AIR CLASSIFIERS

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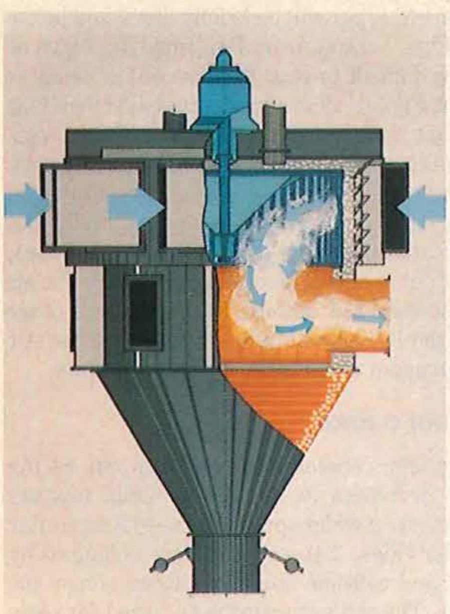

Although there are a great many devices that use air to separate particles by size, they are all based on a few general principles. Here is a rundown on the way that they operate, together with a description of the principal types of classifiers available.

Classification is the separation of a particulate material into a coarse and a fine fraction; the separation is usually by size, but may also be by other particle properties such as density. Depending on the equipment used, classification might also be affected by particle shape, electric, magnetic and surface properties, and other factors.

For example, density is insignificant when using screens or sieves, but is a major factor in air classifiers where fluid-drag forces are involved, as will be discussed later.

Classification should be distinguished from solid–fluid separation, although the two operations overlap and the terms are often used interchangeably. For example, cyclones are considered separation equipment even though a superfine fraction is entrained in the outlet gas and might be recovered in another separation step — as in a bag filter downstream.

(Although cyclones are very efficient particle–fluid separators in a medium size-range, they have a low classification efficiency. This efficiency will be defined later.)

This article is limited to air classifiers that are also called, traditionally but less appropriately, air separators. In such equipment, classification in the medium to submicrometer particle range — 1,000 - 0.1 μm — is effected in a stream of gas, using a combination of any of the following forces: gravity, drag, centrifugal and collision. Classification can be done in any gas, but air is used in the overwhelming majority of cases. However, other gases are advantageous under special conditions, e.g., nitrogen or flue gases if the solid material is highly explosive.

Other classifier devices, such as grates and screens that operate in the large to medium particle-size range (500 mm down to 0.1 mm), will not be considered in this article.

Early classifiers

Classification equipment evolved from two sources, the simple expansion chamber and the Mumford and Moodie Separator. In the former, coarser particles drop out of an air stream as its velocity is decreased upon expanding to a larger space. Baffles, vanes or other directional and impact devices were later incorporated in the expansion chamber to change the air direction and provide collision surfaces to knock out coarser particles.

The Mumford-Moodie Separator, patented in 1885, is similar to the Sturtevant Whirlwind (Fig. 9). Solids are fed into a rising air stream, using a rotating distributor plate that imparts a centrifugal force. Coarser particles drop into an inner cone; the fines are swept upward by the action of an internal fan, separated from air between vanes in the expansion section of the outer cone, and collected at its bottom. The air is recirculated up toward the distributor.

Unlike the Mumford-Moodie machine, the Whirlwind enhances separation by an additional rejection device (called either selector blades or a secondary-, auxiliary- or counter-fan) that knocks out most of the remaining coarse particles. Thus, the Whirlwind incorporates almost all the features used (in modified form) in the later air classifiers.

Based on a paper presented at the May 1984 meeting of the Belgian Engineering Soc. in Brussels.

Modern equipment types

Equipment classification

Air classifiers can be conveniently grouped by the following criteria (see the table on the opposite page):

- Forces that act on the particles. These are gravity, the drag force of air, the centrifugal force exerted either by an air vortex or a mechanical part such as a rotating distributor plate, and collision force, effective when a particle hits a solid surface. Collision force becomes an important classification factor in machines equipped with a rejection device that is part of the rotor. The rejector preferentially knocks out coarser particles entrained by the air. The presence of a rotor is indicated by a positive entry in Column 2 of the table . The table specifically lists only centrifugal forces (Columns 3, 4); the other forces are always present. However, some forces may be insignificant in certain cases. Examples are collision force in expansion chambers, (Item 1) and gravity in classifiers having a horizontal rotor axis (Item 19).
- Relative velocity and direction of the air and the particles controlled by the solid feed system, air vector and position of the rotor if present (Columns 5, 6 and 2, respectively). If particles enter the classifier with the air, the coarser ones will separate as the drag force is overcome by gravity (and possibly centrifugal and collision forces). But, if the solids are fed separately, fines will be swept away by the air, since the drag force prevails (if the feed is properly distributed).
- Directional devices, such as vanes, cones, or zigzag plates, that change flow patterns of the air or particle–air mixture and provide collision surfaces (Column 7).
- Location of the fan and the fines-collection device (Columns 8,9). Although these do not directly affect the separation process, they are important control and design factors. For example, the inside collection of fines in the expansion section of the Whirlwind (Fig. 9) is less efficient than the outside fines separation in the cyclone dust-collector that is part of the external air-recycle loop (Figs. 1,2). Independent airflow control is difficult if the fan is mounted on the same shaft as the feeder plate and selection blades, as in the Whirlwind. Separate shafts (possibly concentric, Fig. 12) can overcome the problem, but an outside fan (Figs. 2,11) simplifies design and allows precise control of the air flowrate.

Individual equipment types will be briefly discussed below with reference to Figs. 1 through 19. Published drawings of some classifiers are difficult to read because of the complex internal design, but Figs. 1–19 are conceptual sketches that emphasize important features rather than showing engineering details. Principal parts, such as distributors, shafts, and the flat surfaces of vanes and blades, are drawn in contours, whereas minor items, such as spokes, walls and partitions, are indicated by single lines only. Furthermore, some parts are left out to show the passage available for air or particles, e.g. spokes, fan details, hub walls and other rotor elements on the left side of symmetrical sections. Air flow inside the equipment is indicated by heavy arrows.

Classifiers without a rotor

In expansion chambers, coarser particles drop out as the linear air velocity decreases (when the air–solid mixture expands from a duct into a wider space). In the grit separator and zigzag classifier (Figs. 3,4), separation is enhanced by tortuous passages and collision surfaces placed across the particle trajectories. The grit separator is designed for separating small amounts of fines from the bulk of coarse material. Linear air velocity is controlled by moving the buoy, or "definer cone" up or down. In the rotary drum classifier (Fig. 5), the rotational movement stirs the solid mass to facilitate disengagement of coarse particles from

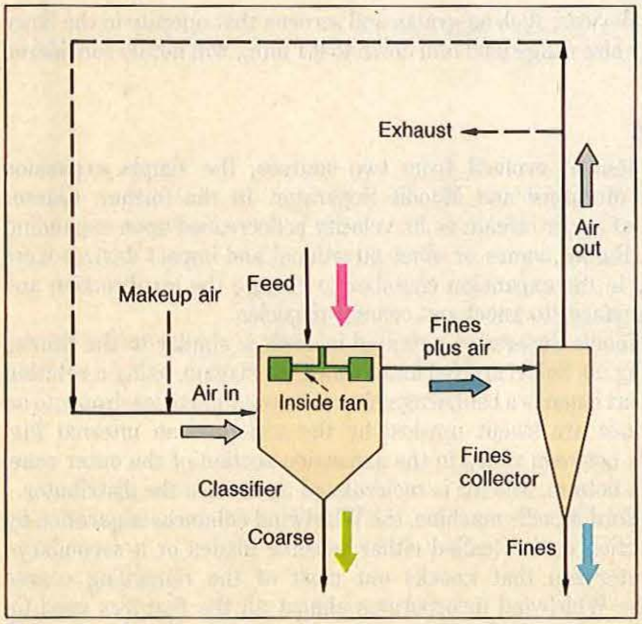

Figure 1 — Classifier System with outside fines collector (Sturtevant Superfine Air Separator)

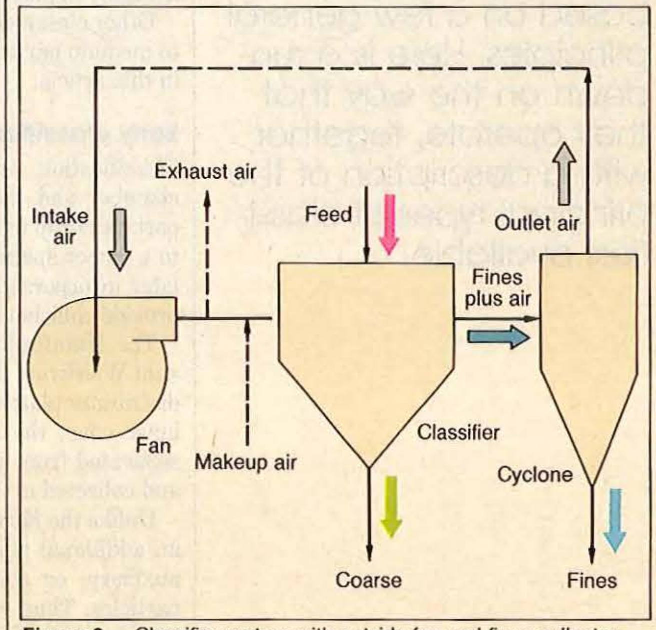

Figure 2 — Classifier system with outside fan and fines collector — broken lines indicate optional air-recycle subsystem (Sturtevant SD)

Table — Air classifiers: devices for separating particulate material into a coarse and a fine fraction, using a gaseous entraining medium

No.	Rotor axis (if any)	Plane of centrifugal force generated by: Air	Plane of centrifugal force generated by: Feeder	Solid feed system	Principal air direction	Stationary directional device	Inside or outside[a]: Fan	Inside or outside[a]: Fines collector	Example of classifier (separator)	Maximum capacity,[b] t/h	Maximum energy	Fig. No.	Ref.
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	None	None	None	Air	Various	None	Out	Out	Expansion chambers	Plant	—	—	1
2	None	None	None	Air	Vert.	Buoy[c]	Out	Out	Sturtevant Grit	500	130 m³/s	3	2
3	None	None	None	Chute	Vert.	Zigzag plates	Out	Out	Alpine Zigzag	100	NA	4	3
4	None	None	None	Belt	Horiz.	None	Out	Out	Iowa Mfg. Rotary Drum	50	16 m³/s	5	4
5	None	Vert.	None	Air	Vert.	Incl.	Out	Out	General Electric Buell	Plant	460 m³/t	6	5
6	None	Vert.	None	Air	Vert.	Incl.[c]	Out	Out	Hukki Centrifugal	Plant	NA	7	6
7	None	Horiz.	None	Air	Horiz.	Ports[c]	Out	Out	Hardinge Double Cone	Plant	NA	8	7
8	None	Horiz.	None	Air	Horiz.	Vert. pipe	Out	In	Cyclones[d]	Plant	24 m³/s	—	8
9	Vert.	None	Horiz.	Rotor	Vert.	None	In	In	Sturtevant Whirlwind	2,700	600 kW	9	9
10	Vert.	None	Horiz	Rotor	Vert.	None	In	Out	Sturtevant Superfine	5	75 kW	10	9
11	Vert.	None	Horiz.	Rotor	Vert.	None	Out	Out	Humboldt Wedag Cyclone Air	1,500	1,000 kW	11	10
12	Vert.[e]	None	Horiz.	Plate[e]	Vert.	None	In[e]	In	Polysius Turbo	Plant	NA	12	11
13	Vert.	Horiz.	None	Air	Vert.	None	Out	Out	Donaldson Majac	6	NA	13	12
14	Vert.	Horiz.	None	Air	Horiz.	Vert. vanes	Out	Out	Onoda O'SEPA	1,400	800 kW	14	13
15	Vert.	Horiz.	None	Chute	Horiz.	None	In	Out	Donaldson Acucut	0.01	6 kW	15	14
16	Vert.	Horiz.	Horiz.	Rotor	Horiz.	None	In	In	Alpine Microplex MPV	13	30 kW	16	3
17	Vert.	Horiz.	Horiz.	Rotor	Horiz.	Vert. vanes	Out	Out	Bauer Centri-Sonic	10	56 kW	17	15
18	Vert.	Horiz.	Horiz.	Rotor	Horiz.	Cones[f]	Out	Out	Sturtevant SD	1,400	500 kW	18	16
19	Horiz.[g]	Vert.	None	Chute	Vert.	None	In	Out	Alpine Microplex MP	1.6	19 kW	19	3

Notes: Vert. = vertical; Horiz. = horizontal; Incl. = inclined; NA = not available;
a. Classifier systems with outside fan and fines collector are shown in Fig. 2; those with inside fan and outside fines collector are shown in Fig. 1.
b. If precise capacity is not known, or dependent on specific model, "Plant" denotes up to approximately 100 tons/h.
c. Adjustable
d. Because of low classification efficiency, cyclones are not considered to be classifiers.
e. Fan is independent of rotor with feeder and selector blades.
f. Alternatively horizontal vanes or none.
g. Gravity not used in classification.

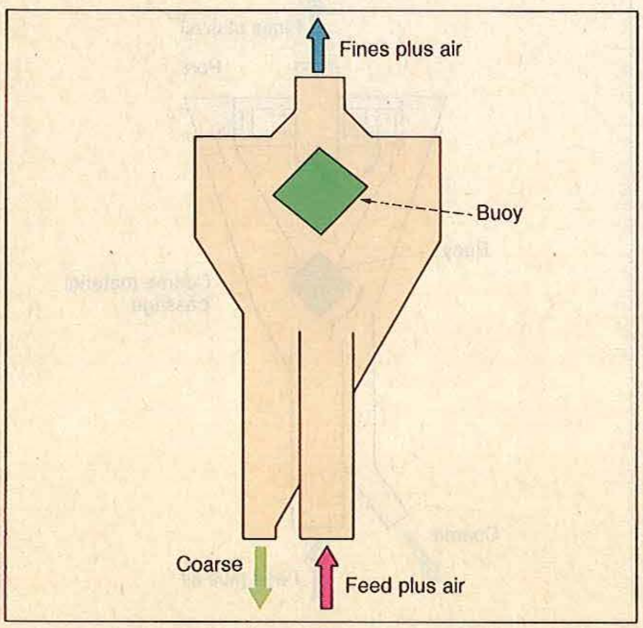

Figure 3 — Diagram of the Sturtevant grit separator

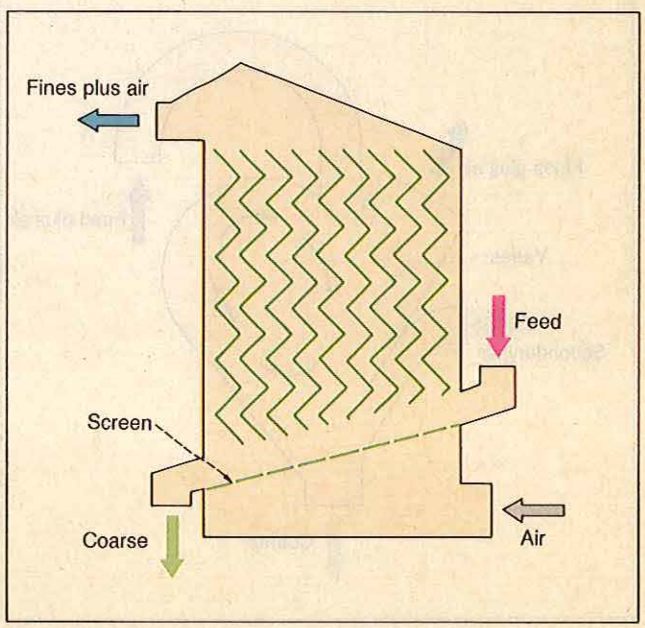

Figure 4 — Alpine Zigzag cassifier employs tortuous passages

fine ones that are then entrained by the air and dropped out upon expansion in the fines collector.

The gravitational-inertial and centrifugal classifiers (Figs. 6,7) use the centrifugal force generated by the rotational flow of air that is directed by wall curvatures and vanes. The Hukki machine has adjustable vanes and a horizontal air-outlet virtually perpendicular to the plane of rotation. In the double cone classifier (Fig. 8), air develops a rotational flow as it passes through adjustable peripheral ports in the upper part of the inner cone. Unlike the grit separator's buoy, this device's buoy serves as an air lock for the coarse material, that flows down after being separated in the inner cone.

Updraft and sidedraft classifiers

The classifiers of Figs. 10–12 are modifications of the Whirlwind (Fig. 9). We call them updraft machines because the principal air direction in the critical separation zone is vertically upward. The central part of the rotor is a hollow hub suspended on a vertical shaft. (Only selected elements of the hub are indicated in the figures.) Two plates, an upper and a

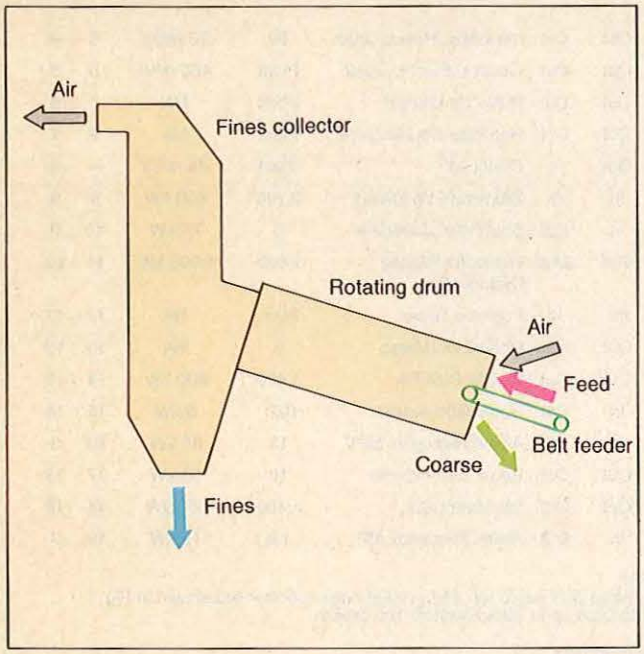

Figure 5 — Iowa Manufacturing Co.'s rotary drum classifier

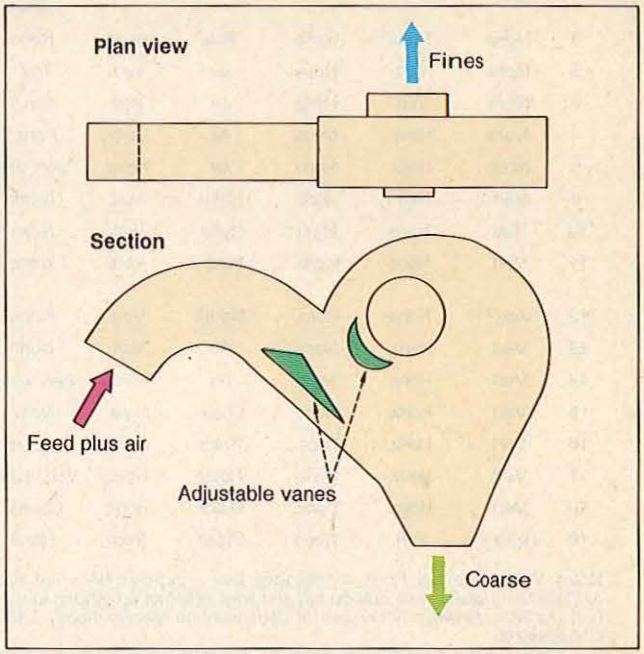

Figure 7 — Hukki centrifugal classifier uses rotating airflow

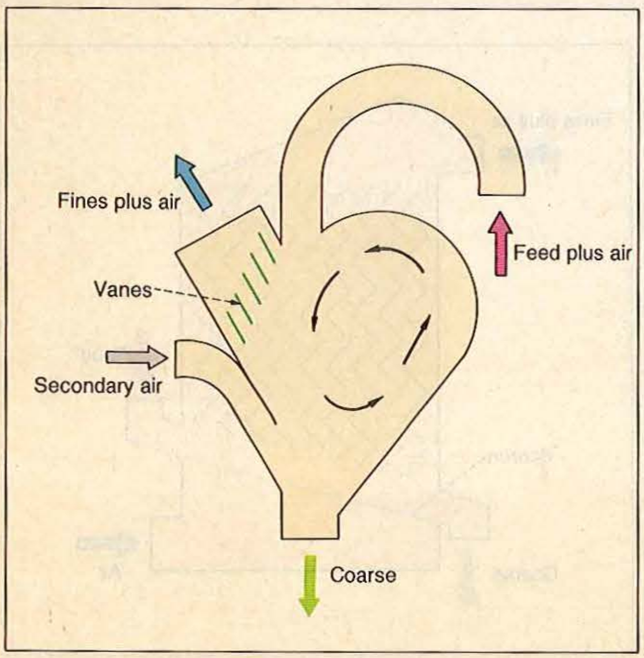

Figure 6 — General Electric Buell gravitational-inertial classifier

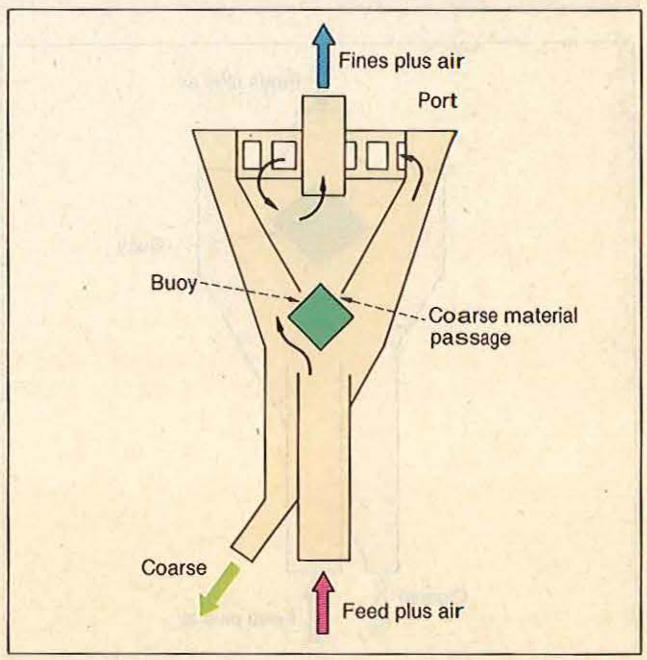

Figure 8 — Hardinge double cone classifier also uses rotating airflow

lower, are mounted on the hub; the upper plate provides support for the selector blades. The Whirlwind and Superfine air separators have a fan mounted on the upper part of the hub; the Turbo Separator has a separate fan shaft. The cyclone air separator has an outside fan (see Fig. 2).

The material, fed via a top or side chute, passes along the shaft and through ports in the hub wall to the lower distributor plate, which spreads the feed into the ascending air. The coarse particles either drop directly or are rejected by the selector blades into the inner cone; fines are carried over to the vessel's top. The upper plate redistributes any rejected particles toward the shaft. In the Whirlwind and Turbo classifiers, fines are then swept down the annular space along the wall of the external cone, and are collected at the bottom. Air, separated from the fines in the expansion section and between the vanes, is returned to the rotor. In the Superfine (Fig. 1) and cyclone (Fig. 2) classifiers, fines are separated in outside collectors. The Majac Air Classifier (Fig. 13) operates on the same principle as the cyclone classifier (Fig. 11) except that feed is introduced in a stream

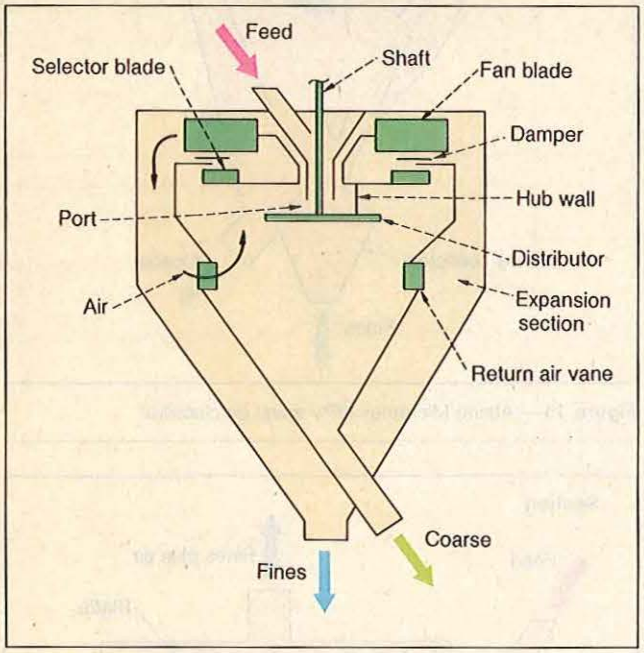

Figure 9 — Sturtevant Whirlwind air separator

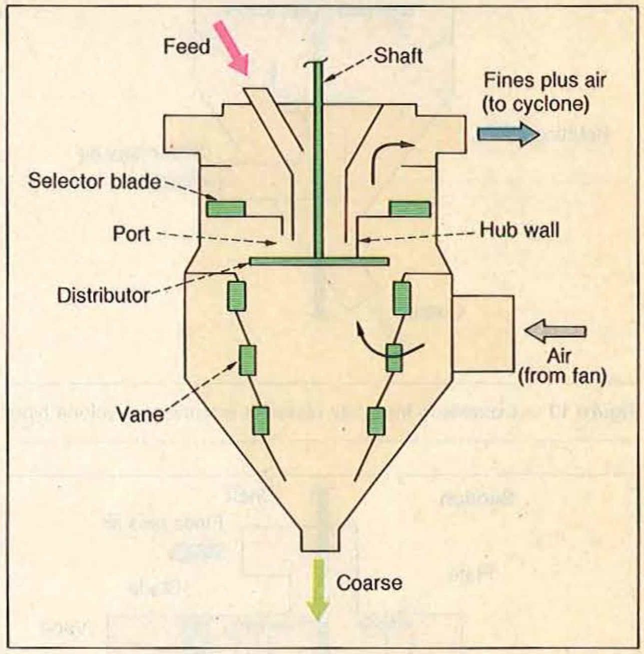

Figure 11 — Humboldt Wedag cyclone air classifier

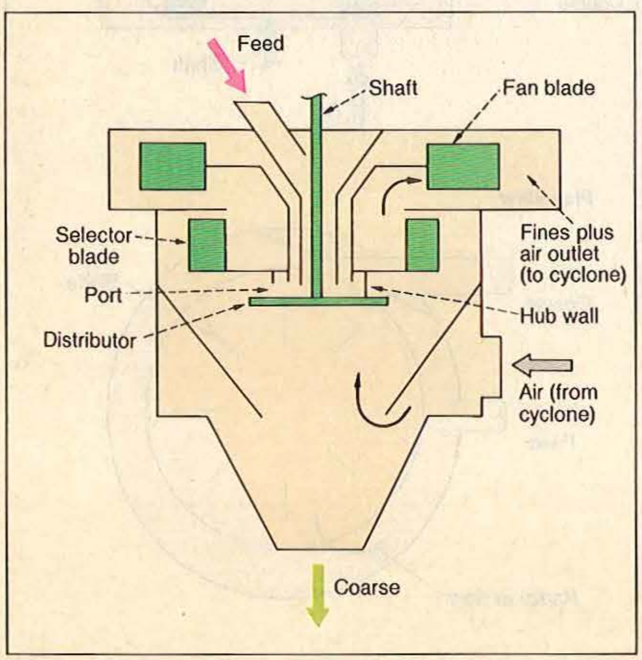

Figure 10 — Sturtevant Superfine separator—a modified Whirlwind

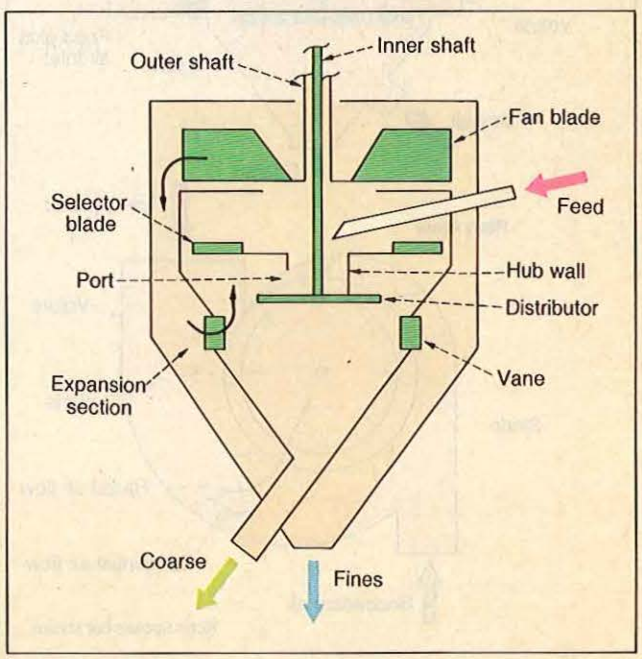

Figure 12 — Polysius Turbo separator has separate fan shaft

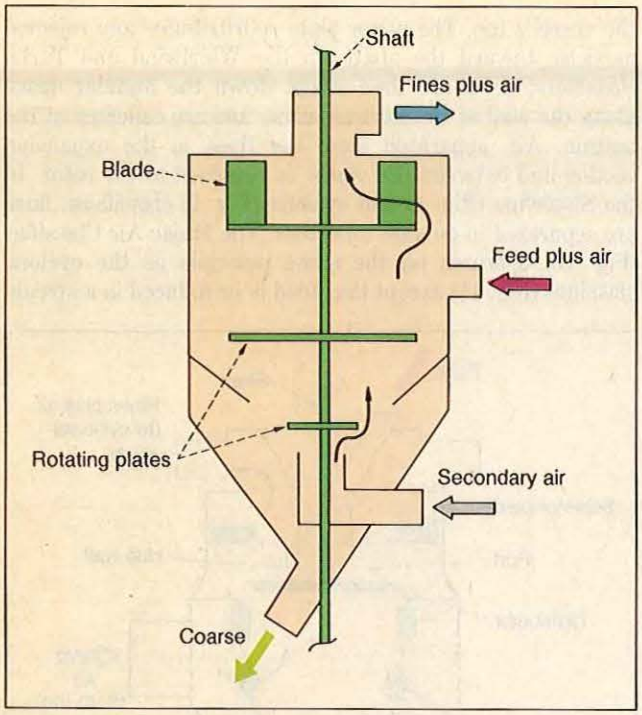

Figure 13 — Donaldson Majac air classifier is similar to cyclone type

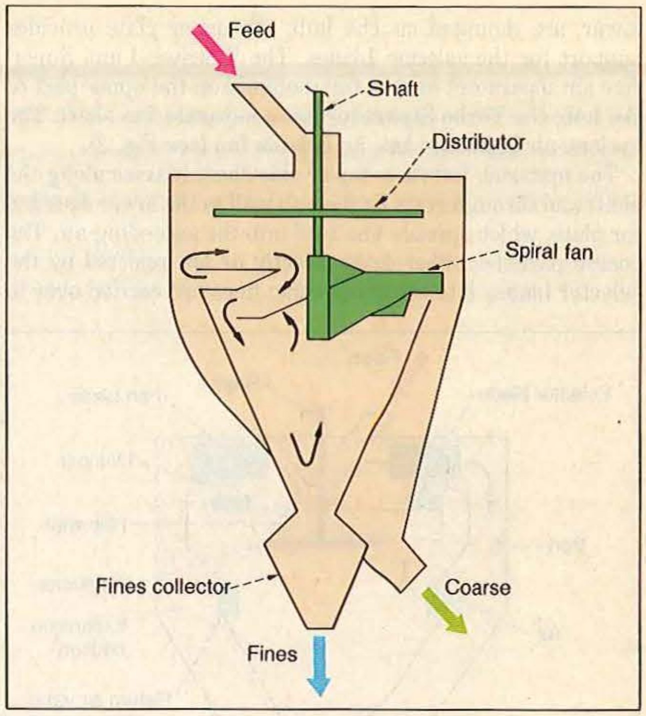

Figure 15 — Alpine Microplex MPV spiral air classifier

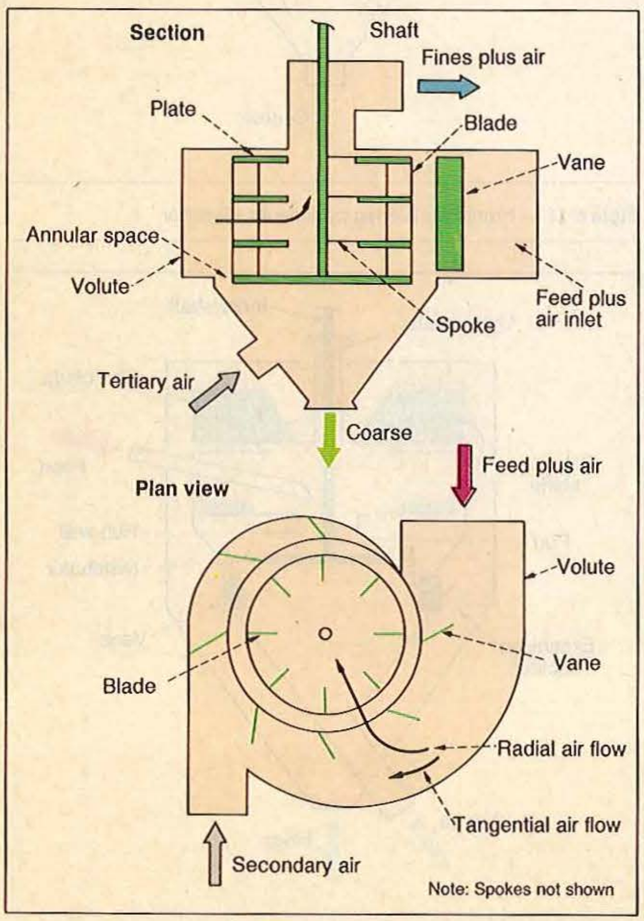

Figure 14 — Onoda O'SEPA air separator uses an external collector

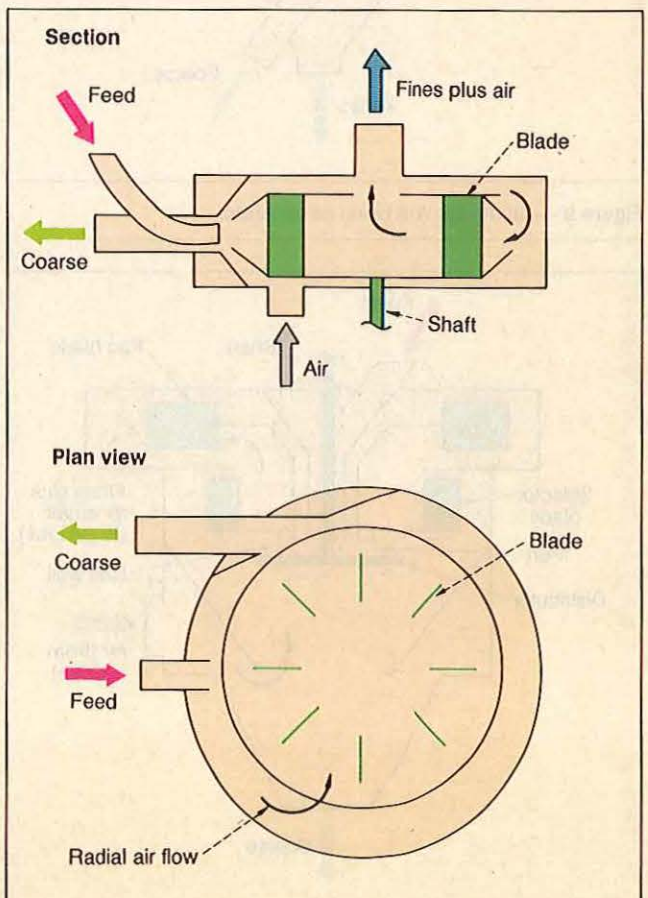

Figure 16 — Donaldson Acucut laboratory classifier

of air. The secondary air and the rotating plates have functions similar to the Whirlwind's return air and upper plate.

Classifiers that have a horizontal air-stream acting on the particles are conceptually different from the previous machines. (Plant-size machines with a rejector will be called side-draft equipment in this article.) In the O'SEPA, Centri-Sonic and SD classifiers (Figs. 14,17,18), all or most of the air is blown (by an outside fan) tangentially through a volute that provides an even radial distribution. Particles carried by the air (in the O'SEPA) or thrown horizontally into the air stream by a distributor (in the other two machines) are classified in a narrow separation zone in front of the rotor.

Coarse particles drop through the annular space between the rotor and volute into one or more collection cones, either directly or after being rejected by the blades or pins of the rotor. Fines are swept inside the rotor and pass to external collectors either through a top discharge (O'SEPA), bottom air-swept volute (Centri-Sonic), or streamlined by horizontal vanes or inclined deflector cones (SD). The cones have the additional advantage of preventing particles from leaving the narrow separation zone before the radial air stream can act on them. The O'SEPA and Centri-Sonic horizontal rotor plates are claimed also to have a streamlining effect.

Miscellaneous equipment

The remaining air classifiers have diverse designs. The Acucut Laboratory Classifier (Fig. 16) feeds material, by gravity, radially against a rejector into an air stream that has a virtually horizontal direction in the separation zone. The air is sucked in from the bottom, and entrained fines leave the classifier through the top and pass to an outside collector; coarse product is rejected tangentially. The fan is downstream from the collector.

The Microplex MPV Spiral Air Classifier (Fig. 15), with its inside fines collection, can be considered a modified Whirlwind-type, with a horizontal air flow in the separation zone. It differs, of course, in that the fan also acts as a rejector, the distributor is above it, and the fine and coarse products separate in the inside and outside cones, respectively.

The Multiplex MP Spiral Air Classifier has a fan mounted on a horizontal shaft (Fig. 19). Material is fed by gravity between the fan and a vertical distributor plate. Air is introduced into the same space from the bottom. Entrained fines leave tangentially from the top. The coarse product is rejected vertically and removed by a horizontal screw located at the top of the machine, off the feed chute.

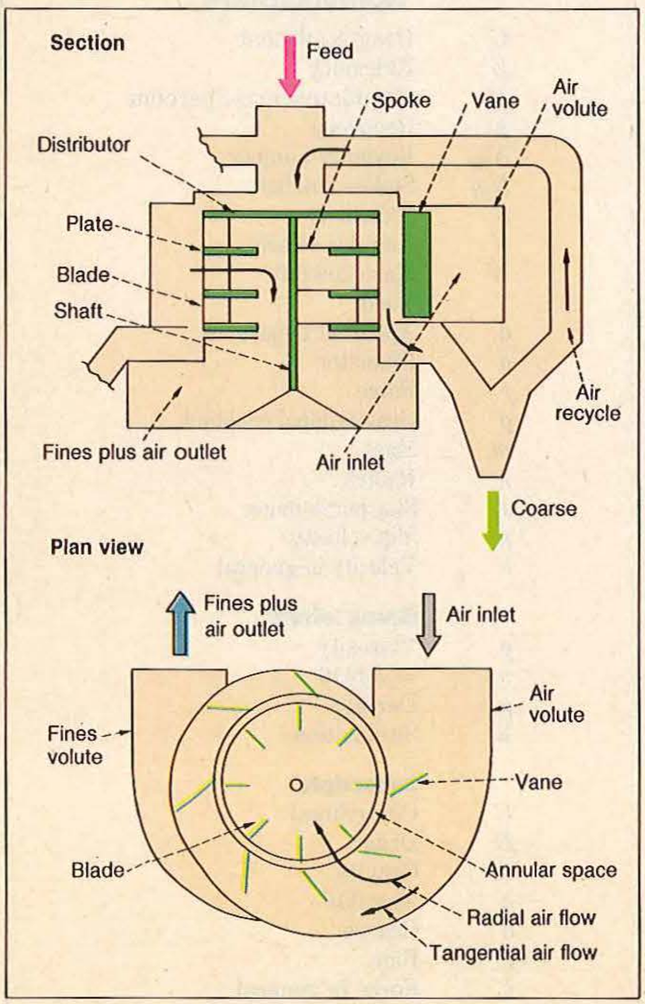

Figure 17 — Bauer Centri-Sonic classifier is a side-draft type

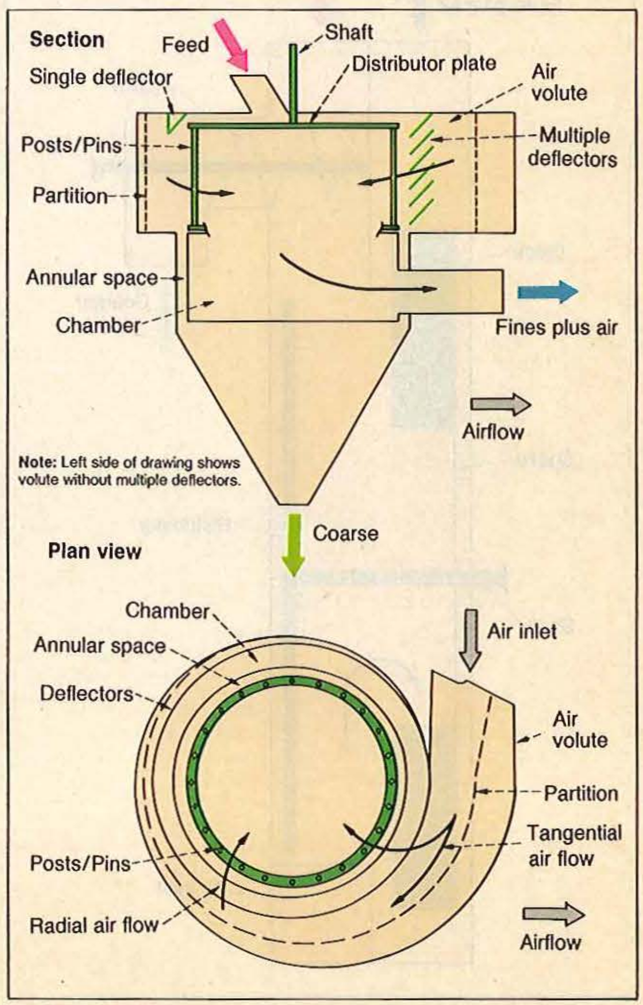

Figure 18 — Sturtevant SD classifier—another side-draft type

Particle dynamics

Bases for design

Classifier designers take advantage of a number of phenomena: small particles fall more slowly in air than do large particles; larger particles have a greater centrifugal force in cyclonic flow than do small particles; smaller particles have less inertia and can change their direction of flow easier than can large particles; larger particles require a higher conveying velocity; and larger particles have a higher probability of collision with a rotating blade. A classifier is designed so that there is a minimum of material interference among the particles in the classification zone.

Forces

Forces acting on the individual particles are responsible for directing large and small particles into their respective collection chambers. The forces that act on particles during air classification are: (a) gravity, (b) aerodynamic drag, (c) centrifugal force, and (d) collision force. Each of the various types of equipment uses one or more of these forces. The interplay among these forces is complex and not very well understood. Hence, no comprehensive mathematical model is available to describe air classifiers.

The forces in action

All the forces listed above are used by the Sturtevant SD Classifier (Fig. 18), so this device will be taken as an example in the following discussion. Furthermore, in this machine, centrifugal forces are caused by both the rotor and the flow of air through the volute, unlike the forces in updraft classifiers.

(The individual expressions for the forces will be valid for other air classifiers. However, the directions of the force vectors may be different and some of the forces may not be necessary.)

The feed is introduced into the Sturtevant SD Classifier at the center of a horizontal rotating feedplate. Friction with

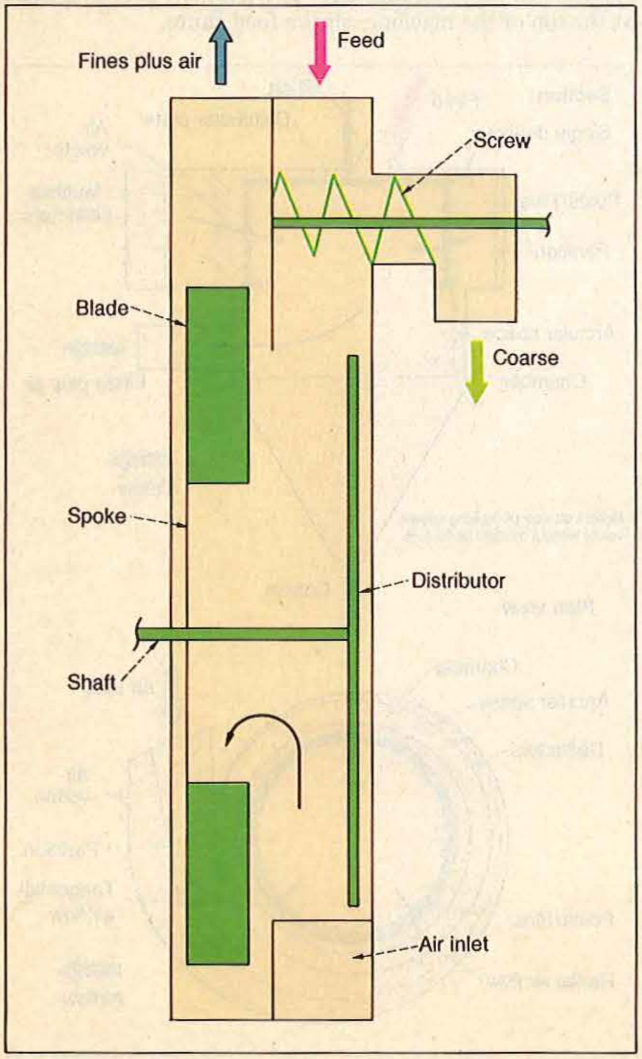

Figure 19 — Alpine Microplex MP spiral air classifier

Nomenclature

C	Drag coefficient
E	Efficiency
M	Cumulative mass percent
R	Recovery
N_{Re}	Reynolds number
N_{St}	Stokes number
S	Selectivity
V	Angular velocity
W	Mass flowrate
Y	Yield
a	Apparent bypass
d	Diameter
f	Force
g	Gravitational constant
m	Mass
r	Radius
s	Sharpness index
u	Slip velocity
v	Velocity in general
	Greek letters
μ	Viscosity
π	= 3.1416
ρ	Density
Σ	Summation
	Subscripts
C	Centrifugal
D	Drag
G	Gravity
a	Angular
c	Coarse
f	Fine
i	Force in general
k	Capture

the plate accelerates the particles radially. Once the particles have an angular velocity, their centrifugal force accelerates them and they bounce and roll to the outside edge of the feedplate, where they fall off. The final velocity attained by the falling particles will approach that of the angular velocity of the outside edge of the feed distributor plate. The direction of this velocity vector is tangent to the circumference of the distributor plate.

Once in the air, the particles encounter gravity, aerodynamic drag and centrifugal force vectors, $\overline{f}_i$, that change the velocity vector, $\overline{v}$, both in direction and in magnitude, according to Newton's Second Law [17].

$$\sum_i \overline{f}_i = m\, d\overline{v}/dt \qquad (1)$$

where m is the mass of the particle (also $\rho\pi d^3/6$ for a sphere of diameter d and density ρ). The gravity force, $\overline{f}_G$, will be directed downward in the classifier, as shown in Fig. 20, and will be given by [17]:

$$\overline{f}_G = m(\rho - \rho_{Air})\overline{g} \qquad (2)$$

where $\overline{g}$ is the gravitational constant.

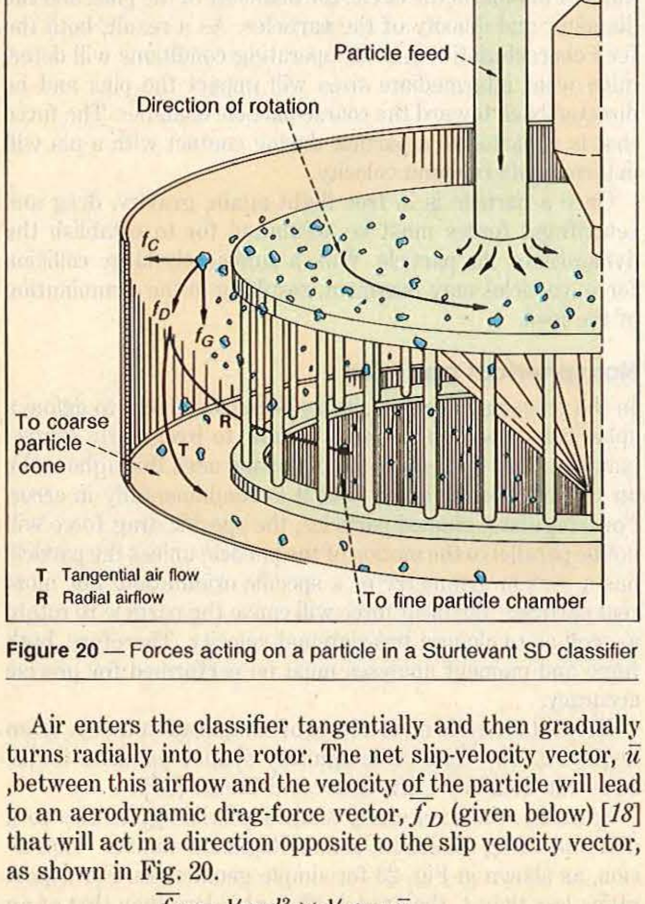

Figure 20 — Forces acting on a particle in a Sturtevant SD classifier

Air enters the classifier tangentially and then gradually turns radially into the rotor. The net slip-velocity vector, $\overline{u}$, between this airflow and the velocity of the particle will lead to an aerodynamic drag-force vector, $\overline{f}_D$ (given below) [18] that will act in a direction opposite to the slip velocity vector, as shown in Fig. 20.

$$\overline{f}_D = \tfrac{1}{4}\pi d^2 \times \tfrac{1}{2}\rho_{Air}\overline{u}_2 \times C_D \qquad (3)$$

In the above expression, $\tfrac{1}{4}\pi d^2$ is a characteristic area, $\tfrac{1}{2}\rho_{Air}\overline{u}^2$ is a characteristic kinetic energy for the flow, and C_D is the drag coefficient. For spheres, the drag coefficient is given as a function of Reynolds number ($N_{Re} = upd/\mu$) [18], as shown in Fig. 21. At low Reynolds numbers (i.e. $N_{Re} < 1.0$), Stokes Law applies, reducing the drag force to the simple formula [18]:

$$\overline{f}_D = 3\pi\mu\overline{u}_d \qquad (4)$$

Owing to the forces acting on the particles, there may be a component of angular velocity, V_a, in the particles' motion. This component will give rise to the centrifugal force vector, [18] $\overline{f}_C$,

$$\overline{f}_C = mV_a^2/r \qquad (5)$$

directed radially as shown in Fig. 20 from the radial position, r, of the particle.

The magnitude of all these forces is highly dependent upon the diameter of the particle, either through its dependence on the mass of the particle, which is equivalent to $\rho\pi d^3/6$, or through the drag coefficient and characteristic area. As a result, the large particles will be affected most by gravity and centrifugal forces and least by aerodynamic drag, and so will end up in the coarse-particle chamber.

Intermediate-sized and fine particles will be affected most by aerodynamic drag and affected least by gravity and

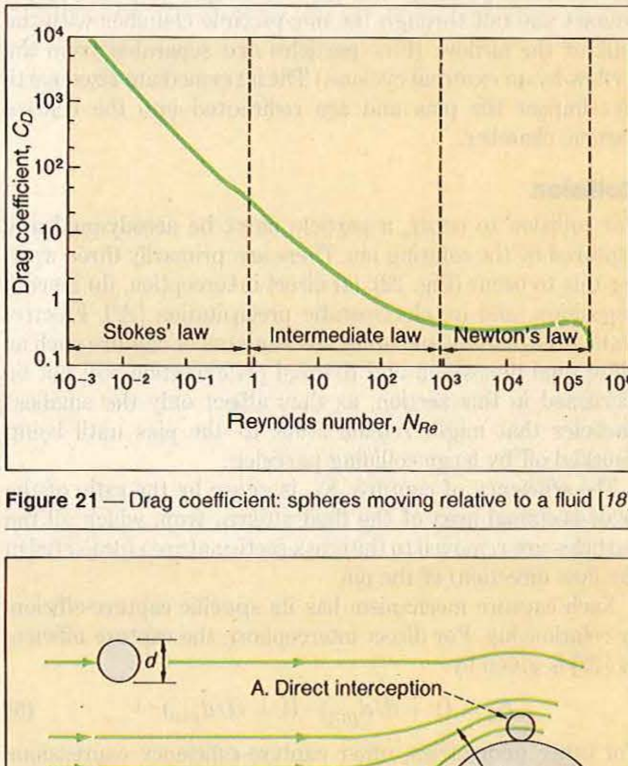

Figure 21 — Drag coefficient: spheres moving relative to a fluid [18]

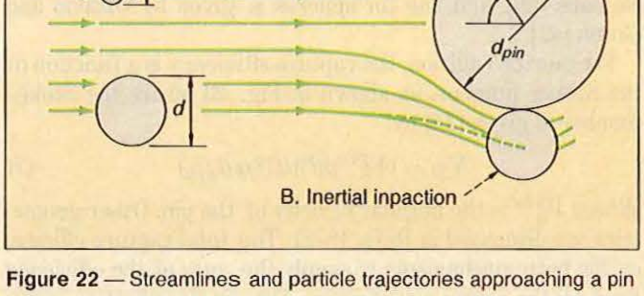

Figure 22 — Streamlines and particle trajectories approaching a pin

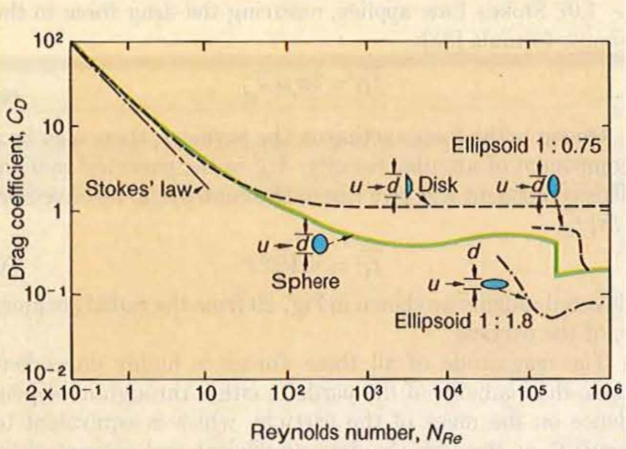

Figure 23 — Capture efficiency by inertial impaction on an isolated cyclinder (Taken from Ref. 22)

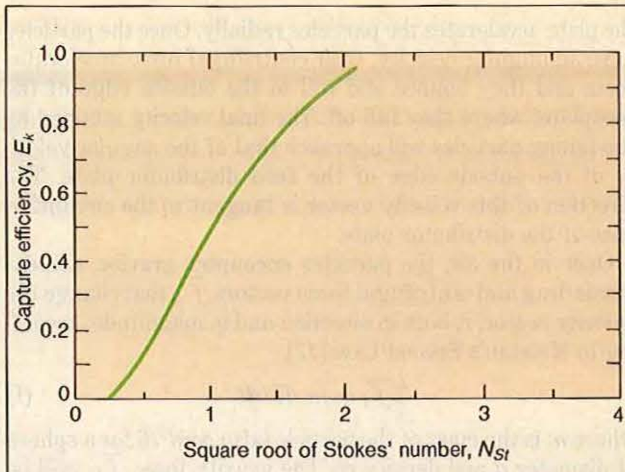

Figure 24 — Drag coefficient for submerged bodies (From Ref. 24)

centrifugal forces, and will be directed into the rotor. Sufficiently small particles will pass through the pins without contact and out through the fine-particle chamber with the bulk of the airflow. (Fine particles are separated from the airflow by an external cyclone.) The intermediate-sized particles impact the pins and are redirected into the coarse-particle chamber.

Collision

For collision to occur, a particle must be aerodynamically captured by the rotating pin. There are primarily three ways for this to occur (Fig. 22): (a) direct interception, (b) inertial deposition, and (c) electrostatic precipitation [*22*]. Electrostatic precipitation and other mechanisms of capture such as diffusional deposition and thermal precipitation will not be discussed in this section, as they affect only the smallest particles that might remain stuck to the pins until being knocked off by large colliding particles.

The efficiency of capture, E_k, is given by the ratio of the cross-sectional area of the fluid stream from which all the particles are removed to the cross-sectional area (projected in the flow direction) of the pin.

Each capture mechanism has its specific capture-efficiency relationship. For direct interception, the capture efficiency [*19*] is given by:

$$E_k = (1 + d/d_{pin}) - (1 + d/d_{pin})^{-1} \qquad (6)$$

For other geometries, other capture-efficiency expressions will apply. A discussion of flat plate geometry is given by Rajhans [*20*], and one for spheres is given by Ottavio and Goren [*21*].

For inertial collision, the capture efficiency is a function of the Stokes number, as shown in Fig. 23 where the Stokes number is given [*19*] by:

$$N_{St} = (V_a^{pin} \rho d^2)/(18 \mu d_{pin}) \qquad (7)$$

Where V_a^{pin} is the angular velocity of the pin. Other geometries are discussed in Refs. 19–21. The total capture efficiency for both mechanisms is simply the sum of the efficiency from all the active mechanisms. For air classification using the cylindrical pins of the SD Classifier, the capture efficiency is dependent on the angular velocity of the pins, the number of pins on the circle, the diameter of the pins, and the diameter and density of the particles. As a result, both the feed characteristics and the operating conditions will determine what intermediate sizes will impact the pins and be directed back toward the coarse-particle chamber. The force that is imparted to a particle during contact with a pin will determine its rebound velocity.

Once a particle is in free flight again, gravity, drag and centrifugal forces must be accounted for to establish the dynamics of the particle. With a sufficiently large collision force, particles may fragment, resulting in the comminution of the feed.

Nonspherical particles

In the preceding sections, it has been convenient to define a spherical shape equivalent in volume to irregularly shaped particles. This is a typical simplification used throughout the air classification industry, but it is fundamentally in error. For irregularly shaped particles, the specific drag force will not be parallel to the motion of the particle unless the particle has a certain symmetry or a specific orientation. For most real particles, the drag force will cause the particle to rotate as well as to change translational velocity. Therefore, both force and moment analyses must be performed for precise accuracy.

Moment analysis adds a level of complication that is often neglected. The drag on irregularly shaped particles is discussed in detail by Clift, Grace and Weber [*23*].

Basically, the irregularly shaped particle gives rise to a different drag-coefficient-versus-Reynolds-number expression, as shown in Fig. 23 for simple geometries. For aspect ratios less than 1, the drag coefficient is less than that of an equivalent sphere, while for aspect ratios greater than 1, the drag coefficient is greater than that of an equivalent sphere. Equations describing the gravity and centrifugal forces for irregularly shaped particles will differ from an equivalent sphere if the movement of the center of mass of the particles is considered.

Measuring classifier performance

Size selectivity, recovery and yield

Size selectivity is the best meausre of classifier performance under a given set of operating conditions. Size selectivity, S, is defined as the ratio of the quantity of particles of size d entering the coarse stream to the quantity of size d in the feed. The equivalent mathematical expression is, on a mass basis [25]:

$$S = W_c M_c^d / (W_c M_c^d + W_f M_f^d) \quad (8)$$

where W_c is the mass flowrate of the coarse fraction; W_f is the mass flowrate of the fine fraction; M_c^d is the cumulative percent mass of the coarse stream less than size d, and M_f^d is the cumulative percent mass of the fine stream less than size d. Selectivity of a typical air classifier is plotted as a function of size in Fig. 25; selectivity monotonically increases from 0 to 1 as size increases (Curve b–b').

While size selectivity is a complete measure of classifier

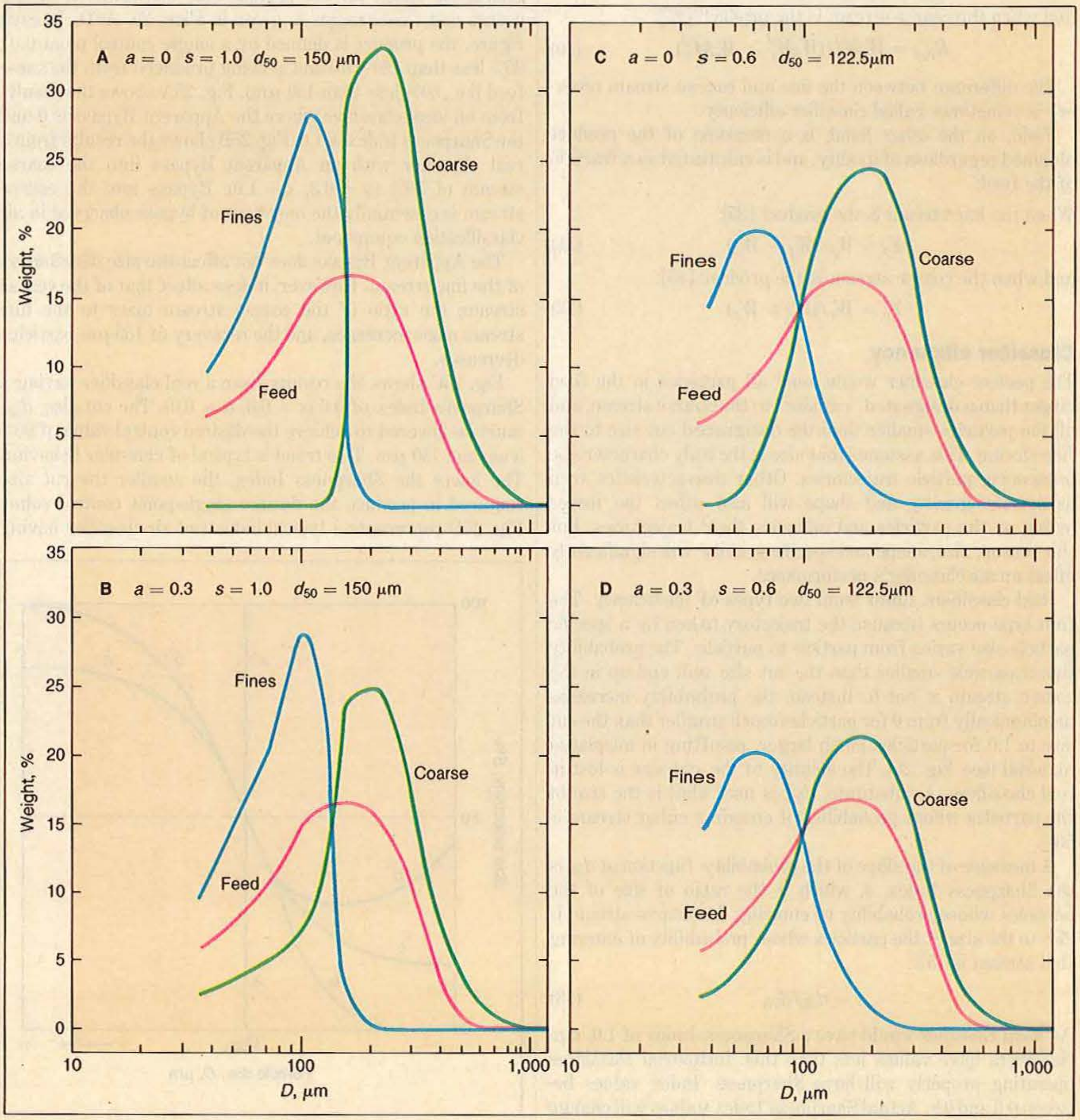

Figure 25 — Size distributions for various types of air classifier performance

performance, the user is often required to take a shortcut method of expressing performance on a specific feed material. A practical measurement of overall classification performance for a given application can be obtained by calculating recovery and yield. Recovery is the relative amount of material in the feed that is finer than size d that is recovered in the product. Recovery, R, expressed as a fraction of the feed can be calculated from the cumulative particle-size-distribution data as follows:

When the fine stream is the product [25]:

$$R_{d,f} = W_f M_f^d / (W_f M_f^d + W_c M_c^d) \tag{9}$$

and when the coarse stream is the product [25]:

$$R_{c,f} = W_c M_c^d / (W_f M_f^d + W_c M_c^d) \tag{10}$$

The difference between the fine and coarse stream recovery is sometimes called classifier efficiency.

Yield, on the other hand, is a measure of the product obtained regardless of quality, and is calculated as a fraction of the feed:

When the fine stream is the product [25]:

$$Y_f = W_f / (W_f + W_c) \tag{11}$$

and when the coarse stream is the product [25]:

$$Y_c = W_c / (W_f + W_c) \tag{12}$$

Classifier efficiency

The perfect classifier would send all particles in the feed larger than a designated "cut size" to the coarse stream, and all the particles smaller than the designated cut size to the fine stream. This assumes that size is the only characteristic influencing particle trajectories. Other characteristics such as specific gravity and shape will also affect the forces acting on the particles and influence their trajectories. For this reason, size, shape and specific gravity will significantly affect an air classifier's performance.

Real classifiers suffer from two types of inefficiency. The first type occurs because the trajectory taken by a specific particle size varies from particle to particle. The probability that a particle smaller than the cut size will end up in the coarse stream is not 0. Instead, the probability increases monotonically from 0 for particles much smaller than the cut size to 1.0 for particles much larger, resulting in misplaced material (see Fig. 25). The identity of the cut size is lost in real classifiers. A substitute, d_{50}, is used that is the size of the particles whose probability of entering either stream is 50%.

A measure of the slope of the probability function at d_{50} is the Sharpness Index, s, which is the ratio of size of the particles whose probability of entering the coarse stream is 25% to the size of the particles whose probability of entering that stream is 75%.

$$s = d_{25} / d_{75} \tag{13}$$

An ideal classifier would have a Sharpness Index of 1.0; real classifiers have values less than this. Industrial classifiers operating properly will have Sharpness Index values between 0.5 and 0.8. Actual Sharpness Index values will change as a function of the properties of the feed and operating conditions.

The other type of air classifier inefficiency is the Apparent Bypass, a. If, because of mutual interference or other reasons, some of the feed material bypasses the separation and reports to either the fine or the coarse stream, then a certain percentage of one of the product streams will have the same particle size-distribution as the feed material. Both the Apparent Bypass and the Sharpness Index dictate the performance of air classifiers [25].

Effects of Apparent Bypass and Sharpness Index

A comparison of the effects of Apparent Bypass and Sharpness Index on the particle size distributions of the coarse and fine streams is given in Figs. 25, A–D. In each figure, the product is defined by a single control point (i.e., 95% less than 150 μm) and is being produced from the same feed (i.e., 50% less than 150 μm). Fig. 25A shows the results from an ideal classifier where the Apparent Bypass is 0 and the Sharpness Index is 1.0. Fig. 25B shows the results from a real classifier with an Apparent Bypass into the coarse stream of 30% ($a = 0.3$, $s = 1.0$). Bypass into the coarse stream is essentially the only type of bypass observed in air classification equipment.

The Apparent Bypass does not affect the size distribution of the fine stream. However, it does affect that of the coarse stream; the ratio of the coarse stream mass to the fine stream mass increases, and the recovery of 150-μm particles decreases.

Fig. 25C shows the results from a real classifier having a Sharpness Index of 0.6 ($s = 0.6$, $a = 0.0$). The cut size, d_{50}, must be lowered to achieve the desired control value of 95% less than 150 μm. This trend is typical of classifier behavior. The lower the Sharpness Index, the smaller the cut size required to produce the desired single-point control value. Fig. 25D represents a typical industrial air-classifier having

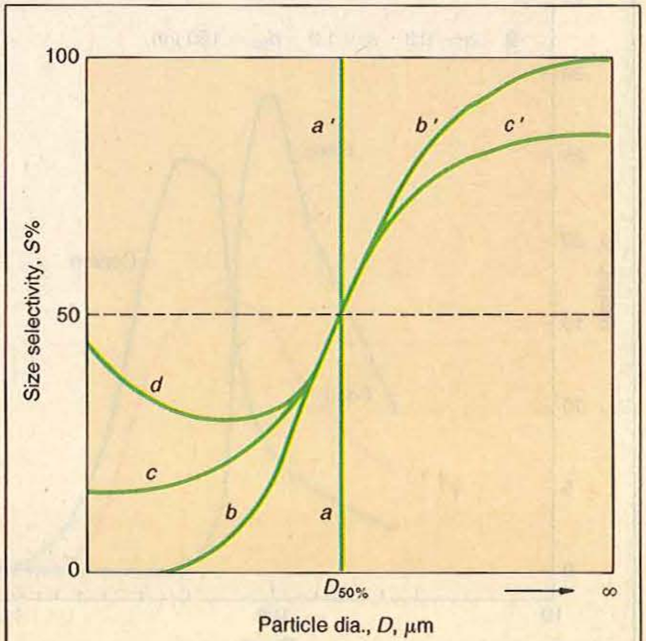

Figure 26 — Types of size selectivity curves

both types of inefficiency ($a = 0.3$ and $s = 0.6$). The ratio of the coarse stream mass to the fine stream mass is further increased and the recovery value of the 150-μm particles is further decreased by the combination of both types of inefficiency.

The effects of bypass on size selectivity are shown in Fig. 26. Bypass reporting to the fine stream moves from Curve b to Curve c. Bypass reporting to the coarse stream moves from Curve b' to Curve c'. Grinding of the particles by an air classifier will give rise to a size selectivity curve such as d.

Analysis of various types of industrial classifiers has led to the observation that the Sharpness Index is essentially constant for a classifier (with a fixed geometrical configuration) over its normal operating range. Assuming that bypass is minimal, only two things affect the size distribution of the fine stream — the size distribution of the feed, and the cut size. Hence, if the size distribution of the feed is constant, only the cut size (d_{50}) will affect the size distribution of the fines. Bypass can be minimized by proper design and operation of the feedplate, and other design factors.

Design and operation

Applications

Air classifiers are used in many solids-processing plants, such as those in the chemical, pharmaceutical, food, pigment, coal, mineral, metal and cement industries. The equipment can operate in an open or closed circuit with a grinding mill. An example of an open circuit operation is coal dedusting. Comminution of coal to small sizes is done in several dry and/or wet stages. If a coal slurry is required (e.g., for physical beneficiation, chemical cleaning, or slurry transportation), it is sometimes desirable to use dry grinding and separate the fine fraction before slurrying the coal, to avoid the expensive handling of sludges that are left after coal has been separated from the liquid. The separation of the fine coal fraction, or dedusting, can be effectively done with a classifier after the milling and before the slurrying step. The fine fraction might be briquetted or discarded.

An example of an air classifier in closed circuit with a grinding mill (see Fig. 27) is a cement plant [*26*]. The raw-mill or finished discharge is fed to a classifier. The fine fraction is the intermediate or final product, while the coarse fraction (or tails) is recirculated to the mill. The circulating load or mass ratio of feed to tails is related to classifier recovery. The higher the recovery, the lower the circulating load and the smaller the equipment and power requirements of the circuit.

Some air classifier types have been modified for cooling, heating or flash drying of the solids, using cold or hot air [*27*]. A typical cement-drying system using a modified Whirlwind is shown in Fig. 28. Hot air at 450°C is supplied by a burner at a rate of approximately 140 m^3/ton of feed having up to 8% moisture. The air passes through the classifier and is exhausted to a bag filter at 80°C.

Equipment specification, cost and selection

Air classifier capacities range from 1-kg/h solids throughput for small laboratory units to 3,000 tons/h for large equipment in cement manufacturing or coal preparation (see Column 11 in the table). Column 12 of the table lists the

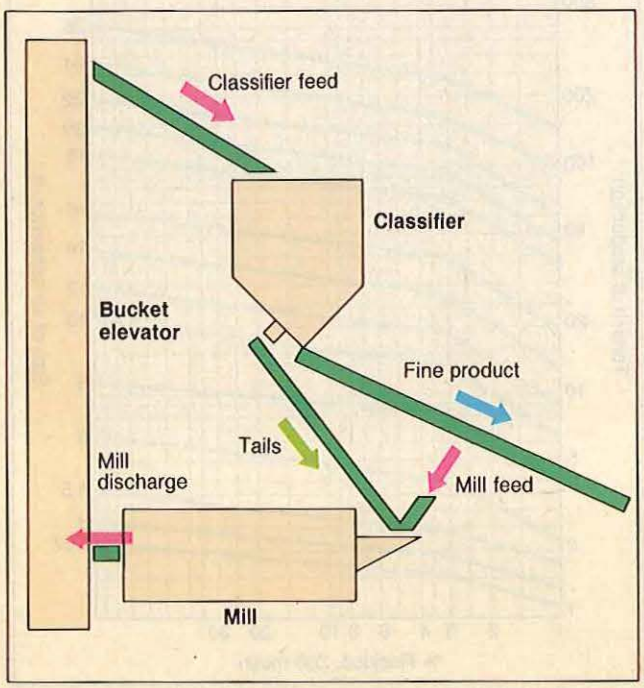

Figure 27 — Classifier in closed circuit with mill

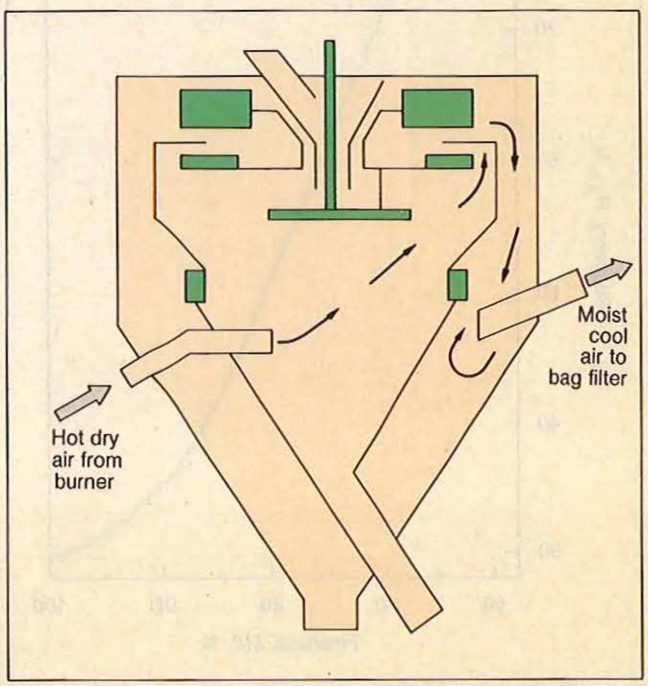

Figure 28 — Drying in a Whirlwind air classifier

maximum energy requirements of the individual equipment examples. Equipment prices in 1984 dollars range from \$10,000 for the smallest laboratory models to \$300,000 for the largest standard classifiers, i.e. units having an internal fan and fines collector. Systems with outside fans and cyclones might cost twice as much or more. Any classifier or classification system price can be scaled up or down using the equation:

$$\text{Cost/Reference cost} = (\text{Throughput/Reference throughput})^{e} \quad (14)$$

where the exponent $e = 0.46$ for standard classifiers (1 to 8 m dia.). Installation-material and labor costs vary widely with geographic location and overall plant design. The large standard classifiers (3 to 8 m dia.) require a five to six man erection crew with total workhours rising from 0.061 to 0.084 per 1 m^2 cross-sectional area as the size increases. During regular operation, large automated classification systems need very little attention by plant personnel. For a typical entire closed circuit shown in Fig. 27 the allocation of 0.5 operator workhours/shift suffices.

For the selection of air classifiers, empirical relationships have been developed by equipment manufacturers, particularly for the cement industry. Fig. 29 shows the correlation between recovery and fineness of product that can be used for standard classifiers in conjunction with Eqs. (9) and (10). Selection of the right size of this equipment type is facilitated by Fig. 30, which shows the correlation of fines production rate with classifier diameter, and with product quality expressed as the percentage of the plus 74 and 90 μm fraction [12]. Both Figs. 29 and 30 are valid for cement and similar materials having a density of around 3 g/cm^3 but the data might be roughly adjusted to other materials as well as to different equipment types, using concepts and equations discussed in the Particle Dynamics section above. The nomograph in Fig. 31 is an example of a density correction method for the production rate on the Y-axis of the chart in Fig. 30. Before using the chart, the required production rate is multiplied by the factor read from the nomograph.

Performance

The classification process is primarily the result of the balance of at least two of the four forces that may act on the particles—i.e., collision, drag and centrifugal forces, and gravity. Collision is controlled by mechanical devices, particularly the rotor, the speed of which can be varied. Stationary directional devices affect classification only indirectly, in most cases by speeding up or slowing down the air and/or by turning it in the desired direction. The drag force is controlled by the air vector, i.e., the velocity and direction of the air. This can be again varied. Centrifugal force is generated either by the rotor or by rotating air. The air rotation can also be conveniently expressed in terms of the air vector. Finally, gravity is independent of the equipment and airflow. It can be seen that the two most important variable parameters that control classification are the air vector and rotor characteristics.

To discuss performances of all commercial classifier types

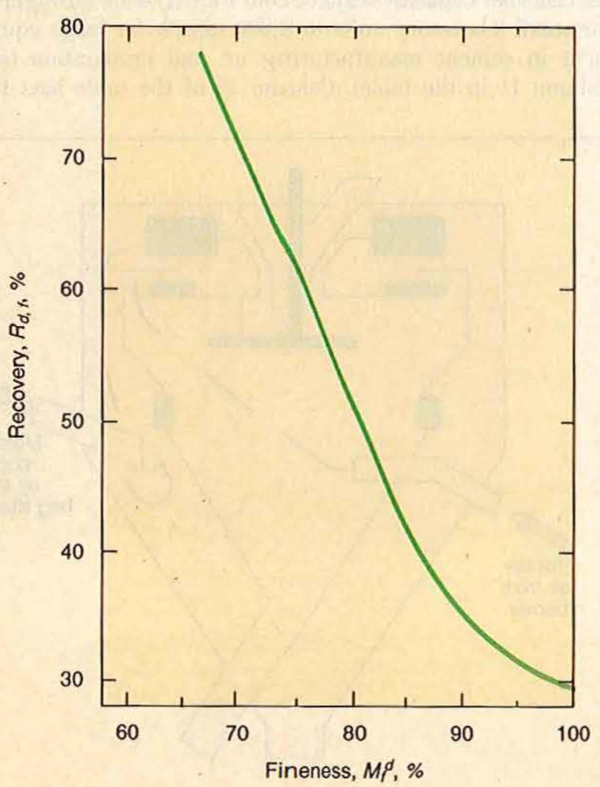

Figure 29 — Fines recovery: % of given size (cumulative) that goes to fine product, vs. fineness (% passing that size screen). See Eq. (9)

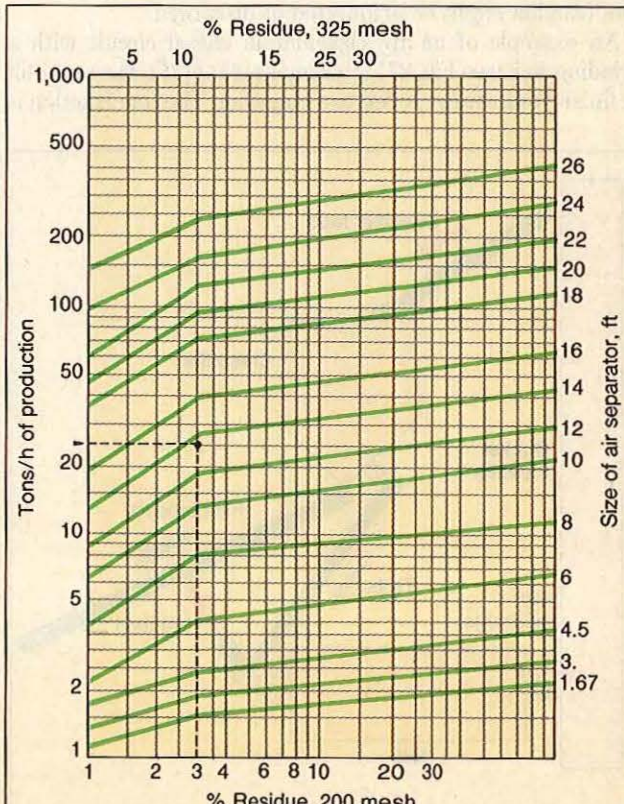

Figure 30 — Whirlwind size selection: Size (ft. dia.) as a function of fines production rate (t/h) and quality (% on 170 or 200 mesh screen)

listed in the table, and how each is affected by equipment design and operation control, is beyond the scope of this article. The discussion will be limited to rotor-equipped large industrial units. The reader will be able to apply the following concepts to simpler equipment without a rotor and to the smaller units. There are two basic categories of rejector-equipped large industrial classifiers, the traditional updraft machines with vertical airflow (Figs. 9–12) and the new side-draft equipment with horizontal airflow (Figs. 14,15).

Classifier yield increases with linear air velocity in the separation zone upstream from the rotor, and generally decreases with increasing rejection that, in turn, is controlled by raising the speed and active surface area of the rejector. As this area is usually provided by a set of rejection elements such as blades or pins, yield decreases with the increasing size and number of rejection elements. The rejector preferentially knocks out coarser particles. Accordingly, product fineness or the ratio of fine to coarse particles in the fine product increases with rotational speed and with the size and number of rejection elements.

Performance of a classifier can be controlled by selecting or designing the machine for a particular application, setting certain equipment parameters in advance before startup, and varying others during operation, either manually or as part of an automatic control system in response to changes in process parameters such as feed available or products desired. The required performance is virtually attained by carefully balancing rejection and air velocity.

Equipment design

Classification efficiency is negatively affected by two factors [*28*]: entrapment of fine particles by coarse ones, and fines bypassing. The former can be overcome by spreading the descending curtain of particles evenly across a wider area and providing a longer residence time in the separation zone.

The shape of the curtain can be controlled by the rotational speed and form of the distributor, as well as by the aerodynamic design of the surrounding space. For example, in an SD Classifier version without the multiple deflector cones shown in Fig. 18, the even density of the curtain is controlled by a single deflector plate positioned at an optimum angle and distance from the distributor, see Fig. 32. In the Centri-Sonic Classifier (Fig. 17), the width of the curtain is affected by the air recycle.

Residence time can be increased by raising the height of the separation zone and, in the case of side-draft separators, by enhancing the spiral motion of the particles around the rejector as discussed in the previous paragraph. There obviously are limits to the height of the separation zone, dictated by equipment cost and, for an updraft classifier, by requirements for the power to pump the air through longer passages. In the sidedraft machines, the increase in volute height to match the rejector height causes problems for the even vertical air-distribution that are best solved by horizontal vanes or conical deflectors (Fig. 18).

Fines bypassing is most serious in updraft classifiers having an internal fan and a fines collector. It is caused by the inefficient separation of air from particles in the expansion section (Fig. 9). The particles slide down the outer cone while the air is returned to the separation zone. The more particles stay entrained the higher the buildup of fines in the return air and the more fines eventually end up in the coarse product. This type of bypassing has been successfully resolved by the introduction of outside fans (Fig. 2) at the price of higher capital and power costs.

A less-serious bypassing occurs in the side-draft classifiers as some of the particles are thrown outside the separation zone and deposit at the bottom of the volute at the vertical outside wall where the tangential air velocity is relatively small. While coarser particles settle down prefer-

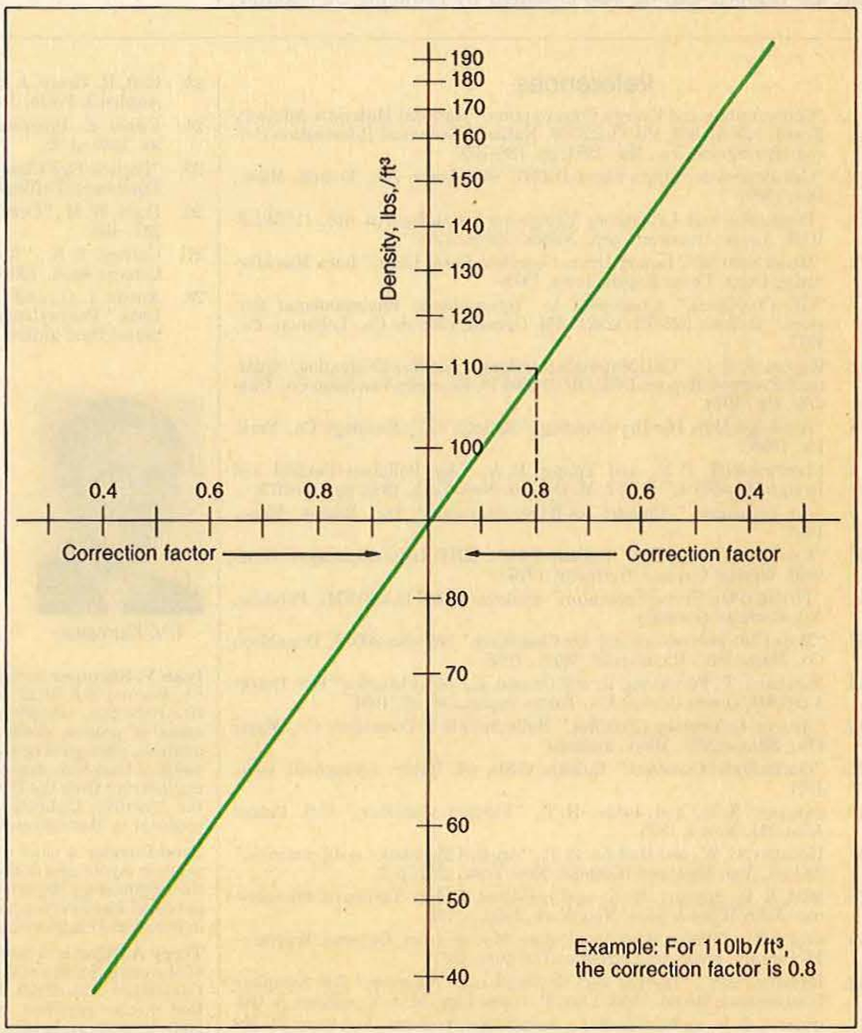

Figure 31 — Correction-factor nomograph. Multiplier for production rate (use with Fig. 30)

entially, they trap finer particles among them, and the entire deposit gradually slides down to the coarse product, contaminating it with fine particles.

This bypassing can be prevented by installing a set of inclined overlapping deflectors in the form of stacked concentric truncated cones that direct the particles back to the separation zone (Fig. 18).

Operation control

In the classical Whirlwind (Fig. 9), the number of rejector blades can be controlled independently of the air velocity whereas their rotational speed cannot, because the fan is also a part of the rotor. This has since been corrected in two ways. Either the rejector is mounted on a separate shaft (Fig. 12), or the air is pumped by an outside fan (Fig. 2). Increasing the size or number of rejector elements is limited to shut-down periods but, because of only a slight change in the interaction between air and rejector, this does not affect power consumption whereas the increase in rejector speed requires more power.

In addition to varying the rotational speed of the fan, whether it is mounted on the rotor or outside the classifier, the air velocity can be also changed by reducing or expanding the air passage. In the updraft classifiers, the cross-sectional area of the passage is controlled by horizontal sliding dampers between the selector and fan blades (Fig. 9). In sidedraft machines, this is accomplished by vertical vanes (Fig. 14) that also help to turn the air radially, or by a single long vertical spiral partition that seals off the outer half of the volute (Fig. 18).

This optional partition is unique in that it reduces only the tangential-air-velocity component without affecting the radial component as long as the volumetric flowrate is maintained. In this way, the trajectories of the particles descending through the separation zone around the rejector are bent into a more spiral pattern, resulting in longer residence time and better separation. However, if the air velocity increase is too high, the volute might act as a cyclone, pulling even some of the fine particles down toward the annular space and thus contaminating the coarse product.

Acknowledgment

The authors would like to acknowledge the help of William English, president of Sturtevant, Inc., who supported the state-of-the-art study of air classification technology.

Roy Hughson, Editor

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