Gravity Concentration

Frank F. Aplan

INTRODUCTION

Gravity concentration is a process in which particles of mixed sizes, shapes, and specific gravities are separated from each other in a fluid by the force of gravity or by centrifugal force. The process is designed to separate particles by specific gravity, but to a certain extent it also separates particles on the basis of size and shape.

Historically, the process has been used to separate ore minerals or coal from their associated gangue (refuse) on the basis of mineral density (Table 6.1). Gravity concentration is often equally applicable to other common industrial processes, such as degritting food grains, paper pulp, and chemical raw materials; recycling municipal solid waste; recovering and recycling spills, splatters, skim-mings, skulls, turnings, and grindings from metal production and fabrication; and remediating toxic waste piles.

Early Use and Development of Gravity Concentration

Gravity concentration of heavy minerals is a natural geological process, and Mother Nature has concentrated minerals, such as gold, cassiterite, ilmenite, and diamonds, into natural placer (alluvial or glacial) deposits. Humans have used gravity concentration processes for thousands of years. Egyptian monuments of about 3000 BCE depict the washing of gold ores (Anon. 1970) and the Athenians undoubtedly used flowing film concentration to process ores from their mines at Laurium before the birth of Christ (Gaudin 1939). In the sixteenth century, Agricola (1556) in De Re Metallica described several gravity concentration devices used in Europe, and seventeenth-century Chinese concentration technology is described in T'ien-kung K'ai-Wu (Sung 1637). In the nineteenth century, Rittinger in Europe performed theoretical and practical studies, and in the later part of that century, Richards in the United States did much to establish the basic principles of gravity concentration that were published in his classic four-volume treatise (Richards 1906–1909). In the 1920s, Finkey (1924) established many of the mathematical relationships describing the process, and Gaudin (1939) and Taggart (1945, 1951) extended and codified the principles on which gravity concentration is based. Other valuable references that describe either processes or devices are Richards and Locke (1940), Mills (1978), Burt and Mills (1984), Aplan (1985a), Weiss (1985), Osborne (1988), and Leonard and Hardinge (1991).

Importance of Gravity Concentration in Minerals Processing

A glance at the literature reveals that gravity concentration has been studied much less than its more glamorous counterpart, flotation. Yet, in terms of commercial use, about 25% more coal and ore tonnage is treated by gravity concentration in the United States than is treated by flotation. It has been estimated that in 1988, 529 million metric tons was treated by gravity concentration, 529 million by flotation, and 153 million by magnetic separation (Aplan 1989). Of the gravity concentration tonnage,
about 500 million tons was raw coal treated in coal preparation plants. Although these tonnage estimates were made in 1988, the values probably are not much different today (in 1999). Of the raw coal sent to preparation plants, about 94% is cleaned by gravity methods as compared with only 6% cleaned by flotation (Aplan 1989).

Over the years a bewildering number of gravity concentration devices have been developed. Concentrating the finer sizes is difficult, and as the particle size of the material to be treated decreases, the number of devices invented to capture the fines seems to increase exponentially. Some of the more important devices are listed in Table 6.2. For details on these and similar devices, the older, more recent, and current literature should be consulted (see previous citations).

**Applicability to Concentration Processes**

Particles respond differently to various concentrating devices depending on the fluid, the force field, and specific properties of the particles, such as density, size, shape, chemistry, surface chemistry, magnetism, conductivity, color, and porosity. Various concentration devices are applicable to particles in various size ranges (Figure 6.1), and for any given size range, several processes or devices might be used. Gravity concentration works best in the 130-mm (about 5-in.) to 74-µm (200-mesh) range. Below about 74 µm (200 mesh), separation of particles by specific-gravity differences is increasingly difficult, and it is generally inapplicable below about 15 µm except in special circumstances. Of the processes listed in Figure 6.1, only flotation and wet magnetic separation effectively separate ~10-µm particles. If minerals are liberated at a coarse size, gravity concentration is often an inexpensive and effective way to separate them from their associated gangue minerals; if not, other methods may be more attractive.
**TABLE 6.2 Size ranges treated by typical gravity concentration devices**

Coarse concentration (+¼ in. [+6.4 mm])
- Sorting with hand (held) devices
- Jigs
  - Pulsion-suction
  - Pulsator
  - Baum
- Heavy media
- Heavy media hydrocyclone
- Hindered-settling classifiers
- Pneumatic jigs, tables, launders

Intermediate concentration (¼ in.–100 mesh [6.4–0.150 mm])
- Jigs
- Heavy media hydrocyclone
- Water-only cyclone
- Hindered-settling classifiers
- Kelsey jig
- Pneumatic jigs and tables
- Sluices
- Shaking tables
- Humphreys-type spirals
- Pinched sluices
- Cannon concentrator
- Reichert cone
- Wright impact tray
- Falcon concentrator
- Knelson concentrator
- Burch shaken helicoid
- Bartles-Mozley concentrator
- Mozley multigravity separator
- Buddles
  - Planilla
  - Lanchute

Fines concentration (–100 mesh [–0.150 mm])
- Jigs that emphasize suction
  - Kelsey jig
  - Shaking table
  - Humphreys-type spirals
  - Pinched sluices
  - Cannon concentrator
  - Reichert cone
  - Wright impact tray
  - Falcon concentrator
  - Knelson concentrator
  - Burch shaken helicoid
  - Bartles-Mozley concentrator
  - Mozley multigravity separator
  - Buddles
    - Planilla
    - Lanchute
  - Round table
  - Tilting frames (e.g., Denver–Buckman)
  - Vanners
    - Frue
    - Bartles crossbelt concentrator
  - Strakes
    - Blanket and corduroy tables
    - Johnson concentrator
    - Endless belt
  - Plane table
Settling phenomena, especially hindered-settling, underlie all gravity concentration processes.

**Free Settling**

Free settling may be defined as that process in which individual particles fall freely in a fluid without being hindered by other particles (paraphrased after Richards and Locke [1940]). The settling of these particles, which are assumed to be spheres, can be calculated from the equations of Newton and Stokes and for the Allen range from measurements or approximations, as outlined in the previous chapter. The terminal settling velocity of spheres of various densities as a function of particle diameter and the density and nature of the fluid (water or air) is given in Figure 6.2 (as modified from Lapple et al. [1956]). Above about 2,000 \( \mu m \) the slope of the curves is 0.5, corresponding to \( \sqrt{d} \) in the Newtonian equation:

\[
V_m = \frac{4}{\sqrt{3f}} \frac{\rho - \rho'}{\rho'} d g
\]  

(Eq. 6.1)

where

- \( V_m \) = the terminal settling velocity of the particle
- \( f \) = the friction factor or coefficient of resistance (\( f \) is \( \sim 0.4 \) for spheres)
- \( \rho \) and \( \rho' \) = the densities of the solid and fluid, respectively
- \( d \) = particle diameter
- \( g \) = the force of gravity

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Source: Modified from Lapple et al. 1956.

**FIGURE 6.2** The terminal settling velocities of spheres of various sizes and densities settling in water and in air.
Below about 100 µm the slope of the curve is 2, as dictated by the Stokes' equation:

\[ V_m = \frac{1}{18} \frac{\rho - \rho'}{\mu} d^2 g \]  
(Eq. 6.2)

where

- \( V_m \) = terminal settling velocity of the particle
- \( \rho \) and \( \rho' \) = densities of the solid and fluid, respectively
- \( \mu \) = fluid viscosity
- \( d \) = particle diameter
- \( g \) = the force of gravity

**Hindered Settling**

Hindered settling describes that process in which particles of mixed sizes, shapes, and specific gravities, in a crowded mass yet free to move among themselves, are sorted in a rising fluid current (paraphrased after Richards and Locke [1940]). Collisions between particles are continuous, and the assemblage will settle much more slowly than the freely settling individual particles. Hindered settling may, most conveniently, be promoted by agitation of the suspension (stirring, or the use of jets or a rapidly rising fluid current) or by the introduction of a constriction (such as a punched plate, screen, or Venturi).

The generalized curve for the settling of common mineral suspensions (typically ~10 mesh) is given in Figure 6.3. The approximate numerical values for the three settling regions (unstable, metastable, and stable) are shown for the case of coal or limestone ground to a nominal ~100 mesh (150 µm; Datta 1977). The settling rate values of 0.4 and 0.7 cm/min are generally applicable to ground ores except for closely sized or high-density particles. However, the values for the percent solids by volume (% SV)
required for stabilization depend not simply on the shape and density of the particles; they are acutely sensitive to the size consist (size distribution) of the feed (e.g., the size parameter, \(K\), and the distribution parameter, \(a\), in the Gaudin–Schuhmann equation for ground ores [Eq. 2.55, Particle Characterization chapter]). To stabilize suspensions of most other ores, or of more coarsely ground material, will require a substantially higher percent \(S_V\) than that shown in Figure 6.3, while material of a finer size consist can be stabilized at a lower percent \(S_V\). As more than a few particles are settled together in water, the settling rate decreases linearly as percent \(S_V\) increases, up to the onset of metastability.

**Equal Settling Particles**

If a heavy (\(H\)) and a light (\(L\)) particle are settled under the same free-settling conditions, some smaller dense particles will settle at the same rate as some larger light particles, and under Newtonian conditions (Eq. 6.1), the ratio of their diameters at the same settling rate is

\[
\frac{d_L}{d_H}_{\text{Newt, FS}} = \left(\frac{\rho_H - \rho'}{\rho_L - \rho'}\right)^{1/3}
\]

(Eq. 6.3)

and using the same approach for Stokesian conditions (Eq. 6.2), the exponent \(n\) will be 0.5. All-range particles will have an exponent between 0.5 and 1.0. Typically, the ratio of diameters is small, and particles settle in about the same settling regime, so the equation may be approximated as

\[
\frac{d_L}{d_H}_{\text{FS}} = \left(\frac{\rho_H - \rho'}{\rho_L - \rho'}\right)^{0.5 \leq n \leq 1}
\]

(Eq. 6.4)

and under hindered-settling conditions, the equation becomes

\[
\frac{d_L}{d_H}_{\text{HS}} = \left(\frac{\rho_H - \rho''}{\rho_L - \rho''}\right)^{0.5 \leq n \leq 1}
\]

(Eq. 6.5)

where \(\rho'\) is replaced by the apparent specific gravity, \(\rho''\), of the suspension.

Knowing the density of the solid in the hindered-settling zone and its volumetric percent solids, \(\gamma_s\), the \(\rho''\) of an aqueous suspension may be approximated by the formula

\[
\rho'' = \gamma_s \rho + (1 - \gamma_s)\rho'
\]

(Eq. 6.6)

Table 6.3 indicates that galena (\(\rho_H\)) of 2-mm diameter, assumed spherical, with a free-settling ratio of 3.94, will settle at about the same rate as 8-mm-diameter quartz (\(\rho_L\)). Thus, all particles of galena greater than 2 mm will be separated from all quartz particles less than 8-mm diameter. However, in a 45% quartz–water suspension, +2-mm galena can be separated from all quartz particles less than 12.7-mm diameter. Fine particles are separated less effectively, although their separation is better in a suspension than in a true fluid.

**TABLE 6.3** Free- and hindered-settling ratios for spheres of the mineral pair galena (\(\rho_H = 7.5\))/quartz (\(\rho_L = 2.65\)) settling in water and in quartz/water suspensions

<table>
<thead>
<tr>
<th>System</th>
<th>Settling of Large Particles (+10 mesh)</th>
<th>Settling of Small Particles (-150 mesh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free-settling ratio, water</td>
<td>3.94</td>
<td>1.98</td>
</tr>
<tr>
<td>Hindered-settling ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25% quartz suspension = 1.41</td>
<td>4.91</td>
<td>2.22</td>
</tr>
<tr>
<td>45% quartz suspension = 1.74</td>
<td>6.33</td>
<td>2.52</td>
</tr>
</tbody>
</table>

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