

Analysis of Broken Rice Separation Efficiency of a Laboratory Indented Cylinder Separator

Myoung Ho Kim, Seung Je Park*

*Department of Bio-industrial Machinery Engineering (Institute of Agricultural Science and Technology),
Chonbuk National University, Jeonju, Korea*

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Abstract

Purpose: Using a laboratory indented cylinder separator, broken rice separation experiments were conducted and the characteristics of the separation process were studied to provide information for developing a prototype indented cylinder broken rice separator. **Methods:** Rice (Ilmi variety) milled in a local RPC was used for the experiment. Rice kernels were classified into four groups according to their length l ; whole kernels ($l > 3.75$ mm), semi-whole kernels ($2.5 < l < 3.75$ mm), broken kernels ($1.75 < l < 2.5$ mm), and foreign matters ($l < 1.75$ mm). A laboratory grain cleaner, Labofix '90 (Schmidt AG, Germany) was used for the experiments. Experiments were designed as a 4×4 factorial arrangement in randomized blocks with three replications. Cylinder rotational speeds (17, 34, 51, 68 rpm) and trough angles (15, 37.5, 60, 82.5°) were the two factors and feed rates (25, 50 kg/h), indent shapes (U, S₁ type), and indent sizes (2.5, 3.75 mm) were treated as the blocks. Two 125 g samples and one 125 g sample were taken at the cylinder outlet and from the trough, respectively. The whole, semi-whole, and broken kernel weight ratio of the samples and feed was determined by a rice sizing device. From these weight ratios, purities, degrees of extraction and coefficient of separation efficiency were calculated. **Results:** Trough angle, cylinder speed, and their interaction on the coefficient of separation efficiency were statistically significant. Cylinder speed of 17, 34, and 51 rpm made the most effective separation when the trough angle was 15°, 37.5°, 60°, and 82.5°, respectively. Maximum values of coefficient of separation efficiency were in the range of 60 to 70% except when the indent size was 2.5 mm and were recorded for the combinations of low cylinder speed (17 rpm) with medium trough angle (37.5° or 60°). Indent shape did not appear to make any noticeable difference in separation efficiency. **Conclusions:** Due to the interaction effect, the trough angle needs to be increased appropriately when an increase in cylinder speed is made if a rapid drop of effectiveness of separation should be avoided. In commercial applications, S₁ type indents are preferred because of their better manufacturability and easier maintenance. For successful separation of broken kernels, the indent size should be set slightly bigger than the actual sizes of broken kernels: an indent size of 3.0 mm for separating broken kernels shorter than 2.5 mm.

Keywords: Broken rice, Indented cylinder, Length grader, Separation efficiency, Trier.

Introduction

In Korea, the so-called "high-quality milled rice" are generally of Japonica type varieties, have good eating quality and characteristic flavor, and have kernels which are transparent, glossy, and sound with no foreign materials. "Head rice", on the other hand, is a terminology

referring to the special products of milled rice: on weight basis, at least 96% of their contents should be undamaged, non-chalky, and whole or large broken kernels whose lengths are no less than 3/4 of the average length of whole kernels. For head rice, therefore, more emphasis is put on the external appearance than any other quality attributes found in high-quality milled rice. External appearance of rice such as kernel shape, size, transparency, and gloss can be directly judged by consumers and plays a decisive role in buying decision. In this

*Corresponding author: Seung Je Park

Tel: +82-63-270-2615; Fax: +82-63-270-2620

E-mail: sjpark@jbnu.ac.kr

regards, one of the measures to improve the quality of milled rice products could be the increase in their whole kernel ratio.

Since the first Rice Processing Complex (RPC) was introduced in 1991, they have been taking a major role in the postharvest processing of rice in Korea. Besides the basic processing equipment, many new breeds of equipment such as a rice polisher, color sorter, and broken rice separator continue to be added in the processing line of RPCs with specific purpose to improve the final product quality. A broken rice separator is the equipment used to remove broken kernels, chaffs, foreign matters, and bran particles from milled rice and almost all domestic RPCs adopt and use a rotary sifter as their broken rice separator (Koh et al., 1995).

However, previous study showed that rotary sifter broken rice separators needed improvement both in the separation accuracy for large and small broken kernels and in the separation precision for small broken kernels and foreign materials (Kim, 2001). A rotary sifter, alternatively called a plan sifter or swing sieve, is a compact hexahedral steel box swinging circularly on horizontal plane and contains a vertical stack of six to eight screen trays with different mesh sizes (Food Agency, 1995). Judging from this configuration, the rotary sifter broken rice separator has little theoretical soundness because effective broken rice separation should be done by the kernel length not its width.

Indented cylinder separators or triers have, on the other hand, the differences in kernel length as their basic separating characteristic and have been using in seed cleaning and grain milling industry (Grochowicz, 1980). Yamashita et al. (1979) and Yoshitomi et al. (1980) studied the separating mechanisms and the factors affecting the performance of the broken rice separator of indented cylinder type. Later, they conducted experimental tests in an attempt to use an indented cylinder separator for separating rough rice from brown rice in rice hulling process (Nguyen et al., 1987). Kawamura et al. (2006) developed a rough rice fine cleaning system by combining an indented cylinder separator with a gravity separator. An indented cylinder separator was used to separate hulled rice kernels from the whole sound paddy kernels. Choi (2005) attempted to introduce indented cylinder separators in RPCs to improve head rice ratio of milled rice products. Optimum values of the trough angle, cylinder inclination angle, and cylinder rotational speed

were determined experimentally. It seems previous research works on indented cylinder for broken rice separation are not only scarce but also either theoretically-oriented (Yamashita et al., 1979; Yoshitomi et al., 1980) or empirically-oriented (Choi, 2005).

This work was conducted to provide necessary information required to develop a prototype indented cylinder broken rice separator. Using a laboratory indented cylinder separator, experiments on broken rice separation were done and the characteristics of the separation process were studied.

Materials and Methods

Materials

Rice (Ilmi variety) grown and harvested in Kimje county, Jeonbuk province and milled into a quality-accredited grade product in a local RPC was purchased and used for the experiment. In this study, for more precise separation of broken rice, rice kernels were classified into four groups according to their length l ; whole kernels ($l > 3.75$ mm), semi-whole kernels ($2.5 < l < 3.75$ mm), broken kernels ($1.75 < l < 2.5$ mm), and foreign matters ($l < 1.75$ mm). Since the sound kernels of Japonica type rice is approximately 5 mm long, the delimiting values of 3.75 mm and 2.5 mm correspond to $3/4$ and $1/2$ of the average length of sound kernels, respectively. The minimum length for broken rice was set to 1.75 mm, which was stricter than the official standard value of 1.7 mm (Anonymous, 2011).

After examining twelve 125 g random samples by a rice sizing device shown in Figure 2, the weight ratios of whole, semi-whole, and broken kernels in the 112 kg total batch were manually adjusted to 95.2%, 2.6%, and 2.2% which were the average values for domestic milled rice products (Kim, 2001). The total rice batch was then divided into sixteen 7 kg samples, put in vinyl packs, and kept under ambient condition.

Experimental apparatus

Laboratory indented cylinder separator

A laboratory grain cleaner, Labofix '90 (Schmidt AG, Germany) was used for the broken rice separation experiments. Table 1 shows its specifications. As shown in Figure 1, Labofix '90 is a complex separator in which the necessary elements for pneumatic, screening and

Table 1. Specifications of Labofix '90

Item	Specification
Overall dimension	1250 × 550 × 970 mm (L × W × H)
Weight	75 kg
Power	0.37 kW (3 phase, 220/380 V, 50 Hz)
Rated capacity	50 kg/h (for wheat)
Body inclination angle	0°, 2°, 7° (3 steps)
Cylinder rotational speed	30 rpm (default value)
Speed controller	Starvert-iG5 inverter (LG Industrial System Co., Korea)
Cylinder dimension	Effective length: 373 mm, Diameter: 245 mm
Indent shape and size	Teardrop (Us type): 3.75 mm, 2.5 mm Hemisphere (S ₁ type): 3.75 mm, 2.5 mm

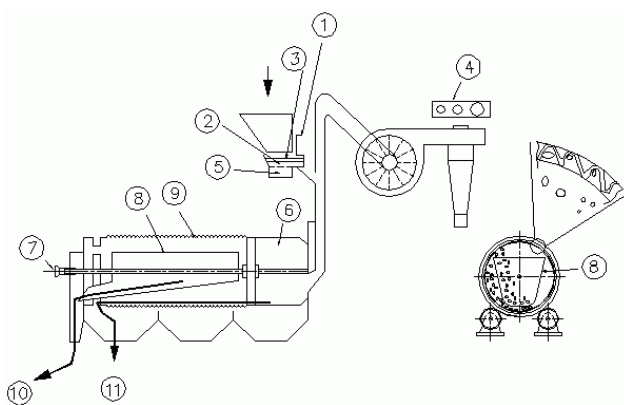


Figure 1. Schematic diagram of Labofix '90: ① Inlet regulator for continuous feed, ② Vibratory conveyor, ③ Pre-cleaning sieve, ④ Baffle for air flowrate control, ⑤ Potentiometer for throughput control, ⑥ Fine screening cylinder, ⑦ Trough angle adjustment handle, ⑧ Trough, ⑨ Indented cylinder, ⑩ Broken kernel outlet, ⑪ Whole kernel outlet.

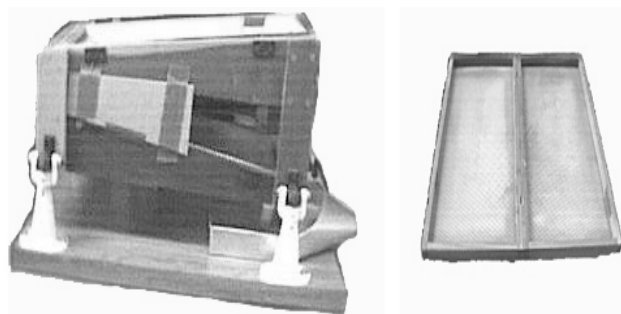


Figure 2. Rice sizing device and sieve plates.

indent separation are fabricated sequentially. In this study, Labofix '90 was used with its pre-cleaning sieve removed and the perforations of fine screening cylinder blocked by adhesive tapes. An inverter was fabricated into the motor driving part of Labofix '90 to make the change in cylinder rotational speed possible.

The rotating cylinder has many indents or pockets on its inside surface. Rice kernels are fed into the bottom of the cylinder and the short kernels are picked up by the indents, moved around the periphery of the circle subscribed by the cylinder, and dropped near the top of the path into the center trough for removal. The long kernels roll out of the indents before they are lifted sufficiently to fall into the trough, drop repeatedly to the pool of kernels on the bottom of the cylinder, and finally come out of the cylinder.

Rice sizing device

A rice sizing device (Grainman, Seedburo Equip. Co., U.S.A.) with 6P plate ($\phi = 6/64''$) and 0.135P plate ($\phi = 0.135''$) as the top and bottom plate, respectively, was used to determine the weight ratios of whole, semi-whole, and broken kernels contained in rice samples (Figure 2). Because of the discrepancy between the SI and British unit system, the 2.38 mm ($6/64''$) diameter round pockets of 6P plate and the 3.43 mm ($0.135''$) diameter round pockets of 0.135P plate were selected to catch the broken kernels ($1.75 < l < 2.5$ mm) and semi-whole kernels ($2.5 < l < 3.75$ mm), respectively. Rice sizing determination was done by following the procedures recommended by USDA (1976).

Methods

Experiments were designed as a 4×4 factorial arrangement in randomized blocks with three replications. Cylinder rotational speeds (17, 34, 51, 68 rpm) and trough angles (15, 37.5, 60, 82.5°) were the two factors and feed rates (25, 50 kg/h), indent shapes (Us, S₁ type), and indent sizes (2.5, 3.75 mm) were treated as the blocks. The body inclination angle was fixed at 2°.

The four levels of the rotational speed were chosen to correspond to 20, 40, 60, and 80% of the critical speed of the cylinder n_c calculated by Eq. (1). When viewed from its outlet side, the cylinder rotates clockwise resulting in broken kernels falling from the indents in the 2nd quadrant as shown in Figure 3. Therefore, trough angle β of 15, 37.5, 60, and 82.5° were used for the experiments. Cylinders having teardrop-like shape (Us type) indents were provided by the manufacturer of Labofix '90, but cylinders having hemispherical shape (S_1 type) indents were made by a local ironworks. Because of this difference, the number of indents per unit area differed depending on the indent type. The indentation density of Us 2.5 mm indents was 8.33 units/cm² but that of S_1 2.5 mm indents was 5 units/cm². Cylinders having Us 3.75 mm and S_1 3.75 mm indents, though, showed little difference in their indentation density—3.22 units/cm² and 3.11 units/cm², respectively.

$$n_c = \frac{30}{\pi} \sqrt{\frac{g}{R}} \quad (1)$$

where,

- n_c : critical rotational speed of cylinder (rpm)
- g : gravitational acceleration (9.8 m/s²)
- R : radius of cylinder (m)

After the rice sample began to be fed from the hopper into the inside of the cylinder, three minutes were allowed to elapse for establishing a steady-state condition.

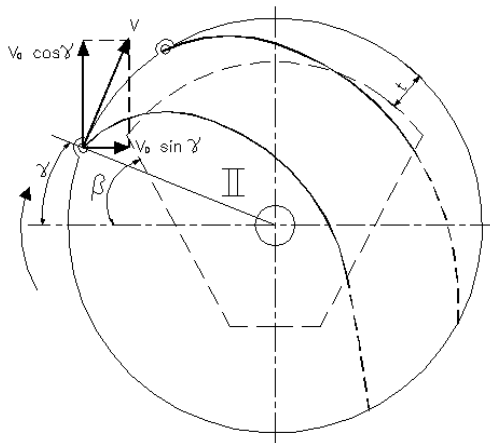


Figure 3. Schematic diagram showing the positional relationship between the trajectory of falling kernels and the receiving trough (β : trough angle, γ : initial trajectory angle of falling kernels, V_0 : initial velocity of falling kernels, t : clearance between trough top edge and working surface of the cylinder).

Then, all the material exiting from the outlet of the cylinder was collected for two minutes. Two 125 g samples were randomly taken from the collected material and the whole, semi-whole, and broken kernel weight ratio of the samples was determined. The material collected in the trough was of small quantity because it consisted of mainly semi-whole and broken kernels. Therefore, one 125 g sample was taken from all the material collected during the total operating time of eight minutes.

From the weight ratios of the feed, the material collected in the trough, and the material sampled at the cylinder outlet, the purities and degrees of extraction of the two fractions were calculated as follows.

$$E_w = \frac{W_c}{W} \quad (2)$$

$$P_w = \frac{W_c}{C} \quad (3)$$

$$E_B = \frac{B_t}{B} \quad (4)$$

$$P_B = \frac{B_t}{T} \quad (5)$$

where,

- E_w, E_B : degree of extraction of the whole and the broken kernels, respectively
- P_w, P_B : purity of the whole kernel fraction and the broken kernel fraction, respectively
- C, T : total weight of the material sampled at the cylinder outlet and the material collected in the trough, respectively
- W, W_c : weight of the whole kernels in the feed and in the material sampled at the cylinder outlet, respectively
- B, B_t : weight of the broken kernels in the feed and in the material collected in the trough, respectively

The terms mentioned in the above equations as “broken kernels” and “whole kernels” need further explanation. When cylinders having 2.5 mm indents are used, kernels shorter than 2.5 mm are supposed to be caught by the indents and collected in the trough; therefore, the term “broken kernels” means the kernels shorter than 2.5 mm. But “whole kernels” represents all

the kernels longer than 2.5 mm; the whole kernels as well as semi-whole kernels according to the previous definition. Likewise, when cylinders having 3.75 mm indents are used, broken kernels ($1.75 < l < 2.5$ mm) plus semi-whole kernels ($2.5 < l < 3.75$ mm) collected in the trough are represented by the term “broken kernels”.

It is not only conventional but also convenient to evaluate the overall effectiveness of a separation process or a separator by using a single value often referred to as

separation index (Grochowicz, 1980; Kuprits, 1967). To represent both the recovering power of whole and broken kernels and the precision of removing broken kernels from the feed material, a coefficient of separation efficiency η was defined as Eq. (6) and used in this study.

$$\eta = (E_w \times E_b \times P_b) \times 100(\%)$$

$$= \left(\frac{W_c}{W} \times \frac{B_t}{B} \times \frac{B_l}{T} \right) \times 100(\%) \quad (6)$$

Table 2. ANOVA of coefficient of separation efficiency η

Source	d.f.	S.S.	M.S.	F-value
Block	7	0.9575	0.1368	
Treatment	15			
RPM (S)	3	0.9228	0.3076	22.13 ^{a)}
Angle (A)	3	0.2774	0.0925	6.65 ^{a)}
Interaction (S × A)	9	1.0950	0.1217	8.76 ^{a)}
Error	105	1.4593	0.0193	
Total	127	4.7120		

a) Statistically significant at the 1% level.

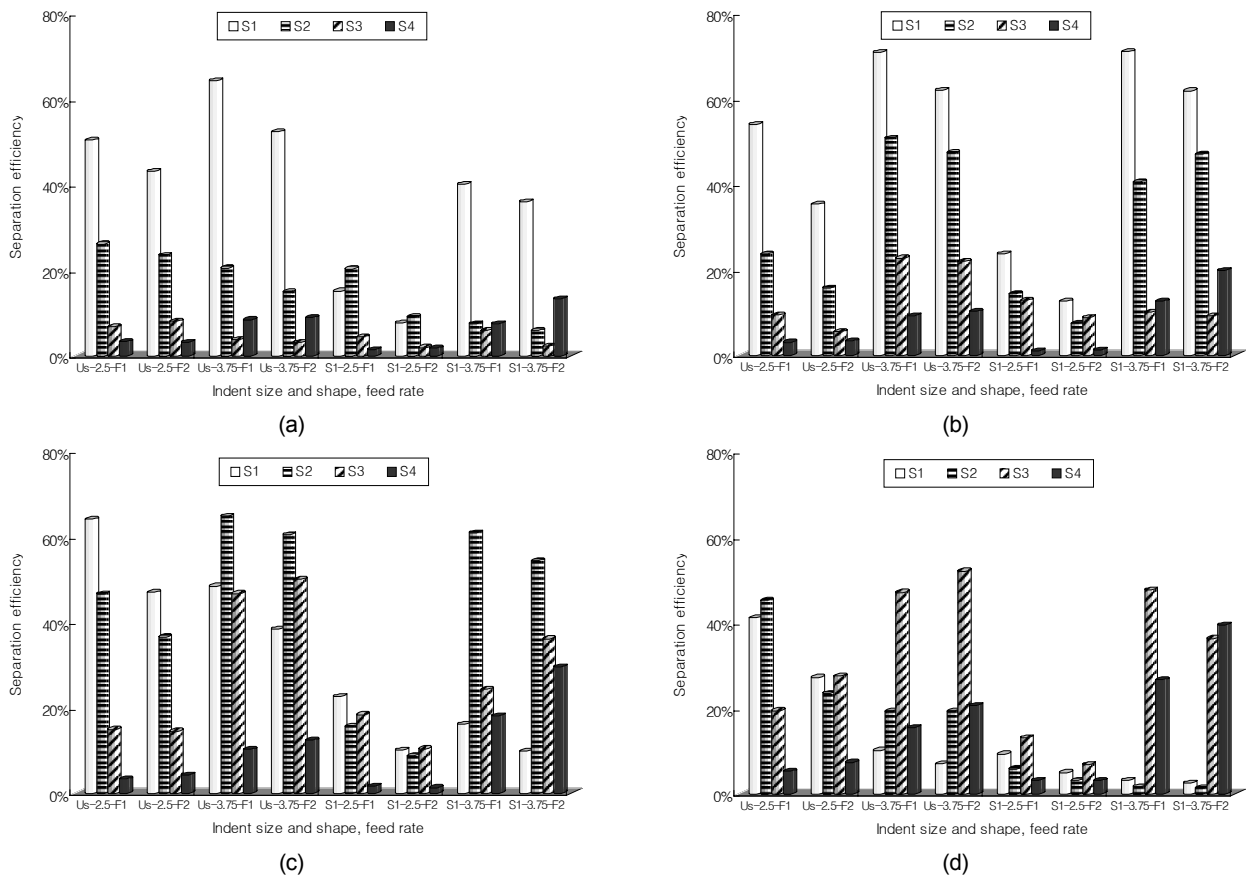


Figure 4. Coefficients of separation efficiency for trough angle of (a) 15°, (b) 37.5°, (c) 60°, and (d) 82.5°.

Results and Discussion

Statistical analysis by SAS (1999) showed that the effect of trough angle, cylinder speed, and their interaction on the coefficient of separation efficiency were statistically significant at the 1% level (Table 2).

Coefficients of separation efficiency calculated for each trough angle are shown in Figure 4. The alphanumeric symbols used in Figure 4 and Table 3 have the meanings as follows: S1 to S4 and A1 to A4 stand for the cylinder rotational speed (17, 34, 51, 68 rpm) and the trough angle (15, 37.5, 60, 82.5°), respectively; Us and S₁ represent the indent shape (teardrop, hemisphere) and the following number 2.5 and 3.75 represent the indent size in mm; and, F1 and F2 represent two feed rates of 25 and 50 kg/h, respectively.

Effects of cylinder speed and trough angle

Due to the interaction effect between cylinder speed and trough angle, the cylinder speed of 17, 34, and 51 rpm made the most effective broken rice separation when the trough angle was 15° or 37.5°, 60°, and 82.5°, respectively. This finding suggests the trough angle has to be increased appropriately when an increase in cylinder speed is made if a rapid drop of effectiveness of separation should be avoided.

Regardless of the indent shape, indent size, and feed rate, maximum values of coefficient of separation efficiency were in the range of 60 to 70% except when the size of indent was 2.5 mm and were recorded for the combinations of low cylinder speed (17 rpm) with medium trough angle (37.5° or 60°) (Table 3).

When the operating speed of a pilot-scale or full-scale indented cylinder separator needs to be determined by scaling-up the test results obtained from a laboratory experimentation, kinematic index K (Eq. (7)), which is the ratio between centrifugal and gravitational force is generally used (Grochowicz, 1980). By setting the kinematic index value equal, the dynamic similarity between two

indented cylinders having similar shapes but different sizes is to be maintained. In order to have a same kinematic index, the rotational speed should be decreased in the power of two as the cylinder size increases linearly.

$$K = \frac{mR\omega^2}{mg} = \frac{\pi^2 n^2 R}{900g} \quad (7)$$

where,

- K : kinematic index (-)
- ω : rotational speed of indented cylinder (rad/s)
- n : rotational speed of indented cylinder (rpm)
- R : radius of indented cylinder (m)
- m : mass of grain kernel (kg)
- g : gravitational acceleration (9.8 m/s²)

Effects of indent shape and size and feed rate

Since the indent shape, indent size, and feed rate were treated as blocks in the experimental design, their effects on the coefficient of separation efficiency were examined by paired t-test and all three factors had a statistical significance as shown in Table 4.

Indent shape and size

As can be seen in Figure 4, the coefficients of separation efficiency for 3.75 mm indents were generally higher than those for 2.5 mm indents. The main reason for this result appears to be due to the difference in the degree of broken kernel extraction. When cylinders having 3.75 mm indents are used, kernels shorter than 3.75 mm are to be caught up by the indents, carried to the trough, and their total mass is used to calculate the degree of broken kernel extraction. Since the indent size of 3.75 mm is 1.5 times larger than the size of most broken kernels whose average length is 2.5 mm, almost all the broken kernels could be picked up by 3.75 mm indents even though the broken kernels assume any random positions while they get into and stay in the indents. With the 2.5 mm indents,

Table 3. Maximum coefficient of separation efficiency η (%) for each treatment

Treatment	Us				S ₁			
	2.5		3.75		2.5		3.75	
	F1	F2	F1	F2	F1	F2	F1	F2
S1-A2			70.8	62.0	23.7	38.2	71.0	61.9
S1-A3	64.1	47.0						

Table 4. Results of paired t-test for the effects of indent shape, indent size, and feed rate on coefficient of separation efficiency η

	d.f.	Mean difference	Std. error	t value
Indent shape	63	0.1071	0.0174	6.138 ^{a)}
Indent size	63	-0.1234	0.0227	-5.449 ^{a)}
Feed rate	63	0.0343	0.0089	3.856 ^{a)}

^{a)} Statistically significant at the 1% level.

Table 5. Results of additional t-test for the effects of indent shape on coefficient of separation efficiency η

	d.f.	Mean difference	Std. error	t value
For 2.5 mm indent	31	0.1436	0.01569	9.154 ^{a)}
For 3.75 mm indent	31	0.0706	0.03727	1.894

^{a)} Statistically significant at the 1% level.

on the other hand, some of the broken kernels would be neither picked up nor carried successfully when their orientation and position is mismatched ever so slightly with the indents.

Table 4 indicates differences in the coefficient of separation efficiency exist according to the shape of indent and Figure 4 shows Us type indents give higher coefficients of separation efficiency than S₁ type indents in most treatments. Because of their teardrop-like shape, the Us type indents are expected to have advantages over the hemispherical S₁ type indents in terms of secure holding of kernels in the indents and preventing premature fall. The effect of indent shape, however, needs to be analyzed more carefully since difference in the indentation density exists between Us and S₁ type—especially for 2.5 mm indents—as mentioned previously. Thus, an additional t-test was performed for each indent size separately and the results are shown in Table 5. For 3.75 mm indents, where there was little difference in the number of indents per unit area of cylinder surface, the effect of indent shape on the coefficients of separation efficiency was statistically insignificant. For 2.5 mm indents, on the other hand, the effect of indent shape had a statistical significance. However, if the previously mentioned indentation density discrepancy between Us type 2.5 mm and S₁ type 2.5 mm indents somehow affected the experimentation results, the acknowledged statistical significance for 2.5 mm indents could not be guaranteed impeccably.

Based on this reasoning, indents shaped as either Us type or S₁ type appeared not to make any noticeable difference in separation efficiency. Therefore, in commercial applications, it might be desirable to adopt S₁ type indent

because of its better manufacturability and easier maintenance. For successful separation of broken kernels, the indent size should be set slightly bigger than the actual sizes of broken kernels. For example, an indent size of 3.0 mm could be recommended for separating broken kernels shorter than 2.5 mm.

Feed rate

Feed rates of 25 and 50 kg/h were used in the experimentation where the latter was the rated capacity of the Labofix '90. Effect of the feed rate on the coefficient of separation efficiency was found statistically significant at the 1% level (Table 4). Coefficients of separation efficiency were generally higher with feed rate of 25 kg/h than with 50 kg/h (Figure 4).

Conclusions

Using a laboratory indented cylinder separator, broken rice separation experiments were conducted and the characteristics of the separation process were studied to provide fundamental information for developing a pilot-scale commercial indented cylinder broken rice separator.

Effects of trough angle, cylinder speed, and their interaction on the coefficient of separation efficiency were statistically significant at the 1% level. Due to the interaction effect between cylinder speed and trough angle, the trough angle needs to be increased appropriately when an increase in cylinder speed is made if a rapid drop of effectiveness of separation should be avoided. Regardless of the indent shape, indent size, and feed rate, maximum values of coefficient of separation efficiency

were in the range of 60 to 70% and were recorded for the combinations of low cylinder speed (17 rpm) with medium trough angle (37.5° or 60°). Indents shaped as either U_s type or S₁ type appeared not to make any noticeable difference in separation efficiency; therefore, in commercial applications, S₁ type indents are preferred because of their better manufacturability and easier maintenance. For successful separation of broken kernels, the indent size should be set slightly bigger than the actual sizes of broken kernels. For example, an indent size of 3.0 mm could be recommended for separating broken kernels shorter than 2.5 mm.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgement

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