

## 垂直컬럼형 風力選別機의 分離效率向上을 위한 bypass流路의 適用

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## Application of Bypass Flow for Improving Performance of the Vertical Column Pneumatic Separator

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### 요 약

수직컬럼형 풍력선별기의 선별능력을 향상시키기 위해 일시적인 중광(middling)의 흐름을 형성할 수 있는 측로(bypass)를 선별컬럼의 중앙에 설치하였다. 측로를 흐름을 조절하여 주선별컬럼에서 상부흐름의 속도는 가벼운 물질만이 상부로 회수하도록 설정하고 하부흐름의 속도는 무거운 물질만이 하부로 회수되도록 설정하였다. 측로로 이동하는 흐름은 사이클론을 통과시켜 중광이 피더로 회수되도록 하였다. 일반 수직컬럼형 풍력선별기와 개조된 선별기에서 유리 및 지르코니아 비드(bead)의 혼합물을 사용하여 성능향상의 효과를 실험하였다.

주제어 : 풍력선별, 수직컬럼형, 측로(bypass), 중광, 분리효율

### Abstract

A vertical column pneumatic separator was modified to improve its separation performance. A branch column was installed at the center of the main column, which created a bypass flow and changed the flow rate of the main column before and after the branch column. To separate a mixture comprising light and heavy materials, the airflow in main column after the branch column was set to lift the only light materials and the airflow in main column before the branch column was set to prevent the flow of the light materials from flowing downwards. Materials directed into the branch column were separated from the flow and returned to the feeder through the cyclone linked to the branch column. The performances of the straight-type separator and the modified separator were compared using glass and zirconia beads with a narrow size distribution.

**Key words** : Vertical pneumatic separator, Bypass flow, Circulation, Separation performance, Improvement

\*Received : March 15, 2013 · Revised : April 22, 2013 · Accepted : May 8, 2013

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## 1. Introduction

In order to increase the separation efficiency of a process using a vertical column pneumatic separator, many types of separator have been designed and compared. For example, applications of a zigzag, a zagzag and a stacked triangle type were tried and their performances were compared by using the pulsed flow or the non-pulsed flow.<sup>1-3)</sup>

These typical separators divide the mixture into only two products, upward and downward flow without any considering of a middling. In these cases, the overall separation efficiencies are often increased by repeatedly processing for one of the product streams.

This research aims at improving the separation performance of the vertical column pneumatic separator and reducing the process time and its effort. The idea was conceived from making temporary middling stream in the middle of separation column and the simple idea of installing the branch column at the center of the main column was tested. The branch column changes a part of main flow into the bypass flow and the main column has two different flows. Velocity of each flow in the main column, before and after the bypass, is arranged to recover only the desired particles at upward flow and downward flow. Particles of the mixture in bypass flow, which considered as a temporary middling, return to the feeder by means of a cyclone linked with the branch column and air of that is exhausted to the cyclone.

Although this technique increases the process time due to circulation of particles, it is expected to require less time and effort than when using a straight-type separator to achieve the same separation efficiency by reprocessing one of the product streams. In this paper, to be improved the flow and flow, y repetition. oved bypass he straight-type vertical separator and the reconstructed separator, i.e. bypass-type separator, were abbreviated and designated as the ÒSTSÓ and the ÒBTS,Ó respectively, and their performances were compared.

## 2. Experimental

Fig. 1 shows a schematic diagram of the BTS. The

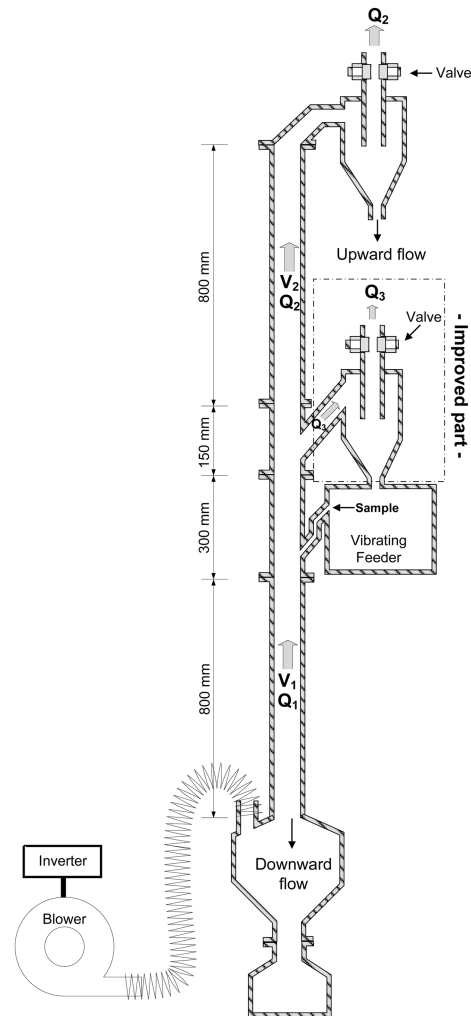


Fig. 1. Schematic of the BTS.

only difference between the BTS and the STS is the existence of the branch column and cyclone. The separation columns were made of an aluminum pipes. The main column has an inner diameter of 49mm and the branch column has an inner diameter of 26 mm.

A bowl vibrating feeder is set in the box linked with the main column, and injects the sample into the main separation column. A cyclone is linked with the branch column and its spigot nozzle is linked with the box of the feeder to recover the particles in bypass flow and return them to the feeder. Another cyclone is connected

**Table 1.** Material and characteristic of samples. (20°C, 101.3 kPa, in dried air)

Sample name	Substance	Density ( $\rho_s$ )	Size ( $\mu\text{m}$ )	Calculated terminal velocity (m/s)
X	Glass bead	2440 kg/m <sup>3</sup>	125~150	0.96~1.16
A	Zirconia bead	6040 kg/m <sup>3</sup>	90~100	1.28~1.42
B			100~106	1.42~1.50
C			106~125	1.50~1.77

This equation of terminal velocity is used for spherical particle in [0.4 < Reynolds number < 500]

$$\text{Terminal velocity (m/s)} = \left[ \frac{4 (\rho_s D \rho_f)^2 g}{225 \mu \rho_f} \right]^{1/2} D$$

$\rho_s$  : Density of particle (kg/m<sup>3</sup>),  $\rho_f$  : Density of air (kg/m<sup>3</sup>)

D : Diameter of particle (m),  $\mu$  : Viscosity (Kg/m s) g : Acceleration of gravity (m/s<sup>2</sup>)

to the top of the main column to recover the light particles.

$Q_1$  is split into  $Q_2$  and  $Q_3$  at the point that both columns are connected. To regulate the split of  $Q_1$ , valves are installed at the vortex finder of each cyclone. Flow velocities,  $V_1$ ,  $V_2$ , and  $V_3$  were measured by anemometers and flow rates  $Q_1$ ,  $Q_2$  and  $Q_3$  were calculated. Except for the branch column and the linked cyclone, the BTS is identical to the STS. Therefore, the STS was prepared by replacing the part including the branch column with a straight pipe of the same diameter and length. Separation experiments were conducted with both units.

Glass and zirconia beads were used for the separation experiments. In order to eliminate the effect of particle shape and to obtain a narrow size distribution, spherical powder (beads) was selected, and each sample was prepared by rigorous sieving. Table 1 shows the terminal velocities and the characteristics of each sample. The terminal velocity was calculated by an equation using Allen's law.<sup>4)</sup>

Each sample and mixtures of X/A, X/B, and X/C were used and fed at the rate of approximately 20 g/min. After the experiment, the recovered samples were divided by heavy liquid separation using tetrabromoethane. The separation efficiency was calculated by

$$\text{Separation efficiency (\%)} = R_L \times R_H \times 100 \quad (1)$$

$R_L$  : Recovery of particles with a low terminal velocity at the top

$R_H$  : Recovery of particles with a high terminal velocity at the bottom

### 3. Modification of the vertical style pneumatic separator

The existence of two different velocity sections ( $V_1$ ,  $V_2$ ) and another path for air and solids ( $V_3$ ) characterize this BTS. The valves installed on the cyclones regulate split of air between  $Q_2$  and  $Q_3$ .  $Q_1$  is mainly regulated by the inverter controlling the blower. Therefore, by means of adjusting the valves and the inverter, the desired airflows can be achieved under the relation of  $\hat{O}Q_1 = Q_2 + Q_3 \hat{O}$ .

The velocity of  $V_2$  is always lower than  $V_1$  because of the flow to the branch column. If the STS obtained the maximum separation efficiency of a certain mixture at the velocity of  $V_s$ , velocities of airflows for the separation in the BTS should be in the order:  $V_1 > V_s > V_2$ .

Fig. 2 shows the concept of the separation procedure. When a separation of the mixture comprising the light material and the heavy material is performed,  $V_1$  is large enough to carry all the light material and a part of the heavy material;  $V_2$  is not large enough to lift any of the heavy material; and  $V_3$  is large enough to direct the mixture accumulated at the diverging point to the cyclone. Therefore,  $V_2$  is the velocity that only light material can be recovered at the top, and  $V_1$  is the velocity that none of the light material remains at the bottom. The flow of branch column passes through

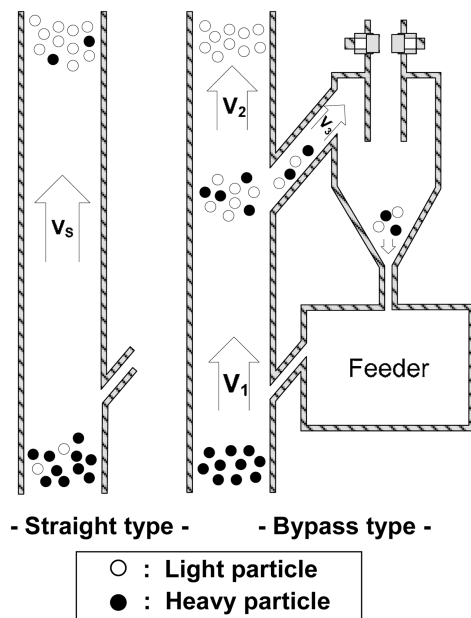


Fig. 2. Conceptual drawing of STS & BTS.

the cyclone, which collects the particles in the flow and returns to the feeder. Thus the flow of the branch column can be considered as a kind of a middling and separation efficiency can be improved by its reprocessing.

However, it is difficult to prevent the light material from remaining at the bottom, because of the velocity distribution across the  $V_1$  section. Many workers have reported radial non-uniformities of airflow or concentration of particles in vertical pipes, and other papers on a pneumatic conveying have reported a downward flow of particles on the inner wall of the vertical pipe. Reddy and Pei, for instance, described that a minimum concentration of particles in flow is situated in the center of the pipe and the profile of the particle distribution tend to flatten with decrease in the loading.<sup>5)</sup> Rhodes confirmed the downward flow of particles on the inner wall of the pipe at high loading by using a sampling probe.<sup>6)</sup> Although most pneumatic separations are conducted under dilute conditions unlike in pneumatic conveying, the downward flow of particles can not be neglected for fine particle separations. Capes and Nakamura reported that annular flow adjacent to the wall is relatively denser than core flow of the center

at near particle's terminal velocity.<sup>7)</sup> Because the separation of fine particles having small differences between their terminal velocities is often conducted at the near particle's terminal velocity in a vertical pneumatic separator, the probability of downward flow of particles should be considered. This mingling of light material at the downward flow occurs commonly in both the STS and the BTS, but can be reduced in the BTS by using a  $V_1$  that is higher than  $V_s$ .

On the other hand, it is not difficult to prevent the heavy materials from mingling with the light materials at the top of separator. This can be achieved by setting the highest velocity of  $V_2$  to be less than the velocity at which the heavy material can be recovered at top. This is also the case for both the STS and the  $V_2$  section of the BTS. However, the mixing is less probable in the BTS, because it uses  $V_2$  that is lower than  $V_s$ . Although the light material near the inner wall may slide down along the wall, it will counter the  $V_1$  and be lifted up to the  $V_2$  zone.

#### 4. Results and discussion

Several investigators tried to predict the optimum separation condition from the recovery of particle in separators. Pierce et al did not feed a mixture but fed each particle of mixture individually into air classifier and got the recoveries of each particle as variation of air velocity.<sup>8)</sup> They multiplied the recovery of the lights at the top by the recovery of the heavies at the bottom, and predicted that the air velocity at the maximum value will be the optimum condition for separation. Yoshida et al used the range of the airflow velocity that the recovery of each particle at top is progressing.<sup>9)</sup> This range is begun from the highest velocity in 0% recovery at the top and finished at the lowest velocity in 100% recovery at the top. It was used as a tool for comparing the performances of the separators and designated as "blowing-range" in this paper.

Fig. 3 shows the recovery at the top of each sample as the variation of  $V_s$  in the STS. Although the terminal velocities of each sample are different in table 1, the blowing-ranges of each sample in Fig. 3 are overlapping.

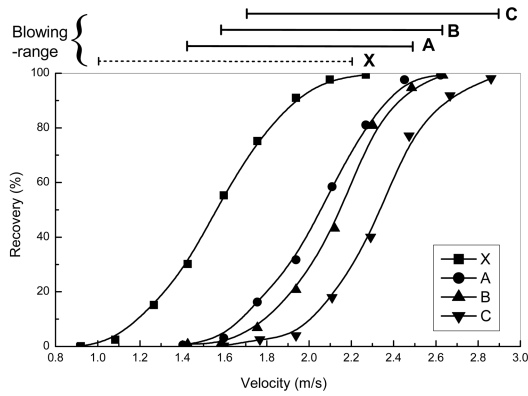


Fig. 3. Recovery at the top of each sample in STS.

This result implies that the STS cannot separate mixture comprising glass beads (X) and any of the zirconia beads (A, B, C).

In this case of the STS, the technique which reprocesses one of the product stream can be used to increase the separation efficiency. A high grade can be achieved more easily at the top than at the bottom, because the disadvantage of radial non-uniformity in flow is caused mainly from the low velocity near wall. From the result shown in Fig. 3, 1.7 m/s was the highest velocity that X could be recovered at the top but A could not. The recovery of X was approximately 68% at this condition. Assuming that each repetition recovers a constant amount X, the separation has to be repeated more than approximately 4 times for X/C to get the over 98% separation efficiency.

Figs. 4 and 5 show the recovery of X and C at the top as a variation of  $V_2$  and  $V_1$ , respectively, in the BTS. The variation of the recovery on each line was obtained by varying only the inverter, while the valves were fixed. The ratio between  $V_1$  and  $V_2$  is different in each line and has a linear relationship below 7 m/s of  $V_1$ , which can be expressed as  $V_2 \approx kV_1$ . Therefore, each line has a different  $k$  and every symbol on each line has the same  $k$ . Each single recovery was made by two different velocities ( $V_1, V_2$ ) and expressed as an identical symbol in Figs. 4 and 5.

Fig. 4 shows the recovery with a variation of  $V_2$  and  $k$ . As shown in the figure, the blowing-ranges of X

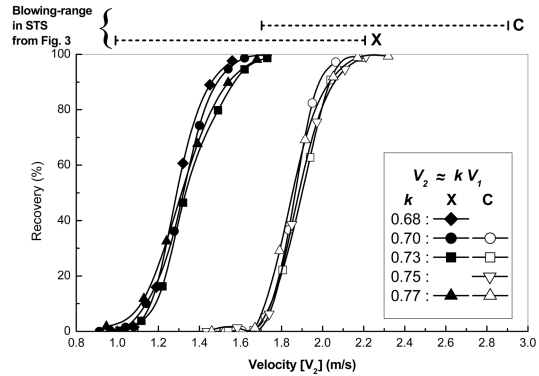


Fig. 4. Recovery at the top of X and C in BTS vs.  $V_2$ .

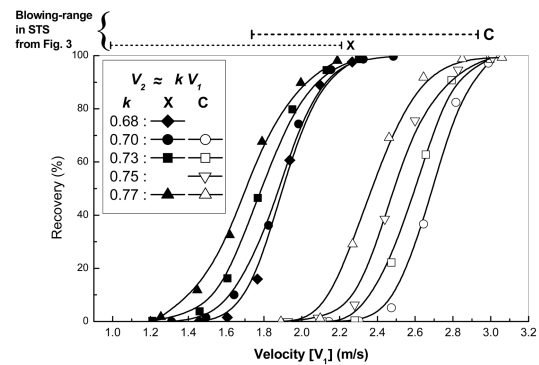


Fig. 5. Recovery at the top of X and C in BTS vs.  $V_1$ .

and C hardly change as  $k$ ; the right limits of the blowing-range shifted to slightly lower velocities with a decrease in  $k$ , but the left limits were fixed. The blowing-ranges for these tests were shorter than that of the STS. This phenomenon can be explained on the basis that  $V_1$  below the section of  $V_2$  increases the retention time of the particles in the separator and increases the possibility of the particles rising to the top. The smaller the value of  $k$ , the higher  $V_1$  has  $V_2$ . Therefore, the reduction in  $k$  can increase the possibility of particles rising to the top and reduce the blowing-range.

Fig. 5 shows the recovery with a variation of  $V_1$  and  $k$ . As seen in the figure, the blowing-ranges of X and C decreased with  $k$ . Contrary to the preceding result, the right limits were fixed but the left limits moved to a higher velocity in proportion to the reduction of  $k$ . Because an increase of the value of  $k$  makes  $V_1$  to

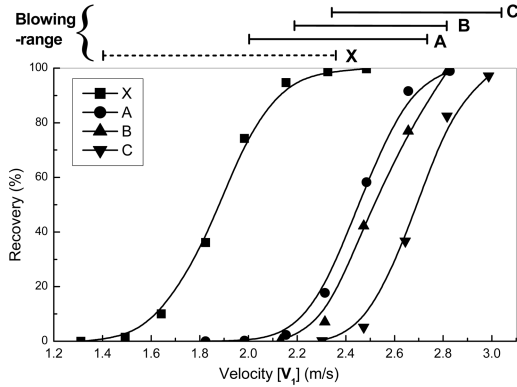


Fig. 6. Recovery at the top of each sample in BTS ( $k = 0.7$ ).

have a low  $V_2$ , the recovery begins at high  $V_1$  and the blowing-range decreases.

Although the blowing-ranges change with the variation in  $k$ , those in the BTS do not exceed that of the STS. The blowing-ranges of X and C in the STS of Fig. 3 are shown at the top of Figs. 4 and 5. In the case of Fig. 4, the blowing-ranges in the STS and the left limits in BTS started at the identical velocity. In Fig. 5, the blowing-range in the STS and the right limits in the BTS finished at the identical velocity. However, the right limits of the BTS in Fig. 4 and left limits of the BTS in Fig. 5 moved within the blowing-range of the STS.

Fig. 6 shows the recovery of each sample for  $k = 0.7$  in the BTS with a variation of  $V_1$ . This result can be compared with Fig. 3 conducted in the STS. As can be seen, the overall blowing-ranges in the BTS were shorter than that of the STS. The blowing-ranges of X, A, B, C in the STS were 1.2(1.0 ~ 2.2), 1.1(1.4 ~ 2.5), 1.1(1.5 ~ 2.6) and 1.2(1.7 ~ 2.9) m/s, but those in the BTS was 0.9(1.4 ~ 2.3), 0.7(2.0 ~ 2.7), 0.7(2.1 ~ 2.8) and 0.7(2.3 ~ 3.0) m/s, respectively.

Assuming that particles having a terminal velocity lower than the air flow velocity are recovered at the top, the possibility of recovering a particle at the top in a vertical-style pneumatic separator can be expressed as a function of the normal distribution. The recovery rate at the top as a function of flow velocity can be expressed as Eq. (2), which is the integral of a normal distribution probability density function of the terminal

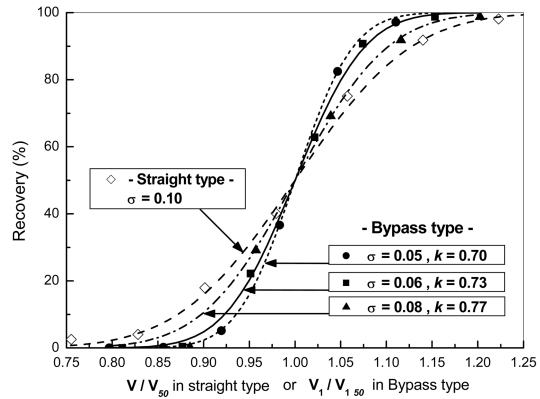


Fig. 7. Recovery of C in both types and recovery curves calculated from Eq. (2).

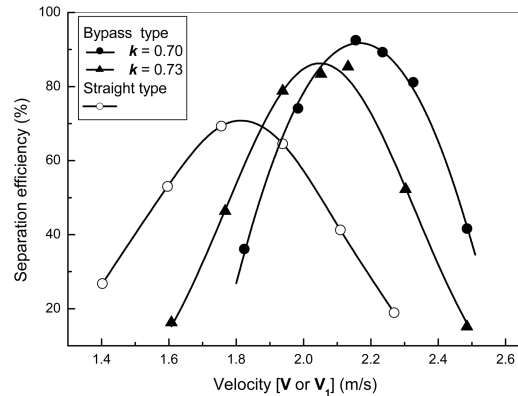


Fig. 8. Separation of X/A.

velocity;  $V_{50}$  is the velocity of airflow at 50% recovery and  $V/V_{50}$  is used to make it dimensionless.  $\sigma$  is the standard deviation.  $\mu$  is an average of  $\chi$  and the value of this in here is 1.<sup>9,10)</sup>

$$\text{Recovery (\%)} = \frac{1}{\sigma\sqrt{2\pi}} \int_{D-\infty}^x \exp\left(-\frac{(x-D)\mu^2}{2\sigma^2}\right) dx$$

$$x = V/V_{50} \tag{2}$$

Performance of a separator can be evaluated from the standard deviation, the smaller value of  $\sigma$  implies a more precise separation. Fig. 7 shows the relationship between  $V/V_{50}$  and recovery. As shown in Fig. 7,  $\sigma$  of the BTS is smaller than that of the STS and is proportional to  $k$ .

Figs. 8, 9 and 10 are separation results of X/A, X/

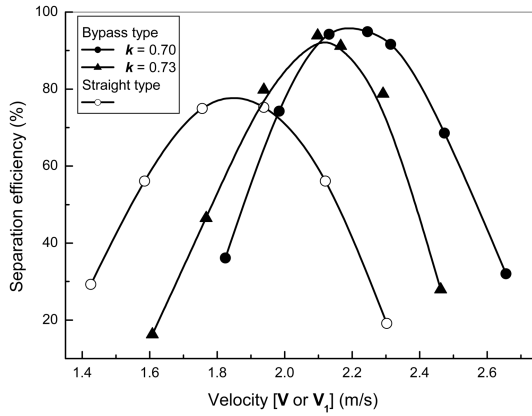


Fig. 9. Separation of X/B.

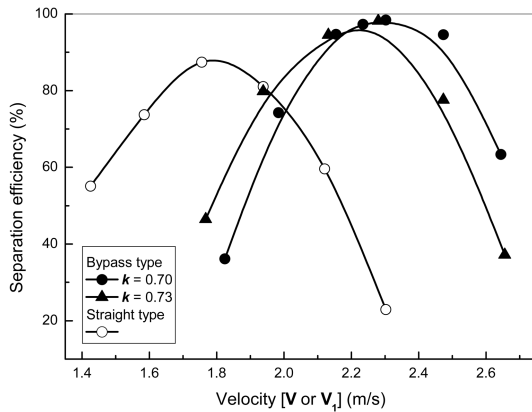


Fig. 10. Separation of X/C.

B, and X/C, respectively, for both separator types. Mixtures used in the experiments were made by mixing the same amount by mass of each sample. The performance of the BTS was better than that of the STS, and this was enhanced with a decrease in  $k$ . In the case of X/A separation, the maximum separation performance was increased by approximately 20%.

When the total sample amount  $Q_s$ (kg) is fed into the separator at a rate  $Z$  (kg/h), the process time can be calculated by  $Q_s/Z$  in the STS, because the retention time of a sample in the main column will be only a few seconds. However, in the case of the BTS, the bypass flow circulates particles and increases the process time.

The split of the particles having the narrow size distribution was considered to be constant at each

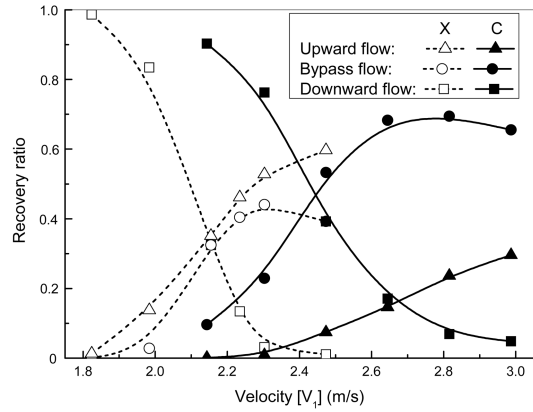


Fig. 11. Split ratio of X and C ( $k=0.7$ ).

circulation and that was confirmed by a preliminary test. If the ratio of particles that passed through the branch column is defined as  $\alpha$  and  $n$  is the number of circulation cycles, the process time,  $T$ , can be expressed as

$$T = \frac{Q_s}{Z} (1 + \alpha + \alpha^2 + \alpha^3 + \dots + \alpha^n) = \frac{Q_s}{Z} \frac{1 - \alpha^{n+1}}{1 - \alpha} \quad (3)$$

Since the value of  $\alpha^n$  will be zero at the moment that separation process completes, the equation can be expressed as

$$T = \frac{Q_s}{Z} \frac{1}{1 - \alpha} \quad (4)$$

Fig. 11 shows a variation of the split ratio of X and C samples to upward, downward, and bypass flow when the particles are not circulated due to blocking of the path between the cyclone and feeder. Because maximum separation efficiency in Fig. 10 was obtained at  $k = 0.7$  and  $V_1 = 2.3$  m/s, experiments were conducted at  $k = 0.7$ .

The values of  $\alpha$  of X and C at  $V_1 = 2.3$  m/s were 0.46 and 0.24, respectively. From Eq. (4), the value of  $\frac{1}{1 - \alpha}$  can be calculated as 1.85 for X and 1.32 for C. Because the entire separation process is finished when total samples are recovered at the top or bottom, separation time in the bypass type will be 1.85 times longer than that of the straight type. However, a precise estimation of process time is difficult, because different values of  $\alpha$  for each sample in the mixture produce

different amounts of each sample that return to the feeder, which causes a change in the injection rate during circulation. When maximum separation efficiencies of X/C in both types were obtained in the actual separations, the process time in the BTS was approximately twice that of the STS.

## 5. Conclusion

A straight-type vertical pneumatic separator was modified and its performance was investigated. The purpose of this modification was to circulate the temporary middling product as often seen in other mineral processing apparatuses. By adding a branch column to an ordinary straight column separator, the modified separator has two different velocity sections ( $V_1$ ,  $V_2$ ) and a bypass flow for the circulation of the temporary middling.

When the minimum terminal velocity difference between glass beads and zirconia beads was approximately 0.34 m/s, this bypass-type separator could separate the glass and zirconia beads mixture around 0.1 to 0.15 mm with 98% efficiency, and maximum separation efficiency was approximately 10% higher than that of the straight-type separator. The process time of this separation in the bypass-type was approximately twice that in the straight-type. However, to achieve identical maximum separation efficiency of the bypass-type by using the straight-type separator, it is anticipated that separation should be repeated 4 times.

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## 감사의 글

본 논문은 한국에너지기술평가원의 ‘지식경제 기술혁신사업’의 지원을 받아 수행되었습니다(과제번호 : 2011IT100100221).

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