Optimization of the separation parameters in inclined channels of liquid-solid fluidized bed

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ABSTRACT
A new theoretical formula can be used to calculate superficial velocity for particle separation with a critical condition, and it is based on the size, density, terminal velocity, Reynolds number of the particle, and equipment parameters. In a continuous system, a series of fractionation experiments were conducted to quantify the separation performance ranges for various operational factors, including channel spacing, solids throughput, and split fluidization rate. A great fluidization environment can be created by the 6 mm channel spacing, and the solids throughput of 10.20 t/(m²·h) provides a well effective separation result in the narrow channels, and the split fluidization of 0.0058 m/s can produce a higher shear induce force in the inclined channels to prevent the low-density particles from being lost in the underflow. The theoretical superficial velocity calculated by the new formula is 0.042 m/s, which can report the particles up and down to 9-fold to the overflow, it is almost the equal to the actual superficial fluidization velocity of 0.04 m/s.

Introduction
With the development of gravity concentration technology in the mineral industry, the gravity separation devices are commonly applied for collecting the valuable products in the mineral processing (Walton, Zhou, and Galvin). The fluidized bed is a classical gravity hydraulic separation equipment, which can be obtained a stable autogenous dense medium bed by changing the superficial fluid velocity or discharging the rate via the bottom, so that it can achieve the result of separating high-density minerals and low-density minerals (Epstein and Pruden 1998; Galvin et al. 2002b). An ideal objective separation of the gravity equipment was based on the particle density and greatly suppressed the effort of size and shape of particle (Galvin, Walton, and Zhou 2009; Galvin, Zhou, and Walton 2010). However, in practice, with a wide range of feed size, the separation performance is obviously affected by size which getting a deterioration of elutriation and the ash content of the clean products to higher. Therefore, it is a considerable challenge for an alternative technique to suppress the impact of particle size in the mineral process (Galvin, Zhou, and Walton 2010).

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A relatively new gravity separation equipment, Reflux classifier (RC), was combined a set of parallel inclined channels with a conventional fluidized bed, as shown in Fig. 1 (Carpenter et al. 2019; Galvin et al. 2005, 2002a), and it has been studied for decade years. The Boycott effect, which made a significant benefit for the high hydraulic advantage due to a larger effective settlement area in the inclined channels than conventional fluidized beds (Boycott 1920; Hunter, Iveson, and Galvin 2014). Meanwhile, the laminar-shear mechanism is a major cause for the low-density coarse particles easily tending to be re-suspended, which largely enhanced the efficiency of RC basis of density separation (Galvin and Liu 2011; Galvin and Nguyentrnam 2002; Laskovski et al. 2006). The research shows that by narrowing the channel spacing, the aspect ratio of inclined channel will increase, resulting in more obvious resuspension effect (Carpenter et al. 2019). In the further research, the final elutriation separation size initial decrease followed by a gradually increase as the number of inclined channels raise (Laskovski et al. 2006). Follow, an empirical formula was introduced to quantify the separation efficiency by Laskowski et al, and it was according to the kinematic theory proposed by Ponder and Nakamura and Kuroda (PNK theory) (Nakamura and Kuroda 1937; Ponder 1925). However, those previous key theories only offer a computational method of separation in the wide inclined channels, without considering of the forces on particles separation in the channel.

![Figure 1. Schematic of a reflux classifier (He et al. 2020).](image-url)
Recently, with the development of RC, a new separation mechanism described by Galvin who had found an elutriation basically based on particle density in the narrow spacing channels (Galvin, Walton, and Zhou 2009). As Fig. 2 shows, in the laminar flow, a parabolic velocity profile was developed within the inclined channel, those particles rest on the surface of plate whose local fluid velocity are linear with their half of the diameter, it shown that coarse particles experiencing the higher local fluid velocity, while the fine particles are opposite (Galvin, Walton, and Zhou 2009). Flow in the narrow channel, different distance from the channel have different local fluid velocities, thus, a high shear velocity is formed in the channel which induces an inertial lifting force. The introduction of the inertial lifting force standard can determine the possibility of particles leaving the surface of the plate and entering the high velocity area or staying on the wall at low fluid velocity (King and Leighton 1997). If the local fluid velocity of the particles is equal to the sedimentation velocity of the particles along the tangential plate surface, the particles will reach an equilibrium position in the tangential direction. However, when the lifting force exceeds the net weight in the normal direction, the particles will be transported upward along the upper plate, otherwise, the particles will slide downward along the surface of the lower plate to the fluid region under the inclined channel. Therefore, He provided a model of particles movement based on those conditions of the lift force equal to net weight force in the normal direction and the superficial fluid velocity match to the terminal velocity in the tangential direction, however, there is an intermediate variable in that paper (He et al. 2020). For the sake of simplicity, this paper provides a new equation to calculate the critical superficial fluid velocity.

Figure 2. Analysis the force for the particle in inclined channels (He et al. 2020). (a) Ash content of overflow products with different spacing. (b) Ash content of underflow products with different spacing.
Many previous works about coal or mineral corresponding to the narrow channels gap under the laminar flow have been proved to be satisfactory (Galvin et al. 2020; Nguyentransalam and Galvin 2001; Walton, Zhou, and Galvin). These are various factors of affecting the RC separation performance, among which the optimal separation parameters are obtained by improving the fluidization environment of particle separation. In this paper, we were concerned with the new formula to describe the critical superficial fluid velocity. Some single factor experiments were conducted to explore the potentiality ranges of various operational parameters in the continuous segregation. The samples of feed, overflow and underflow elutriated at each condition were weighed, analyzed for narrow particle size fractions, meanwhile, quantified the separation performance both on the size-ash curves and washability curve. The accuracy of the new formula is further verified by comparing the theoretical superficial velocity predicted with the actual separation fluidized velocity. Meanwhile, the operating parameters of laboratory-scale experimental provided some guidance for the design of RC geometric structure parameters and process in mineral processing field.

**Experimental Theory**

In the setting, the particle movement is mainly determined by the particle density, size, and flow characteristics. But, the forces on particles in fluid are very complicated, for it conveniently description, so, a coordinate system was established. It can be decomposed into the tangential component and normal component, in which \( y \) denotes the tangential direction, and \( x \) the normal direction, as shown in Fig. 2. For particles stranded on an inclined surface, the local velocity is proportional to the its diameter, so the velocity at the center of the channel is inconsistent with that at the surface of the plate. The flow rate in the center of channel is 1.5 times of the superficial velocity, while the flow rate near the plate surface is less than the superficial velocity. So, a high fluidization gradient was developed in inclined channels, inducing a pressure difference between the upper and lower surfaces of the particles, resulting in a high inertial lift experienced at particle.

\[
J = \frac{R_{es}^2}{R_{ex}}
\]

Where \( R_{es} \) is the shear Reynolds number, \( R_{ex} \) is the particle Reynolds number in the normal direction. If \( J \) is greater than 32, the particle will be migrated toward the high-fluid velocity region under the shear lift force. If \( J \) is less than 32, the result is just be converse. Meanwhile, the \( R_{ex} \) is expressed as:

\[
R_{ex} = R_{et} \cos \theta
\]

where \( R_{et} \) is the particle Reynolds number in the flow, \( \theta \) is the inclination angle relative to the horizontal. Zigzag and Sylvester provided a theoretical description of the particle Reynolds number suspended in the liquid, therefor, the \( U_t \) can be conveniently obtained from the particle Reynolds number

\[
R_{et} = \left[ \left( 14.51 + (g*(\rho_p - \rho_l)*\rho_f)^{0.5} * 1.83*d^{1.5} * \mu \right)^{0.5} - 3.81 \right]^{2}
\]
\[ U_{TY} = U_T \sin \theta \]  \hspace{1cm} (4)

\[ Re = \frac{\rho_f U_T d}{\mu} \]  \hspace{1cm} (5)

Where \( g \) is acceleration of gravity, the \( U_{TY} \) is particle terminal velocity in the Y direction, \( U_T \) is the particle terminal velocity, \( d \) is particle diameter, \( \rho_f \) is the density of the fluid, \( g \) is the gravitational acceleration, \( \mu \) is the fluid viscosity. The shear Reynolds number, \( Re_s \), it is conveniently obtained by:

\[ Re_s = \frac{\rho_f y d^2}{\mu} \]  \hspace{1cm} (6)

Where \( y \) is the velocity gradient, and \( z \) is spaced of channels, the velocity gradient can be calculated by differentiating Equation (8), which was shown that:

\[ y = \frac{6U}{z} \left( 1 - \frac{2x}{z} \right) \]  \hspace{1cm} (7)

\[ u(x) = \frac{6U x}{z} \left( 1 - \frac{x}{z} \right) \]  \hspace{1cm} (8)

where \( U \) is the average superficial velocity, and \( x \) is the distance of particle from the wall, and \( u(x) \) is the local fluid velocity which based on the work done by Bird et al. (Bird et al. 1960). When the \( J \) is less than 32, the sum of the lifting force and buoyancy of the particle is less than gravity force, which lead particles drop down and settle on the plate surface. When settling velocity of particles in the tangential direction is equal to the fluidization velocity at the particle center, so, it means that an equilibrium state will be reached in this condition for those particles.

\[ U_{TY} = U_{d/2} \]  \hspace{1cm} (9)

As \( x = \frac{d}{2} \), by combining the Equations (3), (8), and (9) the superficial velocity of inclined channel can be calculated:

\[ U = \frac{2U_T z^2 \sin \theta}{3d(2z - d)} \]  \hspace{1cm} (10)

When the \( J \) greater than 32, the particles will be suspended at a distance \( x \) from the surface of the plate and reached a critical balanced position. Substituting Equations (1)–(7) lead to define the critical hydraulic velocity. That is,

\[ U = \frac{\sqrt{8} z^2 \mu R_{ex}^{0.5}}{3 \rho d^2 (z - 2x)} \]  \hspace{1cm} (11)

\[ U = \frac{z U_T \sin \theta}{6x(1 - \frac{x}{z})} \]  \hspace{1cm} (12)
However, there is a both in these two formulas of express critical superficial velocity, so, it is not conveniently to calculate the critical superficial velocity for the given feed particles. Therefore, a new formula free of $x$ can be concluded by combining the two formulas above. So, combining the Equation (9) with Equation (10) the formula can be introduced as:

$$\frac{U}{U_T \sin \theta} = \frac{1}{3} + \left( \frac{1}{9} + \frac{8R_{ex}}{9(d/2)^2 R_{ey}} \right)^{0.5}$$  

Equation (13), it is described the quantitative relationship based on the superficial velocity, $U$, of a fluid attend an inclined channel of gap, $z$, the inclination angle relative to the horizontal $\theta$, $R_{ex}$ is particle Reynolds number in the X direction, $R_{ey}$ is particle Reynolds number in the Y direction, and the particle diameter $d$. And, it offered a way of hydraulic velocity to report a particle of a given density and size into an inclined channel.

It is evident that the index of particle size effect in this new formula is reduced to 0.5 power dependency. So, the dependence on particle size in the inclined channel is largely reduced, thus promoting the separation based on the particle density. For the fine particle was difficult to achieve an effective separation in the gravity due to its size. In this paper, the critical superficial velocity is expressed in new formula to obtain a better quality for the given feed, so, for slime to be separated effectively in inclined channels, which is good significant directions for our laboratory-scale separation.

### Experiments

To investigate the influence factors of channel spacing, solids throughput and split fluidization rate on the inclined channels separation performance, a continuous experiment system is established. The system is consisted of the incline zone and vertical zone. The inclined section contains some isometric inclined channels is constructed from Perspex, it is at an angle of 70° to the horizontal, connecting with a horizontal cross-sectional 60 mm wide by 100 mm broad and a height of 800 mm. With 0.6 mm thick inclined plates are inserted and slightly higher than the overflow weir, so that to create a common parallel flow environment in each channel. The vertical zone is connected to bottom of the incline zone, having a cross-sectional area of $60 \times 100$ mm and height of 800 mm. There is a distributor at the base of the vertical section, it can be allowed the fluidization water uniformly added in the system, which can ensure the suspension keep a fluidization within the equipment.

| Size (mm) | Fractional Mass % | Fractional Ash % | Cumulative Mass % | Cumulative Ash % |
|-----------|-------------------|------------------|-------------------|-----------------|
| 2–1.45    | 12.31             | 9.53             | 12.31             | 9.53            |
| 1–1.45    | 9.15              | 6.24             | 21.46             | 8.13            |
| 1–0.5     | 13.5              | 4.97             | 34.96             | 6.91            |
| 0.5–0.25  | 39.31             | 4.56             | 74.28             | 5.66            |
| 0.25–0.125| 2.82              | 4.95             | 77.1              | 5.64            |
| ≤0.125    | 22.9              | 20.43            | 100               | 9.02            |
The particle properties are presented in detail, as shown in Tables 1 and 2. It can be easily found that with range size of 0.125–2.0 mm, the ash content feed is increases at first and then decreases. And the feed density is mainly concentrated in 1250–1400 kg/m$^3$, and the material yield of each density level is basically uniform. In summary, this feed cannot be classified by particle size to obtain better low-grade products, so a good separation result can only be obtained by gravity separation. Before adding the suspension into the system, it should be switched on the fluidization water valve and maintained a minimum fluidization velocity to ensure the suspension was dispersion. Once the fluidization water flows into the overflow weir, the feed pump and the underflow pump should be immediately switched on. With an increasing feed particle added into the vertical region, a dense autogenous bed was gradually formed. After a while, some tests were taken to verify whether the system has reached a stable state. Under the stable state, the system was kept at a fixed fluidization velocity lasted over 1 h, before the next operating conditions change made. The coarse particles were easily to settle on the plate surface, so they basically slide down to the bottom of the vertical section, while the fine particles with a slowly setting velocity are conveyed up the inclined channels and flowed into the overflow weir to be collected. Meanwhile, the overflow solids passing through the 0.075 mm filter screen is collected. Then, the recovery of overflow and underflow products from each steady-state condition were analyzed to characterize the separation performance.

**Results and Discussion**

**Effect of Channel Spacing on Separation**

The different hydraulic gradients are developed within various channel spacings. With a uniform fluidized velocity in the wide channel, which is about equal to the superficial velocity, and the particle should experience a lower state of lifting force from the channel. However, when the particle moves from the boundary of the channel to the center of the channel, it’s the local velocity increases from 0 to 1.5 times of the superficial rate and receives a large lift force. In the new formula, it is shown that in the wider channel, it requires a higher fluidization velocity to obtain an equilibrium state for the given feed. In other words, for a fixed fluidization rate, the narrower the channel, the coarser particles are easily reach the critical equilibrium. The particles are experienced a lower lift force than the narrow channels in wide channel. Therefore, it can be inferred that the ash content of the underflow in the wide channel is lower than that of narrow inclined channel, as result of a few low-density particles losing in underflow under the same superficial velocity. Aim to confirm this hypothesis, runs 1, 2, and 3 were conducted. Table 3 provides a summary of the operating conditions used in the experiment.

| Density (kg/m$^3$) | Fractional | Cumulative |
|--------------------|------------|------------|
|                    | Mass %     | Ash %      | Mass % | Ash % |
| <1.25              | 4.4        | 2.46       | 4.4    | 2.46 |
| 1.25–1.30          | 17.89      | 2.81       | 22.29  | 2.74 |
| 1.30–1.35          | 25.44      | 4.31       | 47.73  | 3.58 |
| 1.35–1.40          | 24.24      | 6.99       | 71.97  | 4.72 |
| 1.4                | 28.03      | 19.64      | 100    | 8.91 |
Table 3. Operating condition for continuous experiments.

| Run | Spaced (mm) | Feed slurry rate, (t/m²h) | Fluidization velocity, (m/s) | Split fluidization velocity, (m/s) | Feed solid rate, (kg/m²) | Overflow solid rate, (kg/m²s) | Underflow solid rate, (kg/m²s) |
|-----|-------------|---------------------------|-------------------------------|-----------------------------------|--------------------------|------------------------------|------------------------------|
| 1   | 6           | 5.000                     | 0.0182                        | 0                                 | 1.389                    | 0.778                        | 0.611                        |
| 2   | 14          | 5.261                     | 0.0184                        | 0                                 | 1.472                    | 0.944                        | 0.528                        |
| 3   | 22          | 5.562                     | 0.0186                        | 0                                 | 1.556                    | 0.889                        | 0.639                        |
| 4   | 6           | 10.207                    | 0.0222                        | 0                                 | 2.833                    | 1.944                        | 0.889                        |
| 5   | 6           | 18.334                    | 0.0304                        | 0                                 | 5.083                    | 3.556                        | 1.528                        |
| 6   | 6           | 5.001                     | 0.0271                        | 0.1248                            | 1.556                    | 1.000                        | 0.556                        |

Figure 3. The influence of spaced channel on the separation performance of the reflux classifier. Fractional ash % curve of the closed narrow size fractions of the feed, overflow, and underflow were obtained according to different channels widths including of 6, 14, and 22 mm. (Experiments 1, 2, 3). (a) Ash content of overflow products with solid throughput. (b) Ash content of underflow products with different solid throughput.
Figure 3a shows the ash of overflow as a function of the channel spacing and particle size, respectively. The ash content of samples generated from 6 mm spacing is slightly lower than that of 14 mm channel spacing in the whole particle size range, and there is a little fluctuation at the size range of 0.75–2 mm in the 14 mm channels spacing. In addition, the 22 mm channel spacing obtained the highest grade of ash for particles size less than 0.125 mm. The main reason is that the high superficial velocity leading high-ash fine particles to overflow for wide channel spacing. It is evidenced that the ash content of each product decreases with increasing particle size and tends to be a fixed ash value of 2.50% in the 6 mm spaced channel. So, it shows that the closely spaced inclined channel can promote separation performance, which in turn leads to obviously strengthen the effort of particle density on the elutriation through the channels. When the particle size is less than 0.1 mm, the spacing of 22 mm shows a better agreement with the feed ash–size curve. And for the size greater than 0.1 mm, the ash content decreases with an increase in particle size, and its trend is common in the traditional hydraulic gravity separation equipment. It can be concluded that the particle size has a higher significantly effect on the separation of wide channel.

Figure 3b shows the ash content of underflow as a function of the channel spacings and size, respectively. The underflow sample ash % of the of 22 mm channel spacing is lower than that of 6 and 14 mm for particle size below 1 mm, which strongly demonstrates that some low-density particles are lost in the wide channel underflow. Moreover, the separation data of channel spacing of 14 and 22 mm for same the particle size range of 1–2 mm shows an almost same result of ash %, and the data of the 6 mm spacing is higher than that of channel spacing of 14 and 22 mm for a given size. With a high lift force of the narrow channel, the re-suspension is more obvious, which makes it easier for coarse particles to be conveyed to the overflow, resulting in higher ash content in the underflow. Further analysis the difference between the overflow ash content and the underflow content at each particle size in the three experiments, it is evidenced that the over-size channels spacing will increase the difficulty to produce high-grade products.

**Effort of Solids Throughput on the Separation**

Throughput is one of the main parameters of the gravity separation equipment’s which the processing capability rapidly decreases as the feed particle size decreases. The particle size range for conventional liquid-solid fluidized bed process is 0.25–1 mm for levels over 17 t/(m² h). To investigate the solids throughput potential in the inclined channel, the 5, 10.20, and 18.33 t/(m² h) were used in this work. It is worth noted that the value of the maximum throughput can only be reached at 18.33 t/(m² h) as the limitation of the system.

Figure 4a shows the separation results of overflow using various throughput values for the 6 mm channel spacing. When particle size is greater than 0.125 mm, the ash value obtained by 10.20 and 5.00 t/(m² h) decreased with the increase of particle size, and the difference of ash value between the two was small. Meanwhile, with a throughput of 18.33 t/(m² h) provide the highest ash % within this size range. In the particle size range of ~0.125 mm, the ash value of three different experiments rapidly increases with the decrease of the particle size, and the ash value between them is very
diversity. Since the relatively high throughput leads to a high in superficial velocity, with a result that the high ash content fines whose size below the 0.125 mm are conveyed up to the overflow.

Figure 4b shows the separation results of underflow using various throughput values with the 6 mm channel spacing. The throughput of 10.20 t/(m²h) curve shows a good agreement with that of 18.33 t/(m²h) curve for the particle size larger than 0.75 mm. Within the same particle size range, the ash content of produced % by the 5.00 t/(m²h) is

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**Figure 4.** The influence of solid throughput on the separation performance of the reflux classifier. Fractional ash % curve of the closed narrow size fractions of the feed, overflow, and underflow were obtained according to different values of the solid throughput including of 5.0 t/m²h, 10.20 t/m²h, 18.33 t/m²h. (Experiments 1, 4, 5). (a) Ash content of overflow products with split fluidization. (b) Ash content of underflow products with different split fluidization.
lower than that of the 10.20 and 18.33 t/(m²h). However, as the particle size is less than 0.75 mm, curve of 10.20 t/(m²h) and curve of 18.33 t/(m²h) tend to overlap, indicating that their separation performance is very similar. It should be noted that over the most particle sizes, the data obtained from the separation of 10.20 t/(m²h) is higher than that of 18.33 and 5.00 t/(m³h). As a result, the throughput of 10.20 t/(m³h) can bring a moderate separation environment.

The Influence of Split Fluidization Rate on Separation

The theory of split fluidization is based on the separation principles of the inclined channel and liquid-solid fluidized bed. The fluidized water is introduced into the system, which includes split water added from the position below the feed pipe and fluidized water directly added to the distributor at the base of the RC. Goals of split fluidization are to resolve the low-density particles easily lost into underflow and to provide a moderate separation environment. Two comparative experiments (Run 1 and Run 6) were conducted in this section, both of their feed volumetric rate puts into the vertical section is 3.68 kg/min that equals to 0.0102 m/s. The Run 1 does not add split fluidization water, but the rate of 2.08 kg/min fluidization water is added into the Run 6 experiment.

Figure 5a shows that the ash value of the overflow relates with the split fluidization in the separation. After introducing the split fluidization water into system, the ash content is slightly decreased within the particle size range of 0.25–1.45 mm, meanwhile, it rapidly increases from 8.85% to 15.6% as the particle size is reduced to 0.25 mm. The superficial fluidization velocity is increased with an increase in the split fluidization rate. However, the high superficial velocity, which maybe disrupt the stable laminar flow, and takes a significant influence on the separation of fines. In practice, fines have analogous terminal velocity in the infinite settling flow, it indicates that movement in separation are slightly different.

Figure 5b shows that the ash value of the underflow relates with the split fluidization in the separation. After the split fluidization water is put into the vertical section, the content of ash presents a decrease from 80.12% to 17.79% at the particle size range of 0.125–1.0 mm since a few lower density particles mixed with the underflow stream. Moreover, the ash content of underflow exhibits a not obviously decrease as the particle size range from 1 to 2 mm. It is evident that the split fluidization can prevent the coarse particles of low-density from mixing into the underflow, but inevitably increase the ash content of the overflow. Therefore, the way of the split fluidization has a limited improvement of separation performance in the inclined channel process.

Separation Effect of Coarse Slime in the Inclined Close Channels

The liquid-solid fluidization bed has a better separation efficiency when the particle size of feed is within the range of 0.25–1 mm, which is commonly applied to the elutriation of coarse slime. When the difficult washability feed particles with a wide range size are entered the liquid-solid separation bed, a poor separation performance will be showed in the process, this specific performance is an amount of the high ash content fine gangue particles transported to the underflow making a low-grade clean coal through overflow, so, further stages are inevitably added to elutriate slime. Meanwhile, a few coarse particles of low-density are misplaced underflow, resulting in low ash content and yield of tailings. That
separation phenomenon is commonly found in the liquid-solid separation and other hydraulic separators since the separation performances are affected by the particle size. From the view of $E_p$, the value of $E_p$ increases with the decreasing feed particle size, and from the separation density of each size product, the separation density of coarse particles is low while the fine is the opposite. As far as the product ash content of each size, it obviously varies with the particle size.

Figure 6 shows that the particle size relation with ash content of overflow for Run 1, 5, 6. The all three experiments ash content slightly fluctuates as the increasing of the particle size is almost and remains kept at around 3.65% for the overflow products covering the size range 0.2–1.8 mm, it means that the separation density is similar, and the value of $E_p$ is low, which

**Figure 5.** The influence of split fluidization on the separation performance of the reflux classifier. Fractional ash % curve of the closed narrow size fractions of the feed, overflow, and underflow were obtained according to different values of the split fluidization including 0.125 and 0 t³/h. (Experiments 1, 6).
is a direct result of the using the closely spaced inclined channels. And, the ratio of upper and lower feed particle size is nine times in the inclined channels, which is two times of the upper and lower particle diameter limit of the liquid-solid fluidized separation bed. It is evident that the separation performance of the inclined channels is better than that of the liquid-solid separation bed for the feed particle with wide size range.

According to the density of each particle size of the overflow products, the relationship between the particle size predicted by the new model and the corresponding superficial velocity is plotted in Fig. 6. For the $U = 0.042$ m/s, the particles of covering the size range 0.2–1.8 mm are conveyed to the overflow with almost similarly probability, which greatly suppressed the influence of particle size, and in turn brought a separation almost dependent on the particle density. In the continuous system, it should be noted that the predict fluidization velocity is 0.042 m/s, while the experimental value is 0.04 m/s, and the reason for the difference is the effect of hindered settling within suspension particles. The predict of superficial velocity shows a good agreement with the experiment result, it fully shown that the new formula can accurately predict the actual separation superficial rate in continuous system and conduce to a good performance of particle separation. Since the predicted fluidization velocity is of the same order of magnitude as the experimental fluidization velocity, it will not affect the application of critical models in inclined channels significantly.

Figure 7 shows the cumulative yield versus cumulative ash % curve in the continuous separation. The high shear flow environment in the narrow channels, which turn to strengthen the feed particles the separation performance of according to particle density. The overflow curve generated by 6 mm spacing is closer to the sink-float curve than that of the spacing of 14 and 22 mm, which is consistent with Fig. 1. The narrower the plate spacing, the higher the overflow yield after separation. As the channel spacing increases, the overflow will be deteriorated, the overflow ash content of the 22 mm channel is higher than that of the 6 and 14 mm channels. So, the 6 mm channel spacing provides a better particles
separation performance. Compared with Run 1, the Runs 4, 5 have higher solid throughput. The data generated by Run 1 and Run 5 are below the sink-float curve, while the data generated by Run 4 separation is closer to the sink-float curve, which shows a better separation performance, it can also be confirmed in Fig. 3. The Run 1 and Run 6 are operated under different fluidization conditions, and the data obtained by Run 6 is obviously closer to the float-sink curve at the given ash % than that generated by Run1, and this result is consistent with Fig. 5. In general, the value of the overflow product under different separation conditions is very close to the value of the sink-float experiment indicating that the inclined channel can indeed improve the density separation.

Conclusions

In this paper, the experimental results shown that the new formula was proved to be effective in purifying the slime separation. Meanwhile, appropriate operation parameters are very important to improve the separation efficiency. A better separation performance can be obtained when the channel spacing is 6 mm for the feed particle size of 0–2 mm in continuous separation, and the corresponding overflow ash content is lower, and the underflow ash content is higher. As the inclined channel spacing increases to 22 mm, the increase in superficial velocity makes a certain low-density particle enter the underflow resulting in low ash content of the underflow. Meanwhile, there is a moderate separation environment when the value of throughput is obtained.
at 10.20 t/(m²h). The moth of the split fluidization can produce a better environment for the low-density particles reporting to the overflow, and it also increases the ash of underflow suppressing the size effort in the inclined channels. In general, addition to 0–0.125 mm particles in overflow products, when the average particle size of products increases from 0.2 to 1.73 mm, the ash content basically remains at about 3.63%. It indicates that the influence of particle size on separation performance has been improved. It can be seen from the experimental results that the particles with the size of 0.2–0.18 mm are transported to the overflow. When the velocity of flow in the inclined channel is 0.042 m/s, this result is consistent with the separation according to the particle density which further showing that the model is practical.

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