Classification of Particles in the Submicron Range in an Impeller Wheel Air Classifier

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Abstract

It is the aim of this paper to show that it is possible in principle to obtain submicron cut sizes with a counterflow centrifugal classifier, provided that a forced vortex is used in the classification chamber and the circumferential velocities are greater than 100 m/s. These findings can be generalized and are not limited to the geometrical dimensions of the classifier used in the experiments. With a new impeller or deflector wheel classifier, cut sizes as small as 0.3 μm have been obtained with feed mass flow rates of 5 kg/h and higher.

1 Introduction

The production of particle size distributions with top sizes of 1 μm or even less is one of the most difficult tasks in the mechanical processing of powders. With comminution and classification in this size range, the separation of the particles from the flow and even the measurement of the size distributions produced demand principles and designs which have to be operated near or at their limits [1].

It appears that with minerals a natural size limit of approximately one micrometer seems to be stipulated by the physical laws which govern the above processes. Problems arising in the classification of fine particles are mainly due to the fact that gravity forces become negligible and stochastic particle movement caused by diffusion or Brownian motion and turbulence of the flow may become predominant. Fine particles follow the drag forces exerted by the flow more readily and it becomes more and more difficult to move the particles in directions which deviate from the direction of the flow. The choice of a size limit of approximately one micrometer is not arbitrary, although depending on the material, the size limit varies. The systematic movement of a particle in a flow, described by its trajectory, is governed by its stationary settling rate, \( w_g \), in the gravity field. The most important forces controlling the systematic particle movement are, for example, drag force, gravity force, dynamic lift, inertia and electrical forces. The different classifier principles are defined by the main forces used and the principal movement of the coarse particles with respect to the flow. If the removal of the coarse particles takes place against the flow, the classifier uses the counterflow principle. If the coarse particles travel perpendicular to the flow, the classifier is called a cross-flow classifier [2].

2 The Counterflow Principle

A gravity counterflow classifier [3] consists of a vertical tube of, for example, cylindrical cross-section. The air rises in the tube. On each individual flow line, a particle is taken to the top of the tube that is removed with the flow if its stationary settling rate, \( w_g \), is smaller than the air velocity, \( v_a \). It settles in the rising flow if its settling rate is greater. The so-called cut size is defined by:

\[
v_a = w_{gc} = \frac{\eta \cdot 8x^2}{18y}
\]  

The cut size, at least theoretically, does not leave the classification zone, because its exit velocity equals zero. In actual operation, cut size particles are distributed evenly to the fine and the coarse fraction, and are therefore sometimes called the equiprobable particles. Due to their small settling rates, gravity counterflow systems are unsuitable for small cut sizes. These demand a counterflow centrifugal system, the basic principle of which is shown in Figure 1 [4]. It consists of a flat cylindrical classification zone of height H. Air is introduced at the periphery under a certain angle, thus inducing a free vortex sink flow passing through the classification zone on a spiral path (flow line). The feed particles enter the classification zone near the outer periphery. Fine particles follow the flow towards the centre while coarse particles remain...
Principle of a counterflow centrifugal classifier or spiral classifier near the outer periphery and must be withdrawn from there. The cut size, however, travels in the classification zone on a circular path. It remains, at least theoretically, in the classification zone. A radial force balance yields the basic equation for pre-calculation of the cut size, $x_0$ or its stationary settling rate, $W_{gc}$:

$$W_{gc} = \frac{v^2}{g} = \frac{W_{gc}}{a/g}$$  \hspace{1cm} (2)

According to Eqn. 2, the radial velocity component of the air, $V_r$, equals the settling rate of the particles in the centrifugal field, $W_{gc}$. The latter exceeds the stationary gravity settling rate by the acceleration ratio, $a/g$. If the particle travels on a radius of $r = 0.1$ m with a circumferential velocity of $v_c = 100$ m/s, the ratio of centrifugal acceleration, $a$, to gravity constant, $g$, becomes ten thousand, thus increasing the stationary settling rate considerably.

It is a well-known fact that counterflow centrifugal classifiers operated under the above or similar conditions have a lower cut size limit of approximately 1 μm to 2 μm for mineral particles. The production of even finer cut sizes demands:

- higher circumferential velocities, $v_c$, of the air and of the particles, respectively, than those used up until today,
- a reduction of the volume flow rate of air, or the size of the classifier,
- operating the classifier at reduced air pressures using the so-called slip between the particles and the gas molecules.

**2.1 Lower Cut Sizes Due to Increased Slip Between the Particles and the Gas Molecules**

If the size of the particles settling in a gas becomes small in comparison to the scale of the molecular processes in the gas—for example, the mean free path of the gas molecules—the non-continuity of the gas becomes apparent and a slip of the gas adjacent to the particle surface may occur. This slip leads to the so-called Cunningham correction, $Cu$, which is equal to the ratio of the true terminal velocity to the terminal velocity in continuum flow.

The mean free path of the gas molecules can be calculated from:

$$\lambda = \frac{kT}{\pi \sqrt{2 d_m^2 p}}$$  \hspace{1cm} (3)

With the Boltzmann constant: $k = 1.3804 \times 10^{-23}$ Nm/K, the temperature: $T(K)$, the diameter of the molecules: $d_m = 3.7 \times 10^{-10}$ m (air), and the gas pressure: $p(Pa)$ one obtains:

$$\lambda / \mu m = 22.7 \frac{T / K}{p / Pa}$$  \hspace{1cm} (4)

The Cunningham correction may be calculated from Eqn. 5, first proposed by M. Knudsen and S. Weber [5] in 1911 and corrected by C.N. Davies [6] in 1945 with respect to their numerical constants:

$$Cu = 1 + \frac{2\lambda}{x} \left[ 1.257 + 0.4 \exp \left( \frac{-0.55x}{\lambda} \right) \right]$$  \hspace{1cm} (5)

Introducing Eqn. 4 into Eqn. 5 yields Eqn. 6, where $T$ has to be introduced in K, $p$ in Pa and $x$ in μm:

$$Cu = 1 + \frac{45.4T}{xp} \left[ 1.257 + 0.4 \exp \left( -0.024229 \frac{xp}{T} \right) \right]$$  \hspace{1cm} (6)

It is convenient to plot $Cu$ as a function of the product $xp$ in μmPa, with the temperature, $T$, as the parameter. Figure 2 shows that the Cunningham correction starts to rise as soon as the product $xp$ becomes smaller than $xp = 10^5$ μmPa, or if the particle size drops to 1 μm at 1 bar air pressure. If the product of particle size and pressure drops by a factor of 100, the Cunningham correction rises from $Cu = 1.167$ at $xp = 10^5$ μmPa to $Cu = 22.62$ at $xp = 10^3$ μmPa.

Y. Yamada, S. Doi and K. Inouya [7] have described experiments performed with a counterflow centrifugal air classifier at a reduced pressure. The classifier was installed together with its ancillary equipment, for example, its feeder, etc. in a special tank and
operated at reduced pressure. The batch experiments were performed at a mass flow rate of 2.2 kg/h and a solids loading of $\mu = 0.03$. The experiments proved the expected shift in the cut size to finer particle sizes. In Figure 3, the cut size is plotted against pressure, $p$, in the classification chamber for two conditions: $v_\varphi = 100$ and 50 m/s and $v_r = 0.5$ m/s in both cases. One realizes that only a pressure reduction below approximately 0.2 bar leads to an effective reduction of cut size. The cut size drops from approximately 0.9 $\mu$m or 1 $\mu$m at 1 bar to approximately 0.35 $\mu$m at 0.0921 bar.

Y. Yamada and his colleagues state [7] that the reduced pressure air classification still has many problems, the most important of which are the continuous operation, problems of dispersing the extremely fine feed materials and the low mass flow rate of solids.

### 2.2 Lower Cut Sizes at Higher Circumferential Air Velocities and in Smaller Classifiers

In a counterflow centrifugal classifier the cut size is defined by Eqn. 2. If one introduces the stationary settling rate of a spherical particle [7]:

$$w_{gc} = \frac{\rho_p g x_c^2}{18 \eta}$$

into this equation one obtains:

$$x_c v_\varphi = \sqrt{\frac{18 \eta}{\rho_p}} v_r r \sqrt{\frac{18 \eta}{\rho_p}} \sqrt{\frac{\dot{V}}{2\pi H}}$$

One realizes from Eqn. 8 that for a given flow rate of air and a given classifier size, the product of the cut size and circumferential speed, $x_c v_\varphi$, remains constant. With limestone particles of $\rho_p = 2710$ kg/m$^3$ and air of 20°C, the product $x_c v_\varphi$ equals:

$$x_c v_\varphi = 3.4673 \cdot 10^{-4} \sqrt{\dot{V} r}$$

Figure 4 shows the dependence represented by Eqn. 9. The lower curve shows the range of cut sizes obtainable if the product $v_r r = 0.1$ m$^2$/s, the second if $v_r r = 0.01$ m$^2$/s.

Cut sizes below 1 $\mu$m demand high circumferential velocities of the air and small products of $v_r r$, i.e. small classifiers and low radial velocities. With $v_r r = 0.01$ m$^2$/s, a cut size of 1 $\mu$m demands a circumferential air velocity of 110 m/s. Halving the cut size to 0.5 $\mu$m doubles the circumferential air velocity. Therefore, depending on the conditions chosen, extremely high circumferential velocities may be necessary to obtain small cut sizes.
A further reduction of the cut size of a counterflow centrifugal classifier can only be obtained if the size of the classifier (r) or the radial velocity component (v_r) is reduced. However, due to the fact that the air can only carry a limited amount of particles, a certain mass throughput demands a certain flow rate of air. Therefore, if a certain volume flow rate of air and a certain radial velocity component have to be used because of:

\[
\dot{V} = 2\pi r H v_r
\]  

the product \( r \times H \) has to remain constant. If one intends to reduce the size or rather the radius, \( r \), of the classifier, either the height, \( H \), has to be increased or more than one classifier has to be used.

The above estimates also show that with small cut sizes, the ratio of radial to circumferential velocities, \( v_r/v_\phi \), i.e. the slope of the flow lines, becomes very small. The angle is of the order of 0.3 to 0.5 degrees, virtually impossible to obtain with a free vortex as used in ordinary spiral classifiers.

This problem can be overcome, however, by the introduction of a special impeller wheel into the centre of the classification zone. These impellers consist of a rotor with a series of radial blades at their outer periphery. Figure 5 shows the set-up used in many cases of application.

At present, these deflector or impeller type wheel classifiers use maximum circumferential speeds of approximately 100 m/s to 120 m/s. They could be used, in principle, with higher speeds of rotation. However, the design of these rotors would then have to be changed for high-speed performance. This line of thinking has up until now not been pursued in actual practice, mainly because the power consumption of these high-speed systems may become high unless special design criteria have been fulfilled [9-11].

K. Legenhausen [9,10] showed in the investigation of flow patterns in a deflector wheel classifier that the flow pattern in the bladed area consists of a superposition of a forced vortex and a sink flow. In actual practice, however, this flow pattern can only be obtained if the flow approaching the outer periphery of the rotor has the same velocity as the tips of the rotor. Only then can vortices be avoided which form within the converging channels between the rotor blades. Under ideal conditions, the radial flow between the rotating blades runs parallel to the rotor blades, as shown in the centre of Figure 6. Due to small radial velocities and the dimensions of the channel, the flow is laminar.

In the investigation of the flow patterns in deflector wheel classifiers, K. Legenhausen [9,10] also found that the flow in the centre of the rotor, i.e. the bladeless zone, changes from a forced vortex into a free vortex flow or a flow with friction.

If one assumes the above flow fields, the course of the radial and the circumferential flow velocities with radius, \( r \), in the outer zone and the inner zone of the impeller rotor can be introduced into Eqn. 8 in order to pre-calculate the course of the cut sizes with respect to the radius of the classification zone.

With:

\[
v_r = \text{constant}
\]  

and:

\[
v_\phi^{-1} = \text{constant} \quad \text{(forced vortex)}
\]  

one obtains:

\[
x_c = \sqrt{\frac{18 g r^2 V}{\rho \omega^2}} \frac{1}{r}
\]  

The cut size rises in a forced vortex spiral flow inversely proportionally to the rotor radius, \( r \).
Fig. 6 Flow patterns with different \( \frac{v_c}{\omega r} \)-ratios

If, on the other hand, as observed in the inner bladeless zone of the rotor, the flow in circumferential direction follows a free vortex flow, one obtains Eqn. 15, because of:

\[
v_c r = \text{constant} \quad \text{(free vortex)} \quad (14)
\]

\[
x_c = \sqrt{\frac{18\eta v_i}{\rho v_i^2 r_i}} r \quad (15)
\]

In a free vortex spiral flow, the cut size rises linearly with radius, \( r \).

One therefore obtains the situation as shown in Figure 7. The cut size rises from a given value at the outer periphery to a larger value at the inner blade radius. It then drops linearly to the centre of the rotor.

H. Rumpf and K. Leschonski [3] pointed out in 1967 in the investigation of a counterflow gravity classifier that a high sharpness of cut can only be obtained and a hold-up of small particles in the classification zone can only be avoided if the cut size in the direction of flow always increases.

If a deflector wheel is used with blades at the outer periphery and a bladeless inner zone, this condition cannot be met, as can be seen from Figure 7. The cut size rises, as intended, within the zone with blades but drops again in the bladeless zone. Particles which passed the outer periphery of the rotor may therefore find a new equilibrium radius at smaller radii. These particles cannot, at least theoretically, be removed.

Fig. 7 \( x_c = f(r) \) with \( v_c \) depending on \( r \) according to \( v_c r^m = \text{const} \)
from the classification zone. In order to avoid this situation, the removal of the fines together with the air should take place immediately behind or near the inner rotor blade edges [6]. This can either be achieved by using long rotor blades, extending to the center of the rotor, and a central fines outlet, or shorter blades and an annular withdrawal section at the inner blade radius. Avoiding the free vortex in the centre also results in an appreciable reduction of the pressure drop of the classifier.

3 Description of the Clausthal High-Speed Classifier

Based on the flow field measurements and earlier classification experiments, a high speed impeller wheel classifier was developed by the author and J. Galk and investigated in J. Galk's thesis [12]. Figures 8 and 9 show sectional views of the classifier.

The high-speed rotor (Figure 8) consists of two circular discs, made from a special aluminium alloy. To lower the eigenstresses caused by high speeds of rotation, carbon-fibre-reinforced plastic rings are mounted at the outer periphery of the discs. The maximum speed of the rotor is 250 m/s [12].

The radial rotor blades are mounted in radial grooves cut into the plane surfaces of the discs. As shown in the cross-sectional view of Figure 9, only 16 long blades extend to the centre, i.e. the outer radius of the outlet. An additional 80 short blades, five of which are arranged between two long blades, guarantee the desired flow field, described in the centre of Figure 6.

The classifier air is fed into the classification zone at its outer periphery through three small rectangular channels, arranged tangentially. At least one of these channels is also used for the introduction of the feed particles with a special feeding and dispersion unit. Fine particles leave the central outlet together with the air. The coarse ones are collected at the inner periphery of the housing (Figure 8) and are removed from there through tangential outlets (Figure 9).

4 The Feeding and Dispersion Unit

In order to achieve cut sizes in air classifiers in the submicron range, a number of further prerequisites have to be fulfilled. Firstly, the feed material has to be dispersed in an air flow with the largest agglomerates presented to the classification zone being smaller than the desired cut size. Only then will the amount of particles smaller than the cut size in the coarse fraction be small or even negligible and a high fine particle yield be obtained. Secondly, as the sharpness of cut and the cut size of an air classifier depend on the solids loading of the air, the mass flow rate of the feed material should vary as little as possible [14].

For the dispersion of the feed material in the air used for the classification process and the acceleration of both particles and air up to the circumferential speed of the rotor, a combination of a newly developed brush feeder and an injector is used [14, 15]. The unit is shown in Figure 10. It consists of the feeding unit on the right and the dispersion unit on the left-hand side. Air is passing through both units from right to left. The rotating brush (1) receives the feed material from a small hopper (2). The feed material enters the voids between the bristles, is transported to the feeding point (3) and is then released into the incoming air travelling past the feeding point. The brush acts similarly to a rotary
vane feeder, controlling the throughput of particles by means of its speed of rotation, while producing a constant mass flow rate with little fluctuation. The brush also acts, depending on its speed of rotation, as a pre-dispersing unit.

The pre-dispersed feed material then enters the dispersing and accelerating zone of a special injector. The dispersion of agglomerates in the turbulent high-speed zone (5) of an injector has been described by K. Leschonski, S. Röthele and U. Menzel in 1984 [13] and by K. Leschonski, B. Benker and U. Bauer in 1995 [14, 15]. It has been shown that the feeding and dispersion unit of Figure 8 is suitable for dispersing feed materials with particles smaller than 1 μm.

5 Experimental Data as Obtained with the Classifier

The development and the theoretical and experimental investigation of the Clausthal impeller or deflector wheel classifier has been performed mainly by J. Galk [12, 16] and at present by U. Bauer in their PhD theses. Some of the most recent grade efficiency curves obtained with the new classifier are shown in Figure 11 and 12.

The feed material was limestone with a median particle size of \( x_{30.3} = 1.2 \) μm and a maximum particle size of approximately 4.2 μm. The grade efficiency curves given in Figure 11 were obtained with a radial velocity of the air of \( v_{ro} = 1 \) m/s and circumferential rotor velocity of \( v_{zo} = 100, 150, 175 \) and 200 m/s, respectively, at the outer rotor periphery. The cut size that is the median of the grade efficiency curve moves from 1.3 μm to 0.65 μm, 0.33 μm and 0.28 μm at the highest circumferential velocity. The grade efficiency curves were obtained at a feed mass flow rate of approximately 5 kg/h.

These experiments show that it is possible to obtain submicron cut sizes with a counterflow centrifugal
classifier, provided that a forced vortex is used in the classification chamber and the circumferential velocities are greater than 100 m/s. These findings can be generalized and are not limited to the geometrical dimensions of the classifier used in the experiments.

The grade efficiency curves were calculated from laser diffraction measurements of all three products using the method proposed by H. Hermann and K. Leschonski [17] in 1979.

**Figure 12** shows the grade efficiency curves obtained with different solids loadings, i.e. different feed mass flow rates. With a radial velocity of $v_r = 1$ m/s and a circumferential rotor velocity of $v_r = 150$ m/s, the solids loading altered from $\mu = 0.01$ to 0.03, 0.09 and 0.15. The grade efficiency curves shift to smaller cut sizes and the sharpness of cut decreases. It is the aim of the ongoing research to reduce the mass flow rate influence.

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### Symbols

- $a$: acceleration, subscript: air m/s², –
- $c$: subscript: cut size –
- $Cu$: Cunningham correction –
- $d$: diameter m
- $g$: gravity constant, subscript: gravity m/s², –
- $H$: height of classification chamber m
- $k$: Boltzmann constant Nm/K
- $m$: subscript: molecular –
- $O$: subscript: outer periphery –
- $p$: pressure, subscript: particle Pa, –
- $r$: rotor radius m
- $s$: subscript: radial –
- $T$: absolute temperature, grade efficiency K, –
- $v$: velocity m/s
- $V$: volume flow rate m³/s
- $w$: settling rate m/s
- $x$: particle size, equivalent diameter m
- $\eta$: viscosity Pas
- $\lambda$: mean free path m
- $\mu$: solids loading –
- $\varphi$: subscript: circumferential –
- $\rho$: density kg/m³
- $\omega$: angular velocity 1/s

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