# gravity separator

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Synopsis

The use of pneumatically fluidized powders as media for separating mineral constituents of ores is discussed. Particular requirements are considered and the results of bench-scale, batch and continuous operations are presented. The performance of a small-scale fluid-bed separator (20 to 60 lb/h) has demonstrated that crushed ores, down to sizes of at least 22 mesh, can be treated with a recovery of values better than 90 per cent and with excellent product grades. The factors which require further investigation in the design of larger-scale units are indicated.

Heavy-medium systems have been employed with increasing finesse since 1927. Formerly, developments were associated mainly with coal cleaning operations but, since 1936, their field of application has been extended, with considerable advantages, to the beneficiation of a wider range of minerals. In the present state of the art a medium is formed by maintaining suspensions of finely divided solids in liquids, chosen so as to provide fluid densities at controllable levels within the ranges flanked by the densities of the minerals to be separated. As with all commercial separating processes, the effectiveness and economics of heavy-medium separations are directly related not only to the physical properties and associations of the constituents of the feed mixture but also to other factors which are related to the systems themselves. These include the medium losses associated with the float and sink products, and also the maintenance of a medium having a minimum density variation in conjunction with a minimum 'viscous' resistance to ore particle movements. The two components of this latter condition are not compatible and, in practice, it is necessary to tolerate some variation in the density of the medium to achieve adequate freedom of particle movement and separation. A degree of turbulence is often introduced in order to achieve a practical combination of these two components and, as would be expected, this imposes an adverse effect on the resulting separation, particularly of the finer particles in the feed. In any one system all such factors have to be considered and, eventually, optimized.

In certain instances it is necessary or more desirable to operate under dry conditions (for example in arid areas, with soluble mineral constituents, or when previous and/or subsequent separations are dry). A dry, heavy-medium process which appears to provide an adequate, dry, counterpart to the now well known and proved wet system is described. The principles of the wet and dry systems are identical, an air–solids fluidized medium being employed with the dry operation; their practical applications, however, differ with respect to equipment design and possibly with respect to performance characteristics.

## General principles of dry, heavy-medium, separating units

Air–solid fluidized systems are well known, particularly in chemical engineering fields; the large gas–solid contact areas provided by such systems result in advantageous heat or mass transfer conditions. Generally, the gas flow is arranged to produce turbulence within the bed, thereby enhancing the designed transfer coefficients. Clearly, for separation purposes a fluid bed with minimum turbulence would be required.

The fluidizing characteristics of most powders conform to a standard pattern which can be represented by the pressure drop–gas flow graph shown in Fig. 1.

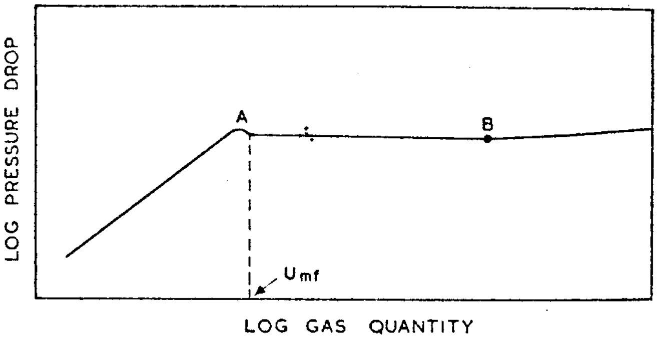

Fig. 1 Pressure drop–gas flow diagram for ideally fluidizing solids

Onset of fluidization occurs at point *A* when the density $\rho$ of the bed can be expressed as

$$\rho = (1 - \varepsilon)\ \rho_s + \varepsilon \rho_f$$

where $\varepsilon$ = overall bed voidage
$\rho_s$ = density of solids
$\rho_f$ = density of fluid

With increasing gas quantity the bulk bed density decreases slowly until point *B* is reached although, within this range (*AB*), the effective density, with respect to the ore, may decrease or increase according to feed particle size. Also, within this range the fluid flow within the bed may change from streamline to turbulent as bubble formation commences. In certain operations such conditions provide an effective mixing system[1,2] and, wherever possible when density separations are sought, they should be avoided. With higher gas rates, beyond *B*, the bed becomes increasingly dispersed and further increases in pressure drop are encountered.

Manuscript first received by the Institution of Mining and Metallurgy on 13 May, 1966; revised manuscript received on 17 July, 1966. Paper published on 10 September, 1966. For discussion at a general meeting of the Institution to be arranged. The paper is Crown copyright.

The most appropriate fluidizing conditions for mineral beneficiations are between points *A* and *B* and, in the initial stages of this investigation, a cell was constructed (Fig. 2) to examine the possibilities of achieving separations, on a density basis, under streamline conditions of fluidization.

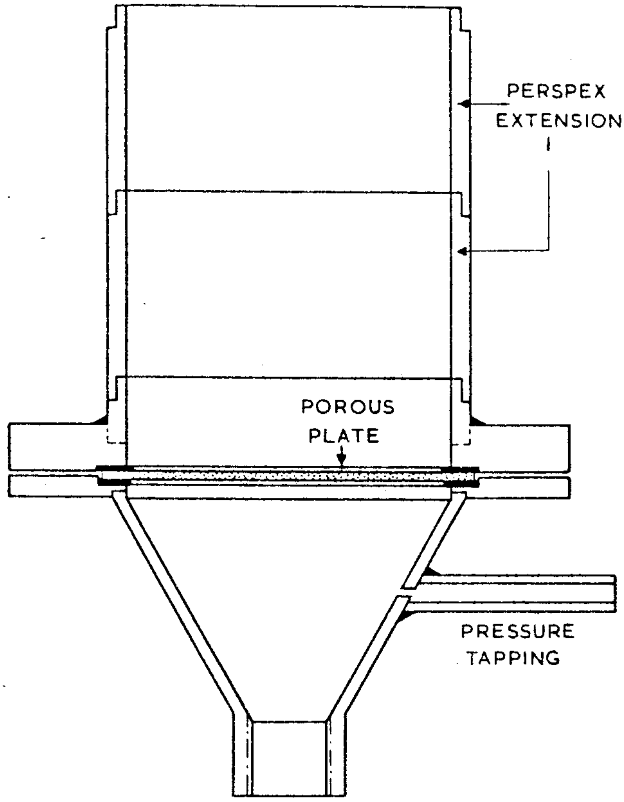

**Fig. 2** Test cell ($3\frac{1}{2}$-in internal diameter)

Initially, a 50/50 (w/w) mixture of −14 +25 mesh (B.S.) quartz (sp. gr. 2·65) and garnet (sp. gr. approx. 4·0) was introduced into a test cell which contained a 2-in deep −150 +200 mesh fluidized ferrosilicon bed. Varying air quantities were used to promote bed conditions, according to the horizontal section *AB* of the characteristics shown in Fig. 1. At each setting the float products were removed and assayed with respect to quartz. The results illustrated in Fig. 3 demonstrate an optimum rate of aeration of 5·3 ft$^3$/min/ft$^2$ (23·5 lb/h/ft$^2$) which, in this instance, is approximately twice the aeration required for initial fluidization. Generally, the air quantities required and the resulting fluid bed conditions produced vary with powder size, vessel dimensions and bed depths; and aeration at the onset of fluidization has been expressed[3] as

$$u_{mf} = \frac{688\, D_p^{1\cdot 82}[\rho_f(\rho_s - \rho_f)]^{0\cdot 94}}{\mu^{0\cdot 88}}$$

where $u_{mf}$ = gas flow, lb/h/ft$^2$
$D_p$ = particle diameter, in
$\mu$ = viscosity, *cP*
$\rho_f$ = fluid density (gas), lb/ft$^3$
$\rho_s$ = solids density, lb/ft$^3$

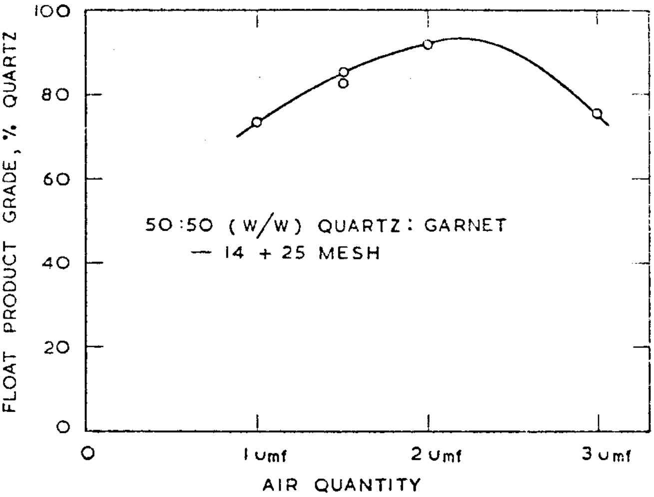

**Fig. 3** Air quantity–float product grade using the $3\frac{1}{2}$-in diameter test cell containing a 2-in bed of −150 +200 mesh ferrosilicon ($u_{mf}$ = quantity of air to produce onset of fluidization)

It is seen that a reduction in the size of the powder to be fluidized will lead to a reduction in fluidizing air requirements—possibly a desirable economic factor. Reductions in air quantities will, however, be limited, in practice for any one powder, by increasing bed viscosities and reducing separation efficiencies; where possible, fluidization must be controlled to provide maximum settling rates and these appear to be associated with maximum air quantities consistent with quiescent non-turbulent beds.

## Choice of medium

Clearly, the density of the selected medium will have the greatest influence on the ultimate operating density of the fluid bed and it is equally obvious that other physical characteristics of the individual particles, for example shape, size and size range, will also have finite, but secondary, effects on this factor.

The magnitude of the variations associated with size are demonstrated in Table 1. Generally, within the

**Table 1** Effect of particle size on bulk and fluidized bed densities

| Size of ferrosilicon, mesh B.S. | Bulk density,* g/cm$^3$ | Apparent density when fluid,* g/cm$^3$ |
|---|---|---|
| +60 | 2·2 | — |
| −60 +90 | 2·3 | 2·2 |
| −90 +150 | 2·7 | 2·5 |
| −150 +200 | 3·0 | 2·7 |
| −200 | 4·1 | 3·0 |
| All sizes | 3·7 | — |

*Method of density measurement: $\frac{\text{weight of powder, g}}{\text{volume occupied, cm}^3}$

range explored both bulk and fluid bed densities increased with decreasing powder size. In this particular series of tests variations in bed density between 2·2 and 3·0 g/cm³ have been measured and, although complete mixing of different sizes within a streamlined bed may not be fully realized in practice, a reasonable density control can be obtained throughout this range.

The working density range can be extended considerably, as is shown in Table 2, by using different materials. With this limited selection it is possible to promote bed densities between 0·8 and 6·3 g/cm³ and, with some confidence, it can be expected that, by using additional materials or mixtures of materials and by exploiting variations due to changes in size, a continuous density spectrum could be obtained. For example, Table 3 indicates the apparent bed densities produced from ferrosilicon–lead mixtures of varying proportions.

**Table 2** Effect of particle density on bulk and fluid bed densities

| Material, −150 +200 mesh B.S. | Bulk density, g/cm³ | Apparent density when fluid, g/cm³ |
|---|---|---|
| Silica sand | 1·15 | 0·8 |
| Barytes | 1·9 | 1·7 |
| Magnetite | 2·25 | 1·95 |
| Ordinary grade ferrosilicon | 3·0 | 2·7 |
| Special grade ferrosilicon | 3·3 | 3·0 |
| Copper | 3·9 | 3·5 |
| Lead | 5·0 | 4·5 |
| Tungsten carbide | 7·0 | 6·3 |

**Table 3** Densities of ferrosilicon (−90 +150 mesh)–lead (−150 +200 mesh) mixtures

| Mixture composition, % ferrosilicon | % lead | Bulk density, g/cm³ | Apparent density when fluid, g/cm³ |
|---|---|---|---|
| 100 | — | 2·7 | 2·55 |
| 83 | 17 | 3·1 | 2·9 |
| 66 | 34 | 3·5 | 3·3 |
| 50 | 50 | 3·9 | 3·7 |
| — | 100 | 5·0 | 4·5 |

At this stage not all of the powders examined can be accepted as economic media; they have been introduced only to demonstrate their characteristics in this particular role although they may, in fact, be useful for laboratory purposes to provide higher density ranges than can be obtained with heavy liquids. The actual industrial economics, however, will be governed largely by the ore product value, the site price of the constituents of the medium and medium losses. From bench test work the last appears to be extremely small and this welcome indication is attributed to minimal disintegration of the medium in a streamlined bed, coupled with the simple and efficient method of recovery by sieving the fine medium from the relatively coarse ore.

## Depth of bed

Bed depth is another factor which directly influences the fluidization process; the pressure drop encountered is directly proportional to fluid bed depth and increases in the latter are associated with increased tendencies for bubble formation and, consequently, for the formation of heterogeneous beds. This trend can be reduced by fitting air distributors with finer pores and it appears that, for adequate air distribution, the pressure drop across the distributor should be at least equal to that across the bed.

Shallow beds provide the best conditions for separation and it is recommended that working depths be governed by the ore feed sizes. For coarse separations on −1½-in ore feeds media depths of 2–6 in might be adequate and, at these sizes, the associated bed turbulences might not be unduly disadvantageous. When finer separations are to be attempted, however, say down to 18 or 22 mesh or finer, bed depths of less than ½ in should be employed to obtain the most efficient performance.

## Apparent viscosity of bed

A knowledge of the resistance to particulate flow (apparent viscosity) in fluid beds is essential when designing separators for specific purposes and, as with wet systems, this factor has been considered by a number of investigators,[4–6] using various techniques for measurement. One of the more realistic and meaningful techniques was that employed by Daniels,[5] who has established the effects of a number of variables on the drag coefficient in various systems. He found the drag coefficient of metal spheres moving through beds of fluidized glass beads to be a function of the Reynolds number, the Froude number and the diameter ratio of the falling spheres and the mean bed particle size. Certain assumptions had to be made in order to determine the exact power for each of these factors and it is considered that these assumptions should be scrutinized more closely before the resulting relationships can be used confidently in practice.

It is doubtful if his use of a simplified Reynolds number is universally valid, although this resort enabled Daniels to formulate drag coefficients in terms of the well known dimensionless groups. In this respect it is particularly important from an equipment design aspect to establish a practical assessment of the rheological nature of fluid powder beds in order to correlate drag coefficients and associated apparent viscosities, and thus provide means for predicting solids settling characteristics in such systems.

mixture (sp. gr. 5·0) which was separated completely under similar conditions to those established in the first test.

### Size recoveries

The preliminary tests with synthetic mixtures were completely satisfactory and clearly warranted more detailed investigations into the working characteristics of this particular type of separator. Thus in further tests some of the effects of feed size were examined, again with a specially prepared quartz–hematite mix (w/w 50/50). The products were assessed on the basis of sink/floats in heavy liquid (TBE, sp. gr. 2·94) with respect to individual size fractions in order to establish the size recoveries and grades which had been achieved. A balance of the separation is shown in Table 4, where it is seen that 98 per cent of the hematite in the feed has been recovered in a 98 per cent pure concentrate. Separation efficiencies decrease with size although, even with the finest −18 +22 mesh fraction, 91 per cent of the hematite content was extracted in a 95 per cent pure sized product. At sizes coarser than 6 mesh the separation of hematite and quartz was practically complete.

**Table 4** Size recoveries with quartz–hematite mixture: feed rate, 20 lb/h

| Size fractions, mesh | Fluid bed floats, % sink | Fluid bed sink, % sink | Recovery of sink to sinks, % |
|---|---|---|---|
| −¼ in +6 | 1·0 | 97·5 | 99·0 |
| − 6 +10 | 2·5 | 97·3 | 98·2 |
| −10 +18 | 5·2 | 96·4 | 96·3 |
| −18 +22 | 14·3 | 95·5 | 91·4 |
| Calc. head | 1·9 | 98·1 | 98·3 |

The completely liberated mineral mixtures employed in the above tests were selected to provide a concrete basis for assessing the separating performances. With such mixtures one would expect more precise and more efficient separations than could be obtained in practice with the natural mineral distributions encountered in crushed ores. Consequently, even a brief account of the operations of this prototype equipment would be incomplete without some indication of its performance when treating commercial type feeds. Accordingly, tests were undertaken on two different ores (a Lancashire fireclay and a Derbyshire fluorite–barytes–galena ore) to provide a more practical account of the commercial potential of dry fluid bed separators. In assessing the results, however, it should be borne in mind that the maximum feed size was limited to ¼ in by the physical dimensions of the small-scale equipment.

### Fireclay

As mined, the fireclay contained deleterious iron minerals, mainly large nodules of siderite (sp. gr. 3·85), to the extent of approximately 4·5 per cent Fe, which cause discolorations and blow-holes in the final fired refractory products. A run-of-mine sample was stage crushed to −½ in and a −¼ in +22 mesh sample, assaying 4·4 per cent Fe, was extracted for the purpose of assessing its amenability to fluid bed separations. A −150 +200 mesh fluidized ferrosilicon bed provided a working bed density of approximately 2·9 g/cm³ and, with a fireclay feed rate of 25 lb/h, the separation represented by the iron balance given in Table 5 was obtained.

**Table 5** Extraction of iron mineral from fireclay

| Product | Wt, % | Assay, % Fe | Distribution, % Fe |
|---|---|---|---|
| Fluid bed sinks | 3·9 | 37·6 | 35·3 |
| Fluid bed floats | 96·1 | 2·8 | 64·7 |
| Calc. head | 100·0 | 4·2 | 100·0 |
| Assay head | — | 4·4 | — |

By removing a heavy concentrate, containing only 3·9 per cent of the feed weight, some 35 per cent of the Fe was removed and the iron content of the fireclay was reduced from 4·4 to 2·8 per cent Fe. To place this result in perspective, the float and sink products were treated in heavy liquid (sp. gr. 2·9) to indicate the maximum weight of iron minerals which were physically available for separation with the bed conditions selected. The results demonstrated that, under optimum conditions, a 5 per cent weight of heavy concentrate would be produced which would contain 42·5 per cent of the total feed iron. On this basis some 83 per cent of the 'available' iron had been recovered by direct heavy-medium separation. Further examinations of the heavy-liquid products demonstrated that size recoveries, based on heavy minerals, varied between 83 and 98 per cent over the size range treated, namely +22 mesh −¼ in.

### Fluorite–barytes–galena ore

This four-component ore was selected for treatment in order to extend and examine the potential of fluid beds over a wide range of separating densities and in the presence of complex mineral associations. It was supplied by courtesy of Glebe Mines, Ltd., and contains approximately 35 per cent fluorite, 33 per cent barytes and 3 per cent galena together with 29 per cent gangue, the latter consisting largely of limestone, chert and various clay minerals.

As in previous tests, optimum separating densities were not established for this particular feed, which was subjected directly to three fluid bed separations. In the first a −¼-in +22 mesh fraction was prepared and fed into a ferrosilicon bed of 2·78 g/cm³ working density in an attempt to float off the gangue constituents and so

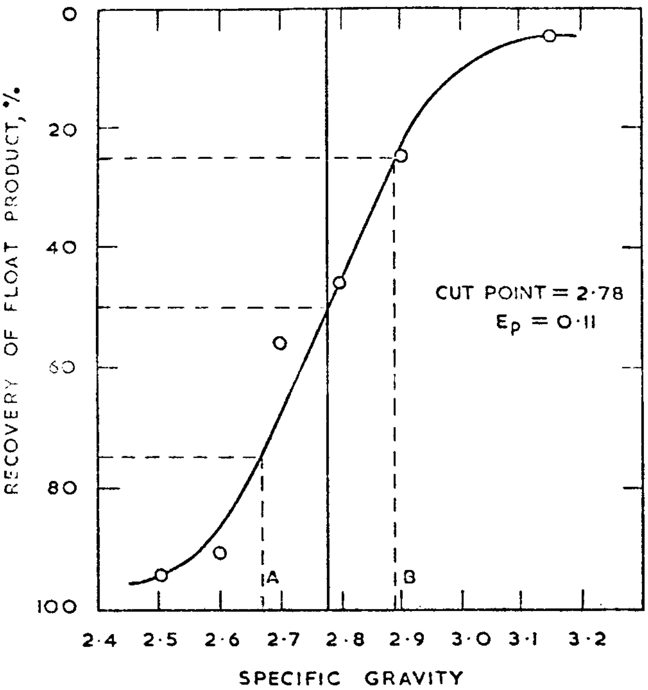

Fig. 7 Recovery of density fractions to float product

separations of the Glebe ore. The straight-line characteristic is typical of those obtained from normal, wet, heavy-medium separations.

Ruff[7] quotes $E_p$ values ranging from 0·03 to 0·05 in practical operating wet systems. From Fig. 7 it can be seen that an $E_p$ of 0·11 was associated with this particular separation and, in view of the cursory nature of this test, the extremely fine size of the feed and the small scale of the unit operation, it is considered to be a satisfactory result. Further, the exact reproduction of the previously specified cut-point (sp. gr. 2·78) should be noted as an indication of the close control which can be applied with these systems.

## Conclusions

This preliminary investigation has demonstrated that pneumatically fluidized powders can be employed to provide media having effective densities ranging up to approximately 6 g/cm$^3$. It has also demonstrated that the resulting apparent bed densities are primarily related to the specific densities of the powders employed (Table 2) and, to lesser extents, to their sizes (Table 1). There is also evidence that particle shape and fluidizing air quantities are other factors which have a secondary influence on resulting bed densities. It was found possible to prepare and mix powders, having different physical properties, to provide continuous ranges of bed densities for the effective separation of the mineral constituents of ores. Further, the slight density gradients which occur in beds of such mixtures can be exploited to provide a fine operational control of the fluid bed density. It should also be reported that throughout the series of tests there has been no indication of unduly severe breakdown or losses of the media employed.

Excellent separations of synthetic mixtures as well as the constituents of natural ores have been made, on a continuous bench scale, using fluid bed techniques. Recoveries in excess of 90 per cent have been achieved, in conjunction with high product grades, with feed sizes ranging from $\frac{1}{4}$ in down to 22 mesh. More specifically, a gravity distribution curve relating to the separation of a $-\frac{1}{4}$ in + 22 mesh complex fluorite–barytes–galena ore demonstrated the metallurgical feasibility of the equipment described for mineral separations. In this instance fluorite, barytes and galena preconcentrates were produced separately; they contained 76·5 per cent $CaF_2$, 85·6 per cent $BaSO_4$ and 28·5 per cent Pb, and were associated with recoveries of 83, 77 and 71·3 per cent respectively.

Thus if the results can be reproduced economically on a larger scale with equipment of a reasonable size, such equipment will provide an effective means of preconcentration in arid areas where normal, wet, heavy-media systems cannot be operated.

Because of the limitations imposed by the small scale of the equipment used, and by the preliminary nature of this investigation, it has not been practicable to obtain much of the information required for more specific design purposes and for practical economic assessments. In this respect it will be necessary to examine in more detail the physical properties and the related variables associated with fluid beds so that the most suitable conditions can be predicted for any particular mineral separation requirement. Equally important, it will be necessary at an early stage to determine the sources and magnitude of media losses. Also, it will be necessary to compare the metallurgical and mechanical advantages of alternative equipment layouts and designs.

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