

Accessed from: http://hdl.handle.net/1959.13/1296300
Gravity separation and flotation of fine particles using the Reflux Classifier platform

Kevin P. Galvin* & Simon M. Iveson

Centre for Advanced Particle Processing and Transport
Newcastle Institute for Energy and Resources
University of Newcastle, Callaghan NSW 2308, Australia

ABSTRACT
Fine particles are the most valuable because they are the most liberated. However, they are also the most expensive and difficult to recover and concentrate. The Reflux Classifier is a novel invention that combines many of the virtues of existing fine particle separation technologies in a way that provides profound synergies. Multiple parallel narrow channels create a laminar-shear separation zone. The laminar flow provides a well-defined velocity gradient that exposes particles on the wall to a conveying velocity that is approximately proportional to their size, thus reducing the dependence of elutriation velocity on particle size. The high shear rate in these channels generates a hydrodynamic lift force that selectively lifts low-density particles off the channel wall and thus causes them to be preferentially conveyed out in the overflow. Particles that are not elutriated slide back down into the mixing reflux zone beneath the inclined channels which gives them multiple opportunities to re-enter the channels. The resultant suspension of both coarse and fine high-density particles in the fluidized bed zone at the base of the unit generates a strong autogenous dense medium that helps to direct large low-density particles back up to the overflow. The fluidization water also simultaneously de-slimes the high density underflow product. When placed in a centrifuge, the benefits of these features multiply with the improvements in capacity and selectivity that arise from high G-forces. When inverted, these features can be used to perform flotation well beyond the conventional flooding limit. Hence this invention platform has the potential to dramatically improve both gravity and flotation separation performance across the minerals processing industry.
INTRODUCTION

One of the greatest challenges in coal and mineral processing is the beneficiation of relatively fine particles, especially those below about 0.20 mm. It is increasingly apparent that new technologies will be needed, due to the significant trend of falling grades, and the need to liberate and recover ever finer particles. However, introduction of new technologies has always been difficult due to the conservative nature of the industry, so any new technology needs to offer a substantial step change in performance.

This paper reviews the development of a new technology platform, the so-called Reflux Classifier. Figure 1a is a schematic representation of the system and Figure 1 b shows a photograph of the equipment at full-scale. The system consists of a vertical fluidized bed zone, with parallel inclined plates mounted above. The feed enters the upper portion of the vertical section. The denser material emerges from the base of the device and the lower density particles via the overflow launder.

![Diagram](image)

**Figure 1** The standard Reflux Classifier, (a) schematic and (b) photograph of the RC™3000 with a 3.0 m diameter (Courtesy FLSmidth-Ludowici)

The Reflux Classifier is able to achieve density-based separations that closely match results from float-sink tests, for both low-density coal and high-density iron-ore separations (Walton et al., 2010; Amariei et al., 2013). In coal beneficiation, this has enabled it to achieve sharp separations at low separation density cut points which has led to significant increases in plant yield by allowing the same
cut point to be used in each circuit (Galvin et al., 2010; Galvin, 2012). In metalliferous ores such as chromite, a single Reflux Classifier stage has replaced multiple stages of spiral separators and upward current classifiers, delivering higher grade and recovery. Figure 2 shows recent data obtained using a laboratory scale Reflux Classifier for finely ground iron ore, demonstrating the Fe recovery and grade of the product as a function of the particle size. Here the system performed down to a size of 20 μm, with the solids throughput at 5.0 t/(m² h). The overall feed, product and tailings Fe% grades were 35.4, 65.4, and 18.2, with 58% by weight passing 38 μm.

![Figure 2](image.jpg)

Figure 2  a) Fe recovery and b) product grade versus average particle size obtained by Reflux Classifier

The Reflux Classifier combines many of the virtues of traditional technologies such as spirals, shaking tables and teetered bed separators in a unique way that achieves profound synergies. The main purpose of this paper is to outline this invention’s major attributes, and how they meet the requirements of a powerful and robust separator. A second purpose is to describe two novel variations for ultrafine particle processing, namely enhanced centrifugal separation and in transforming the hydrodynamics of flotation cells.

**THE SYNERGY OF REFLUX CLASSIFIER SEPARATION MECHANISMS**

Although the Reflux Classifier is often considered as “yet another fluidized bed upward current classifier”, the reality is far different. The powerful laminar-shear separation which occurs in the inclined channels is a totally different mechanism to conventional fluidized bed segregation. It enhances the effectiveness of the fluidized bed separation zone at the base of the vertical section. The
turbulent mixing zone in between provides an effective interface between these two segregation zones. The complementary nature of these zones and the overall operation of the device are now explained.

**Laminar-Shear Separation in Narrow Inclined Channels**

The PNK theory (Ponder, 1925; Nakmura & Kuroda, 1937) predicts the increase in the hydraulic capacity of inclined channels over conventional thickeners based on the assumption that any particle that settles onto the lower channel surface will slide back down into the fluidized chamber. However, this theory incorrectly predicts that capacity should increase indefinitely with increasing channel length $L$, whereas in reality particles that settle onto the incline do not always slide back into the vertical section. Instead re-suspension may occur due to fluid shear, turbulent mixing, etc. Laskovski et al. (2006) developed an empirical expression for the throughput advantage over conventional fluidized beds, $U/u_t$, where $U$ is the superficial fluid velocity in the vertical section and $u_t$ the terminal velocity of the particle at the point of separation. They obtained an asymptotic result for high aspect ratio inclined channels given by $U/u_t = 7.5Re_t^{-0.33}$, where $Re_t$ is the particle settling Reynolds number. This general result applies to fine, dense particle retention and to more widely-spaced channels where the flow is usually turbulent. When more closely spaced channels are used, the flow becomes laminar, and a high shear rate develops, resulting in significant additional benefits.

Figure 3a shows the key forces that apply to the transport of a single particle in an inclined channel with average upwards fluid velocity $U'$. The body force, in this case due to gravity $F_G$, has a component both normal and tangential to the channel wall. The tangential component is opposed by the hydrodynamic drag of the fluid $F_D$. 
Figure 3  a) The body $F_G$, drag $F_D$ and lift $F_L$ forces acting on a particle resting on the base of an inclined channel; b) Laminar parabolic velocity profile gives a near-linear dependence of local fluid velocity $u(x)$ on particle size $d$, which results in particles of different sizes and hence different settling velocities $u_t$, being held in equilibrium.

Figure 3b shows that a hydrodynamic balance can develop between the tendency for a particle to settle in the tangential direction (at velocity $u_t' = u_t \sin \theta$), and the tendency for the particle to convey. Faster settling particles will slide downwards, while slower settling particles will be conveyed upwards. This critical condition can exist simultaneously for particles of very different size. This situation arises when two things happen. Firstly, when the velocity gradient is linear, the local fluid velocity “felt” by a particle on the wall is proportional to its diameter. Secondly, when the particle settles in the Intermediate regime ($1 < Re_t < 500$), the particle terminal velocity $u_t$ tends to increase roughly linearly with diameter (Vance & Moulton, 1965). In this situation, the effects of particle size are suppressed, resulting in a separation that depends mainly on particle density (Galvin et al., 2009; 2010).

Closely spaced inclined channels promote laminar flow. The resulting parabolic velocity profile gives a nearly linear velocity gradient at the wall for $d \ll z$ (Bird et al., 1976). As a result, for dilute separations under laminar conditions, the local fluid velocity felt by a particle resting on the wall is $U'lu_t = z(3d)$ (Galvin et al., 2009). Narrow channels also result in a high shear rate at the wall which generates a hydrodynamic lift force $F_L$, which is well described by King and Leighton (1997). For closely spaced inclined channels a critical and robust window emerges in which $F_L$ is significant. Low density particles are preferentially lifted away from the surface, exposing them to higher local fluid velocities, which further helps to selectively elutriate these particles (Galvin & Liu, 2011). The higher density particles remain in contact with the inclined surface and slide downwards.
The above combination of conditions can be made to occur simultaneously using closely spaced and relatively long channels (typically $z = 6$ mm and $L = 1000$ mm). This length is needed to insure that all particles entering the channel have the opportunity to settle onto the inclined surface while conveying in the upwards direction. It is at the inclined surface that these critical conditions develop between the hydrodynamic drag and the sedimentation forces in the tangential direction, and between the lift force and the sedimentation forces in the normal direction. Figure 4 illustrates the benefits of using high-shear laminar flow by comparing performance with earlier results using widely-spaced channels where the flow was turbulent. Clearly laminar flow gives much less variation in density cut point with particle size (Figure 4a), as well as improved sharpness of separation (Figure 4b).

**Figure 4** Comparison of performance of the Reflux Classifier to separate coal using wide versus narrow channels. a) density cut point versus particle size and b) Ecart probable versus particle size.

At elevated concentrations, the fluid velocities required to achieve these conditions are reduced substantially, due to hindered settling. This effect due to hindered settling has further benefits. The higher solids concentration involves the transport of a higher solids flux, and therefore higher throughput. Further the lower convective velocity results in exceedingly low velocities near the inclined surface. Thus the tendency for relatively fine, dense particles, to be conveyed up the incline is greatly reduced. These fine dense particles, which come to reside at the incline, are shielded from the much larger convective velocities. Furthermore, because of their higher density, the local hindered settling factor that applies to these denser particles at the wall is relatively minor compared to the strong hindered settling factor that applies to the lower-density solids suspended away from the wall.
Asif (1997) provides a density based hindered settling factor that accounts for this observation. This means that the system can be operated at remarkably high volumetric loadings, while preventing fine dense particles from reporting to the overflow. This capacity advantage is consistent with the so-called Boycott Effect (Boycott, 1920) from inclined sedimentation, though the mechanism described here is different.

It should be clear from this discussion that the inclined channels provide an interesting combination of forces that work in unison to manifest a strong and robust separation on the basis of density. This condition has been described previously as a “laminar-shear mechanism” (Galvin, 2012). There are some similarities here with what arises in spirals and shaking tables, in which the shear rate near the surface promotes the lifting of lower density particles, while finer high density particles are shielded from the convective flow. However, in those systems the relatively low and the relatively high density particles both continue to transport in the downwards direction, with a relatively diffuse transition between the eventual output streams. In contrast, in the Reflux Classifier the two product streams exit at opposite ends of the device, so minimising misplacement of material between them. Furthermore, in spirals and tables the fluid flow has a free surface and is often turbulent, making it complex and difficult to define. However, in the constrained system of narrow inclined channels with laminar flow, the fluid velocity can be described much more precisely at all locations.

**Turbulent Mixing Zone**

The Reflux Classifier incorporates a vertical section below the inclined channels. The upper portion of this is called the “turbulent mixing zone” (Figure 1a). This zone is where the feed mixes with material continuously sliding back down from the inclined channels above. The material released back into this zone from the inclined channels effectively becomes “re-pulped” and is re-presented to the channels. This action is described as a form of “reflux”, and is similar to what is now formally encouraged in some of the new spiral separators known as “compound spirals” (Honaker & Ozsever, 2013).

The complex mixing that occurs in this section does not impact on the eventual separation performance, *per se*. This is because the eventual separation is governed by the conditions at the exit points of the technology, which are well defined, and often laminar in nature. There is clearly little or no mixing at the system overflow due to the highly constrained nature of the laminar flow through the inclined channels. And, with respect to the lower discharge, the uniform fluidization produces a steady hydrodynamics though the fluidized bed, adjacent to the point of discharge.
**Fluidized Bed Zone**

The lower fluidized bed promotes a strong density based separation, exploiting the so-called phase inversion phenomenon (Moritomi et al., 1982). A strong dense medium effect develops from these fine dense particles, resulting in the displacement of the relatively low density particles from the bed. It is essential, however, to operate the system at teetered bed conditions, with a near minimum fluidization velocity. This mechanism also occurs in other fluidized bed separators, however in the Reflux Classifier it is amplified due to the strong tendency to retain the relatively fine dense particles below the system of inclined channels. These particles continue to slide downwards and back into the fluidized bed. Thus the ideal conditions exist for developing a fine dense medium. Therefore large, low density, particles that happen to fall into the lower section are displaced upwards and back into the turbulent mixing zone. From there, due to the significant overflow flux, they are readily conveyed into the inclined channels. From there, the lift forces insure these particles remain suspended and reach the system overflow.

Thus, the system effectively sequences the particles according to their density, insuring the densest particles are first in line for reporting to the underflow. Adjustment of the set point to a lower density value simply permits the next densest particles to join this sequence and report to the underflow. While density is the major driver, particle size does play a role, and hence, as with most devices, there is shift in the density separation with particle size. However, the synergy between many of the mechanisms described above conspires to suppress the effects of particle size, as shown in Figure 3. Hence overall, the system provides for a high volumetric and therefore a high solids throughput, while achieving a powerful separation on the basis of density.

**Overall Design, Operation and Control**

Having outlined the internal separation mechanisms, some comment on the overall system design and operation is now required. The separation performance of inclined channels can be accurately predicted using simple one-dimensional models (Laskovski *et al.*, 2006; Galvin et al., 2009; Galvin & Liu, 2011). There is no dependence on the width $W$ of the channels provided it is much greater than the channel gap i.e. $W \gg z$. This gives particles an extra degree of freedom to rotate and thus minimises or eliminates their tendency to form blockages. Samples with some particle sizes larger than half the channel gap have been routinely tested in both laboratory and plant trials without blockage problems arising. As channel width increases, it does become necessary to include internal launders so that particles do not have to travel far in the horizontal transverse direction to exit from the channel. These
internal launders are essential for achieving scale-up. Performance at full scale has repeatedly been shown to be well predicted by laboratory-scale trials (e.g. Iveson et al., 2014).

The use of a single large unit to treat an entire plant’s throughput is usually preferable to technologies where scale up can only be achieved by using a large number of small units operated in parallel. In such cases great care must be taken to representatively distribute the feed between all the units and to make sure that they are all operating with the same set points. Otherwise the sharp separation achieved in an individual unit is blurred when its product is combined with other products obtained at slightly different cut points. In contrast, the Reflux Classifier processes significant tonnages, with uniform conditions driven by the fluidized bed, and the independent action of the inclined channels.

The fluidization rate is set at the minimum level sufficient to ensure that all particles present in the bed are fluidized. This fluidization prevents particles from consolidating onto the base of the device. The fully suspended bed therefore moves gradually towards the underflow discharge point.

The density cut-point is controlled via a single control variable, the lower suspension bed density, measured by a pair of pressure transducers (Figure 1a). Once the bed density exceeds the set point, the lower discharge valve opens. Thus typically the underflow is at a relatively low rate with a high solids concentration. All other material reports to the overflow at a relatively low solids concentration. The control system automatically adjusts to variations in the plant feed composition and/or flowrate to target a constant cut point.

**NOVEL VARIATIONS OF THE REFLUX CLASSIFIER CONCEPT**

This section describes two novel applications of the Reflux Classifier concept. The first places the device in a centrifugal field to enable separation of ultrafine particles. The second inverts the device and applies it to flotation.

**Enhanced Gravity – the Development of the Reflux Graviton Separator**

Existing centrifugal separators such as the Knelson (Honaker & Mondal, 1999) and the Falcon (Kroll-Rabotin, 2010, 2012) achieve a capacity advantage over conventional fluidized beds due to the strength of their centrifugal acceleration, $gG$, where $g$ is the acceleration due to gravity, and $G$ is a scalar. These technologies, referred to as “enhanced gravity”, also improve density separation performance by shifting the settling regime of the particles from the Stokes to the Intermediate regime, thus reducing the dependence of settling velocity on particle size from $d^2$ to $d^1$ (Vance & Moulton, 1965).
The Reflux Graviton separator incorporates the basic arrangement of the Reflux Classifier into a centrifugal field. Figure 5a provides a schematic arrangement showing the horizontal direction of the centrifugal force $F_c$, and the orientation of the device. Galvin and Dickinson (2013) modelled the benefits of combining the centrifugal forces with the benefits of the so-called “Boycott Effect” (Boycott, 1920). They predicted that the capacity advantage should increase by the factor $G$ due to the centrifugal acceleration field. The capacity advantage is defined as the ratio of the superficial flow velocity through the system, $U$, relative to the terminal velocity, $u_t$, of the $D_{50}$ particle, the particle with an equal tendency to report to the overflow or be retained. Figure 5b shows the capacity advantage, $U/u_t$, versus the theoretical capacity advantage, $Gz/(3d)$. The result is extraordinary. Firstly a capacity advantage of more than 1000 fold was achieved, even though the maximum value of $G$ was only 73. Secondly, there was remarkable parity between the actual and theoretical capacity advantage, which indicates that the benefits of the centrifugal force and the Boycott effect multiplied. Galvin and Dickinson (2013) also demonstrated that the high shear rate within the inclined channels leads to significant inertial lift, with reasonable agreement with the theory of Galvin and Liu (2011). The work to date, while clearly of a preliminary nature, demonstrates the potential for a significant advance over all other centrifugal technologies.

**Development of the Reflux Flotation Cell**

Flotation is arguably the most significant of the fine particle beneficiation technologies. Current technologies include (i) mechanical cells (ii) flotation columns and (iii) Jameson Cells. These well-established technologies are here described as “conventional cells”. Conventional flotation cells are all
described by Drift Flux theory. Hence they are all constrained to operate within essentially the same operating limits shown in Figure 6a (Galvin & Dickinson, 2014), defined in terms of the downwards wash water flux, \( j_w \), versus the gas flux, \( j_g \). High recovery requires, among other things, a high gas flux through the flotation cell. However, gas fluxes exceeding about 2.0 cm/s tend to result in excessive entrainment of slimes. Increasing the wash water flux to remove these slimes leads to flooding, at which the concentration of bubbles in the froth layer becomes identical to that in the bubbly zone and so no separation is possible. This is especially true when relatively fine bubbles are used, due to entrainment of bubbles into the tailings (Miettinen et al., 2010). While much flotation research has focussed on improvements in reagents and bubble-particle collision efficiency, little attention has been paid to the flooding limit as it was considered a fundamental and unavoidable limitation.

![Figure 6](image)

**Figure 6** a) Wash water flux versus gas flux operating regimes of conventional flotation compared with the Reflux Flotation Cell (Galvin & Dickinson, 2014); b) Schematic of the Reflux Flotation Cell and downcomer

Flotation is usually considered to be a distinctly different technology to gravity separation. However, once particles have attached to bubbles, the recovery of these bubble-particle clusters becomes a gravity separation process, albeit one that is concerned with positively-buoyant entities. An inverted Reflux Classifier had already been used successfully to recover buoyant cenospheres from fly ash (Li et al., 2014). So this inverted configuration was also applied to flotation, in a device referred to as the “Reflux Flotation Cell” (Figure 6b). The feed enters via the central downcomer, resulting in fine hydrophobic particles attaching to the air bubbles, leaving the fine hydrophilic particles to flow with the water. In this system independent control of the shear rate and bubble generation is achieved conveniently using the sparger arrangement (Dickinson & Galvin, 2013).
The inclined channels at the base prevent the loss of bubbles in the underflow, even when extremely high wash water rates are applied. Figure 6a compares the operating regime of the Reflux Flotation Cell with conventional flotation. The crosses denote actual experimental conditions studied (Galvin & Dickinson, 2014). A major paradigm shift is that the device can be operated without a froth zone i.e. beyond the flooding limit. Froths provide a method for water rejection and therefore slimes rejection. However, they are relatively impermeable and thus become unstable at significant wash water flows, resulting in poor wash water distribution, break down and lower recovery (Neethling & Cilliers, 2001).

In the Reflux Flotation Cell, a bubbly zone is formed which is highly permeable to wash water flow, thus allowing very efficient de-sludging. Another significant feature is that the top of the device is enclosed by a fluidization distributor, forcing the bubbly product to accelerate and exit via a central outlet. We believe this promotes more even wash water distribution and reduces levels of coalescence. This approach contrasts with conventional devices which operate with a free-surface and external overflow launder. A free surface above a large cell leads to considerable coalescence (and hence loss of product), given the journey associated with bubbles migrating horizontally to the overflow.

CONCLUDING REMARKS

From what began as simply an effort to increase the throughput capacity of conventional fluidized bed separators, the scope, separation power and flexibility of inclined channels have far exceeded initial expectations. The synergies achieved by using laminar flow with high shear rates, combined in some cases with high G-forces, have enabled very sharp density-based separations to be obtained down to very fine particle sizes. In cases where there is too little difference in density to perform adequate separation, then the approach can be used in inverted form to expand the operating regime for flotation well beyond the flooding limit, to promote rapid flotation and de-sludging of ultrafine particles. Hence this technology provides the major step-change improvement in performance that is needed to meet the challenges of fine particle beneficiation that are being faced by the mining industry.

ACKNOWLEDGEMENTS

The authors acknowledge the large number of colleagues, students and technical staff from the Department of Chemical Engineering at the University of Newcastle who have assisted in this work over the last decade. Research on the development of the Reflux Classifier has been supported by a number of Australia Research Council (ARC) grants, Australian Coal Association Research Program (ACARP) grants, and by a research and development agreement with FLSmidth-Ludowici on
applications involving the Reflux Classifier and related technologies. The University of Newcastle owns relevant international patents, and the technology is licensed to FLSmidth-Ludowici.

REFERENCES


