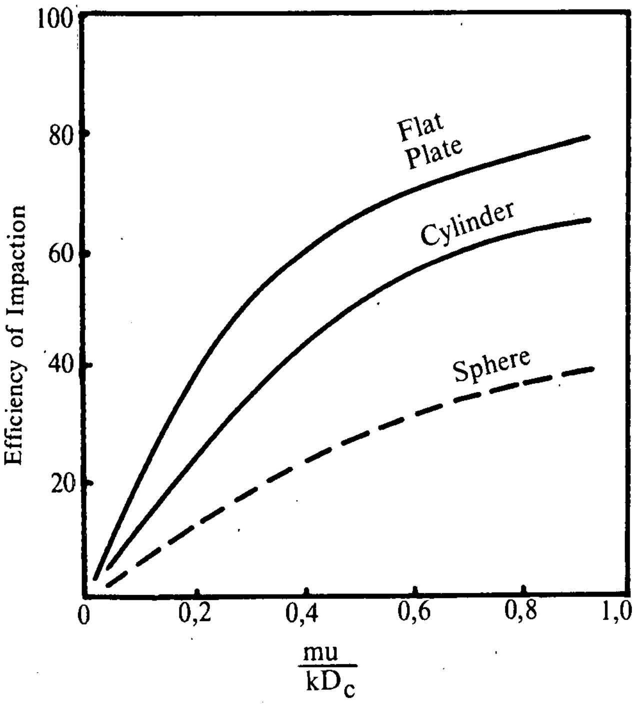

FIGURE 6: INERTIAL IMPACTION EFFICIENCY

One other serious criticism is that electrostatic precipitators are found in practice to be far less size sensitive than would be expected from the drift velocity concept. Heinrich ([5]) for example show experimentally that particles above about 5 micron are collected with much the same efficiency.

In conclusion we do not have a simple description of the particle trajectory yet. The manufacturers still sell their wares quoting the exponential law but as discussed above this has some serious limitations.

Particles on the collector electode

Some particles stick nicely to the collector plates and drop off obediently into the dust hopper with a gentle tap, other particles no sooner have they touched the collector are immediately repelled and re-entrained into the stream, others hop along the plate being alternately repelled/attracted, while some particles stick so well that actual water washing of the plates is required. Indeed the overall collection efficiency of the device is frequently controlled by the behaviour of the particles on the collector electrode ([15]).

It is prudent to read widely in this connection as the particle sticking characteristics can be effected profoundly by a few parts per million of the right substance. For example extraordinary increases in efficiency have been reported by adding traces of SO_3 to flyash collectors ([25]); also great improvement to cat cracker catalyst collection has been reported by adding a trace of NH_3 ([26]).

Conclusion

The choice of the right collector for a dust/mist problem is not an easy task. The efficiency with which particles can be removed depends strongly on the physical properties of the particles such as density, dielectric, size and so on. There is no cheap panacea for all dust problems and indeed the cost of scrubbing is an almost unique function of the desired efficiency. This is clearly shown in the plot of relative costs against efficiency in Figure 7. ([19])

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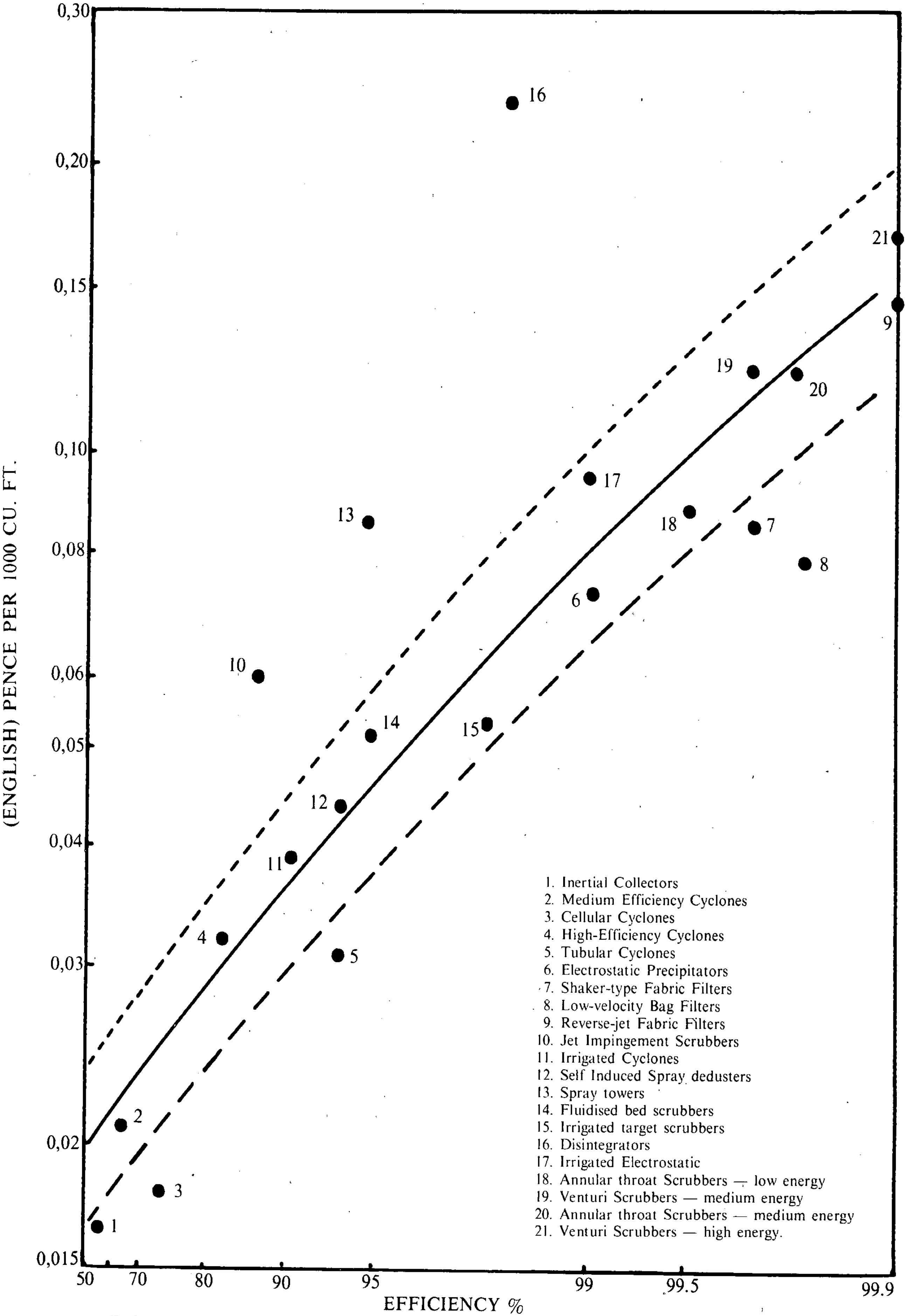

FIGURE 7: RELATIVE COSTS OF GAS CLEANING (4)

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Nomenclature

A	Surface area of all particles in unit volume
A_i	Inlet X-sectional area
C	Cunningham correction factor
C_d	Drag coefficient
d	Outlet diameter
D	Cyclone diameter
D_p	Particle size
D_c	Target size
E	Electric field strength
H	Total height of cyclone
i	Corona current
k	Proportionality constant between relative velocity and drag
L	Distance between wire and plate
L'	Length of collector
m	Mass of particle
N_t	Number of turns of dust particle in cyclone (~3 to 5)
q_t	Electric charge on particle at time t
r	Radial position of particle in electrostatic device
R	Distance between electrodes
R_1,R_2	Radial position entering, leaving
S	Distance of particle from cyclone wall (R^2 - R.)
t	Time
u	Relative velocity between particle and target
u_i	Mobility of ions
V_g	Gas velocity
V_o	Initial dust particle velocity
V_c	Inlet velocity
W'	Distance between successive wires
w	Drift velocity
x,y	Displacements, in x, y directions
Xmin	Smallest particle to be collected
α,β	Flow directions, see Figure 5
ϵ	Dielectric of particle
ρ	Density of gas
ρ_s	Density of dust particle
μ	Viscosity of the gas
ξ	Electronic charge.