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An Improved Method for the Production of White Rice with Embryo in a Vertical Mill

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This study was carried out to improve a vertical mill to produce white rice with embryo of 15·0–16·5% moisture content. Milling experiments were conducted by modifying a vertical mill in a rice mill plant. The effects of rice moisture content and the shaft speed of the mill on embryo adherence ratio, whiteness, broken rice ratio, and cracked rice ratio were investigated with short grain rice. The effect of the mesh size of emery stones on the embryo adherence ratio was also investigated. The embryo adherence ratio of white rice decreased rapidly with the increase of the moisture content of brown rice. The embryo adherence ratio increased by 10·3 and 11·0%, respectively when brown rice samples with moisture contents of 16·2 and 15·5% were milled by the vertical mill with a shaft speed of 900 min^{-1} and emery stones of mesh size no. 50 instead of mesh size no. 35.The optimal milling conditions of the vertical mill for producing embryo rice were a moisture content of about 15%, shaft speed of 900 min^{-1}, emery stones of mesh size no. 50, zero outlet resistance and milling rate of 2·3 t h^{-1} considering the embryo adherence ratio, broken rice ratio, and whiteness of milled rice.

1. Introduction

Research on the production of rice with high quality such as functional rice and specialised rice is required (Chung, 1995). Especially, white embryo rice (white rice with embryo) has many valuable nutrients and fibre, so the consumer interest for white embryo rice is high. The factors affecting the adherence of rice embryo include mill characteristics (Koh, 1993; Hosokawa *et al.*, 1995) and physical properties of rice itself. The embryo adherence for polished white rice sold in Korea is usually less than about 3% based on our surveys conducted during past 2 yr. Some physical and mechanical properties of three varieties of rice were determined by Shitanda *et al.* (2001) for investigating the performance analysis of an impeller husker. The grain exit velocity resulted in an impact force above the yield force of the husk but below the yield force of the grain. The adherence ratio in a vertical mill is usually higher than that in a horizontal mill as the internal pressure in the milling chamber of a vertical mill is uniform (Hosokawa *et al.*, 1995; Hong & Song, 1990) and lower than that of a horizontal mill (Yan & Chung, 2002). Rice embryo is very easily removed by instant impact and friction between brown rice kernels and emery stones. Hence, the adherence ratio of rice embryo is affected not only by the internal pressure, but also by shaft speed, the mesh size, outlet resistance, clearance between roller and screen and moisture content (MC) of brown rice. Mohapatra and Bal (2004) found that the abrasion coefficient of rice decreased with the degree of milling using three varieties of rice differing in slenderness ratio at different degrees of milling levels. To predict and improve the productivity of a rice mill process, a simulation was conducted by Chung and Lee (2003) using a simulation language for alternative modelling.

Improvement of a vertical mill to produce white rice with embryo in the MC range of 15·0–16·5% was needed. Therefore, the objective of this study was to improve a commercial, vertical mill through analysing the effects of the moisture content of brown rice, shaft speed, mesh size of emery stones, outlet pressure resistance and milling rate on the embryo adherence ratio for producing white rice with embryo.

2. Materials and methods

2.1. *Experimental vertical mill*

A friction and abrasion type vertical mill was used with a capacity of $3\,t\,h^{-1}$ (HRW-4, Hyundai Machinery Co., Korea, *Fig. 1*). It consists of a 45 kW motor, a milling chamber of the vertical type, a roller shaft with two emery stones, screens with eight emery stones, outlet pressure resistance adjusting pendulum and a 0·746 kW feeding screw with a gate adjusting milling rate (Table 1). The suction pressure of a fan used for the mill was set at $2{\cdot}8 \times 10^4$ kPa. The mesh size of the emery stones originally installed was no. 35. For reducing the impact force, emery stones of mesh size no. 50 were used in the modified vertical mill. The outlet pressure resistance was varied by the position of a pendulum (counterweight), which was installed on the discharge exit of the mill (Erdman *et al.*, 2001). The outlet resistance was expressed as torque in N m, which was determined by the distance of a pendulum from a hinge of discharging outlet. The outlet resistance was varied from 0 to 0·3 and 0·6 N m.

2.2. *Experimental method*

Milling experiments were conducted to investigate the effects of the rice moisture content, the speed of the roller shaft, and the emery stone mesh size on the embryo adherence ratio and rice qualities of whiteness,

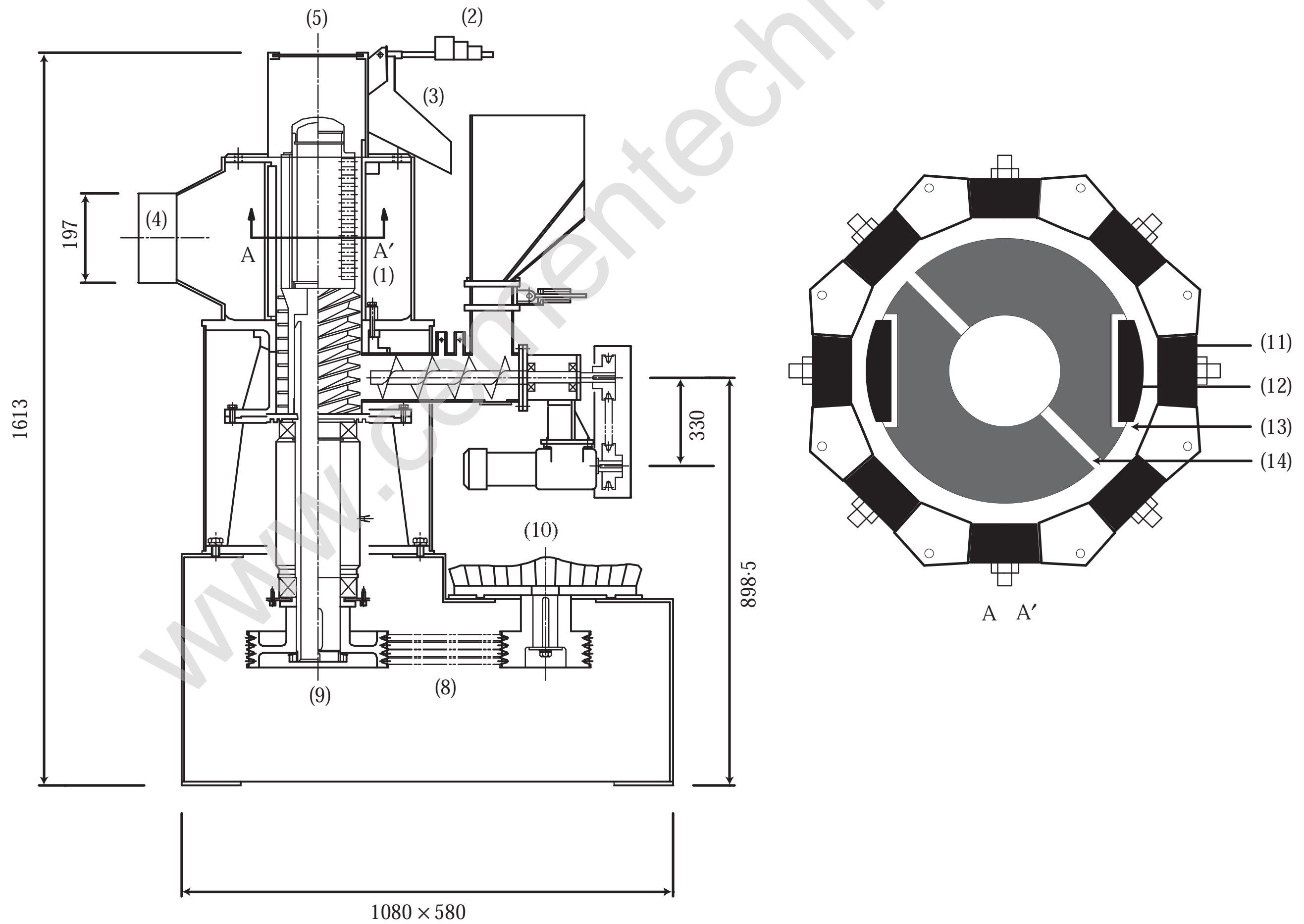

Fig. 1. Schematic diagram of a vertical rice mill for producing white embryo rice; (1) emery stone; (2) resistance pendulum; (3) rice exit; (4) rice bran exit; (5) upper cover; (6) feeding screw; (7) shaft roller; (8) belt; (9) pulley; (10) driving motor; (11) emery stone (fixed); (12) emery stone (rotational); (13) screen; (14) air hole; all dimensions in mm

Table 1
Specifications of a vertical mill used in this study

Components	*Specification*	*Remarks*
Model	HRW-4	Hyundai machine co.
Dimension	L1080 mm by W962 mm by H1613 mm	
Mill capacity	$3\,t\,h^{-1}$	Abrasion & friction type
Roller shaft	Outside diameter 150 mm	
Roller with emery stones	Outside diameter 165 mm	With 2 stones of mesh no. 35/50
Screens	Inside diameter 185 mm	With 8 stones of mesh no. 35/50
Mill driving motor	45 kW, 380 V, 3 phase	
Feeding screw motor	0·746 kW, 220 V, 2 phase	
Fan suction pressure	2·8 kPa	

L, *W*, and *H*, length, width and height.

broken rice ratio, and cracked rice using a vertical mill. The moisture content of raw brown rice was measured by a moisture meter (Kett C305, Kett Electric Laboratory, Tokyo city, Japan). The whiteness of rice in % was measured by a whiteness meter (Kett C-300-3). The ratios of embryo adherence, broken rice, and cracked rice were counted visually. The broken rice was defined as below two-thirds of whole milled rice in length. The variety of rice was a short grain of the Japonica type (DongJin variety No. 1). The moisture content of rough rice was controlled by aeration after rough rice was naturally dried up to about 17% in a steel grain bin. Rough rice was hulled by an automatic huller, and broken rice in the brown rice was removed by a thickness grader before testing. The quantity of a brown rice sample was 200 kg.

2.2.1. *The effects of the rice moisture content and the roller shaft speed*

The milling experiments were conducted with different moisture contents of brown rice at roller shaft speeds of 900 and $1100\,min^{-1}$. The adherence ratio of rice embryo, whiteness, broken rice ratio, and cracked rice ratio were measured and analysed in triplicate. The mill was set at emery stone mesh size no. 35, and the experiments were done at $2{\cdot}3\,t\,h^{-1}$ milling rate and zero outlet resistance as a proper operating condition.

2.2.2. *The effect of emery stone mesh size*

The effect of emery stone mesh size no. 35 and no. 50 was also investigated at $900\,min^{-1}$, because the adherence ratio was higher than that at $1100\,min^{-1}$ for the MC range of 13·0–17·2%. First, the adherence ratios with emery stones of mesh size no. 35 were investigated at two moisture contents of 15·5% and 16·2%, five levels of milling rates, and three levels for the outlet resistance of 0 (no pendulum), 0·3, and 0·6 N m. The levels of milling rates were 1·5, 1·7, 1·9, 2·1, and $2{\cdot}3\,t\,h^{-1}$. Tests were also carried out with emery stones

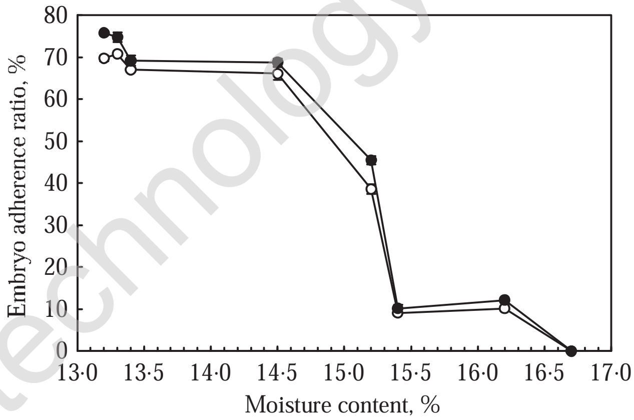

Fig. 2. Embryo adherence ratio variation with moisture contents of brown rice in a vertical mill operated with emery stones of mesh no. 35 and two different shaft speeds: ○, $1100\,min^{-1}$; ●, $900\,min^{-1}$

of mesh size no. 50 at the same conditions. After the effect of emery stone mesh size at the above different conditions was analysed, the embryo adherence ratio and the whiteness of rice were investigated in the MC range of 13·2–16·7%.

3. Results and discussion

3.1. *Effects of rice moisture and shaft speed on rice qualities*

3.1.1. *The embryo adherence ratio of rice*

The average embryo adherence ratio with brown rice moisture content is shown in *Fig. 2* for a milling rate of $2{\cdot}3\,t\,h^{-1}$, zero outlet pressure resistance and shaft speeds of 1100 and $900\,min^{-1}$. The adherence ratio decreased with the increase of brown rice moisture content. The adherence ratios at the shaft speed of 1100 and $900\,min^{-1}$ were about 70% and 76%, respectively, at the moisture content of 15·2%, about 66% and 69%, respectively, in the MC range of 13·4–14·5%, and about 0·1% and 0·1%, respectively, at 16·7%. The adherence ratio at 900 min^{-1} was higher than that at 1100 min^{-1} by 2–8% in the MC range of 13·2–15·2%. Although reduction of the shaft speed decreased the milling rate, the maximum milling rate at 900 min^{-1} was about 2·3 $t\,h^{-1}$. Hence, it was recommended that the proper moisture content for a high adherence ratio should be less than about 15·2%. The reduction of the shaft speed by 200 min^{-1} increased the adherence ratio rice embryo up to about 8% when the moisture content of was less than 15·2%. The effects of shaft speed and moisture content were statistically significant at the 95% and 99% confidence levels.

3.1.2. *Whiteness of embryo rice*

The whiteness of embryo rice increased with the increase of rice moisture content at the shaft speeds of 1100 and 900 min^{-1} (*Fig. 3*). The whiteness of embryo rice increased from 23% at 13·2% MC up to 40% at 15·2% MC. At 15·2% MC, the rice bran was easily removed. The whiteness at shaft speed of 1100 min^{-1} was higher than that at 900 min^{-1} by 1·3–4·0% in the MC range of 13·2–15·4%. However, there was little difference when moisture content was more than 16·7%. Therefore, the whiteness of white embryo rice was much affected by low moisture content. The effects of the shaft speed and the moisture content on the whiteness were statistically significant at the 95% and 99% confidence levels, respectively.

3.1.3. *The broken rice ratio*

The broken rice ratio gradually decreased from about 3·5% at 13·4% MC to about 1·0% at 16·7% MC at the shaft speeds of 1100 and 900 min^{-1} (*Fig. 4*), but it increased with the increase of moisture content as rice strength decreased at more than 16·7% MC. Besides, the broken rice ratio at 900 min^{-1} decreased by about 0·6–1·0% compared to that at 1100 min^{-1} in the MC range of 13·2–15·4%. Equations of broken rice ratios at the shaft speeds of 1100 and 900 min^{-1} were expressed as

$$y_b = -0{\cdot}0831x^2 + 0{\cdot}4272x + 2{\cdot}6518 \quad (1)$$

$$y_b = -0{\cdot}0431x^2 + 0{\cdot}1506x + 2{\cdot}4077 \quad (2)$$

where: y_b is the broken rice ratio in %; x is the moisture content in %; with values for the coefficient of determination R^2 of 0·818 and 0·708, respectively.

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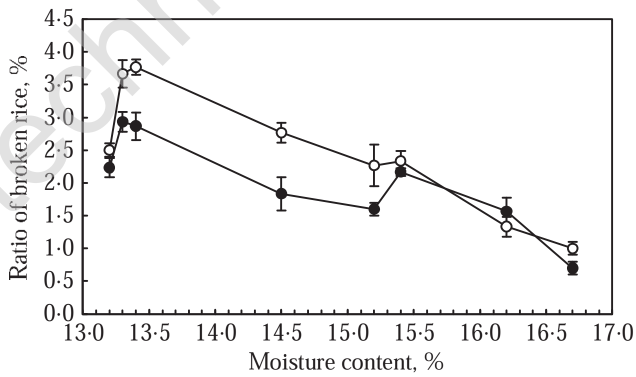

Fig. 4. Variation of broken rice with moisture content in a rice vertical mill operated with with emery stones of mesh no. 35 and two different shaft speeds: ○, 1100 min^{-1}; ●, 900 min^{-1}

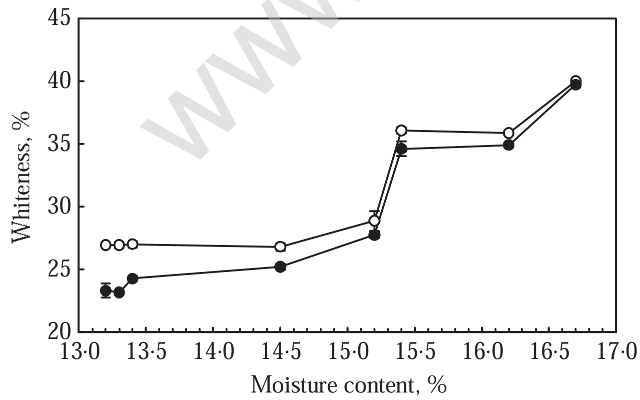

Fig. 3. Variation of rice whiteness with moisture content of brown rice in a rice mill operated with emery stones of mesh no. 35 and two different shaft speeds: ○, 1100 min^{-1}; ●, 900 min^{-1}

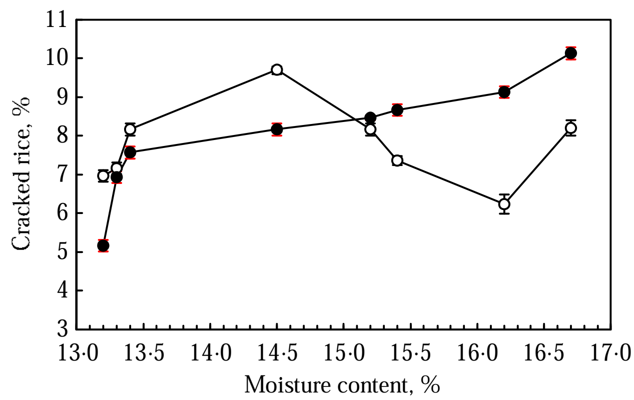

Fig. 5. Percentage of cracked rice with moisture content in a rice vertical mill operated with emery stones of mesh no. 35 and two different shaft speeds: ○, 1100 min^{-1}; ●, 900 min^{-1}

3.1.4. *The cracked rice ratio*

The cracked rice ratio was constant at less than 9% in the range from 13·2% to 16·2% MC at the two shaft speeds (*Fig. 5*). However, it increased from 10% at 16·7% MC to about 20% at 17·0% MC. There was little difference in the cracked rice ratios between 1100 and 900 min^{-1} when the moisture content was less than 16·7%. Equations of cracked rice ratio at 1100 and 900 min^{-1} were expressed as

$$y_c = 0{\cdot}3798x^2 - 1{\cdot}4488x + 27{\cdot}8940 \quad (3)$$

$$y_c = -0{\cdot}0518x^2 + 1{\cdot}0538x + 4{\cdot}6077 \quad (4)$$

where, y_c is the cracked rice ratio in %; and with values for R^2 of 0·928 and 0·942, respectively.

3.2. *Effect of emery stone mesh size on the embryo adherence ratio*

3.2.1. *Emery stone mesh size no. 35*

(1) *Embryo adherence ratio based on milling rate*

The change of embryo adherence ratio with milling rate was investigated using emery stone mesh size no. 35, 900 min^{-1} shaft speed and brown rice at 15·5 and 16·2% MC (*Fig. 6*). The embryo adherence ratios increased at these moisture levels with the increase of the milling rate up to 2·3 t h^{-1} when outlet pressure resistance was zero. The highest adherence ratios at 15·5% and 16·2% MC were 47·3% and 45·0% respectively at zero outlet pressure resistance and 2·3 t h^{-1} milling rate.

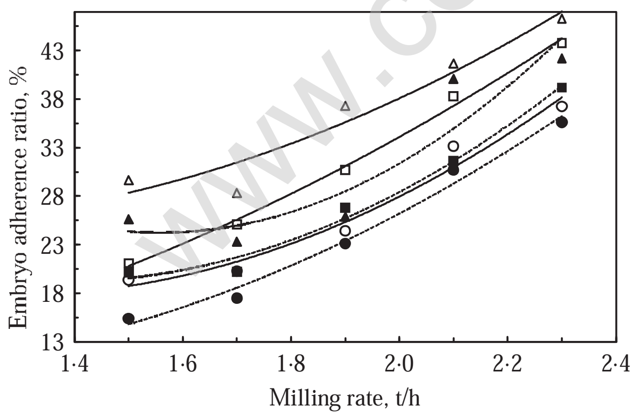

Fig. 6. Variation of embryo adherence ratio with milling rate and the outlet resistance in a vertical rice mill with emery stones of mesh no. 35 and shaft speed of 900 min^{-1}: ○, 0 N m at 15·5% MC; □, 0·3 N m at 15·5% MC; △, 0·6 N m at 15·5% MC; ●, 0 N m at 16·2% MC; ■, 0·3 N m at 16·2% MC; ▲, 0·6 N m at 16·2% MC: —, 15·5% MC; - - -, 16·2% MC; MC, moisture content

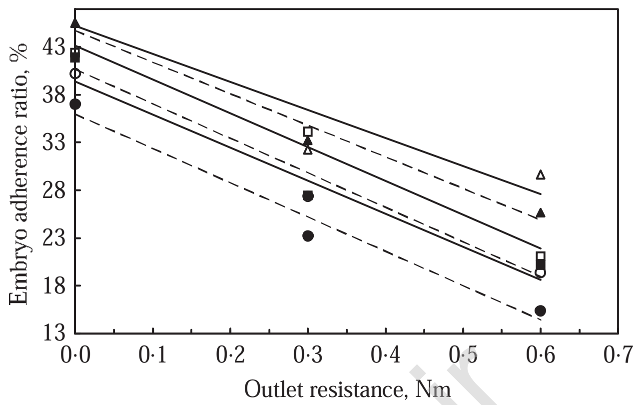

Fig. 7. Variation of embryo adherence ratio with outlet resistance of a vertical rice mill with emery stones of no. 35 and shaft speed of 900 min^{-1}: ○, 1·5 t h^{-1} at 15·5% MC; □, 1·9 t h^{-1} at 15·5% MC; △, 2·3 t h^{-1} at 15·5% MC; ●, 1·5 t h^{-1} at 16·2% MC; ■, 1·9 t h^{-1} at 16·2% MC; ▲, 2·3 t h^{-1} at 16·2% MC; —, 15·5% MC; - - -, 16·2% MC; MC, moisture content

(2) *Variation of embryo adherence ratio with outlet resistance*

The adherence ratio variation with outlet resistance was investigated for brown rice at 15·5% and 16·2% MC (*Fig. 7*). As the outlet resistance increased, the adherence ratio rapidly decreased. The adherence ratio was the highest at the zero outlet resistance because the internal pressure of the mill chamber was lowest. The adherence ratio at 15·5% MC was higher by 4–12% than that at 16·2% MC under the same milling rate.

3.2.2. *Emery stone mesh size no. 50*

(1) *Embryo adherence ratio with milling rate*

The change of embryo adherence ratio with milling rate was investigated using emery stone mesh size no. 50 and shaft speed of 900 min^{-1} at 15·5 and 16·2% MC (*Fig. 8*). The highest adherence ratios at the two moisture contents were 58·3% and 55·2%, respectively, for a 2·3 t h^{-1} milling rate and zero outlet resistance. Although the adherence ratio increased with milling rate up to 2·3 t h^{-1}, it decreased above 2·3 t h^{-1} for mesh size no. 35. The embryo adherence ratio for emery stones of mesh size no. 50 was higher than that for mesh size no. 35 by about 10% under the same operating conditions.

The mill with emery stones of mesh size no. 50 increased the embryo adherence ratio up to 42% compared to the conventional, commercial one with emery stones of mesh size no. 35 for brown rice at 16·2% MC. The whiteness of embryo rice at the milling rate of 2·3 t h^{-1} was lower than that at the milling rates of 1·9 and 1·5 t h^{-1} by 2·0% and 3·6%, respectively, when using emery stones of mesh size no. 50.

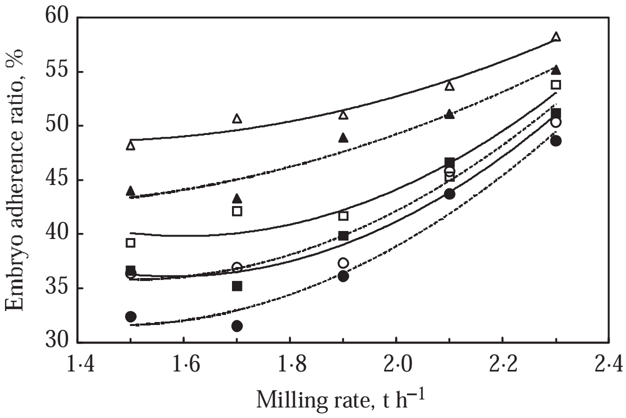

Fig. 8. Variation of embryo adherence ratio with milling rate of a vertical rice mill with emery stones of mesh no. 50 and shaft speed of 900 min^{-1}: ○, 0 N m at 15·5% MC; □, 0·3 N m at 15·5% MC; △, 0·6 N m at 15·5% MC; ●, 0 N m at 16·2% MC; ■, 0·3 N m at 16·2% MC; ▲, 0·6 N m at 16·2% MC: —, 15·5% MC; - - -, 16·2% MC; MC, moisture content

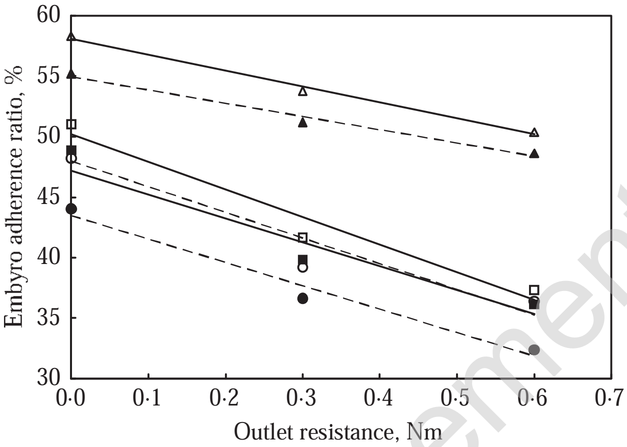

Fig. 9. Variation of embryo adherence ratio with the outlet resistance of a vertical rice mill with emery stones of mesh no. 50 and shaft speed of 900 min^{-1}: ○, 1·5 t h^{-1} at 15·5% MC; □, 1·9 t h^{-1} at 15·5% MC; △, 2·3 t h^{-1} at 15·5% MC; ●, 1·5 t h^{-1} at 16·2% MC; ■, 1·9 t h^{-1} at 16·2% MC; ▲, 2·3 t h^{-1} at 16·2% MC: —, 15·5% MC; - - -, 16·2% MC; MC, moisture content

(2) *Embryo adherence ratio with outlet resistance*

The adherence ratio variation with outlet resistance was investigated at three milling rates (*Fig. 9*). The adherence ratio decreased with the increase of outlet resistance at each milling rate irrespective of moisture content. The adherence ratios at the milling rates of 1·5, 1·9 and 2·3 t h^{-1} decreased by about 12, 10 and 7%, respectively, at the moisture content of 16·2% when the outlet resistance increased from 0 to 0·6 N m.

3.2.3. *Effect of emery stone mesh size*

The performance of the mill with emery stone mesh size no. 50 was much improved in view of the embryo adherence ratio compared to that with emery stone mesh no. 35, irrespective of the outlet resistance and milling rate. The adherence ratios at 16·2%, 15·5%, and 14·3% MC increased by 10·3%, 11·0%, and 3·5%, respectively, for emery stone mesh size no. 50, shaft speed of 900 min^{-1}, and the milling rate of 2.3 t h^{-1}. The effect of emery stone mesh size at high moisture content was higher than that at low moisture content. The effect of mesh size was statistically significant at 99% confidence level (at 14·3% MC, probability $P = 0{\cdot}00044 < 0{\cdot}05$; 15·5% MC; at $P = 0{\cdot}005 < 0{\cdot}05$ at 16·2% MC, $P = 0{\cdot}0004 < 0{\cdot}05$)

3.3. *Comparison between the improved vertical mill and the commercial one*

A commercial, vertical mill was improved by adjusting shaft speed and emery stone size. The embryo adherence ratios in the MC range of 13·2–17·0% were compared using the improved mill and a commercial mill for shaft speed of 900 min^{-1}, zero outlet resistance, the milling rate of 2·3 t h^{-1} (*Fig. 10*). The adherence ratio in the commercial mill was 13·0%, while that in the improved mill was 55·2% at 16·2% MC. The improved vertical mill increased the adherence ratio at 16·2% MC by 42% compared to the commercial mill. The improved mill produced a higher adherence ratio for the MC range of 15·5–17.0% than that at 14·5% MC. The broken rice ratios for the improved mill and the commercial one were about 2·5% and 3·0% respectively for brown rice at 14·2% MC and 2·3% for brown rice at 15·1%. There was little difference in the whiteness between the improved mill and the commercial one at the same moisture content. Equations of embryo

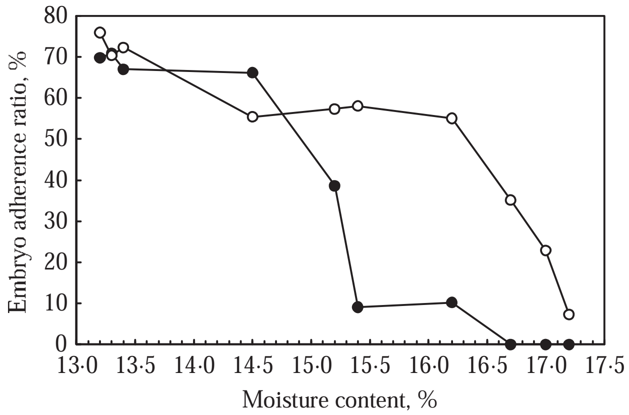

Fig. 10. Comparison of embryo adherence ratios for a commercial, vertical mill and the improved vertical mill with emery stones of mesh no. 50 and shaft speed of 900 min^{-1}, milling rate of 2.3 t h^{-1} and zero outlet resistance: ●, commercial mill; ○, improved mill

adherence ratios in the commercial vertical mill and the improved mill were expressed as

$$y_a = 0{\cdot}3972x^2 - 31{\cdot}788x + 423{\cdot}89 \quad (5)$$

$$y_a = -3{\cdot}9575x^2 + 106{\cdot}76x - 648{\cdot}64 \quad (6)$$

where y_a is the : embryo adherence ratio in %, and with value for R^2 of 0·904 and 0·901, respectively.

4. Conclusions and recommendations

A commercial, vertical mill was improved by changing shaft speed and emery stone size to produce white embryo rice in 15·0–16·5% moisture contents (MC). The effects of rice moisture content and the shaft speed of the mill on the embryo adherence ratio, whiteness, broken rice ratio, and cracked rice ratio were determined. Also, the effect of emery stone size on the embryo adherence ratio was investigated. The embryo adherence ratio of white rice decreased rapidly with the increase of brown rice moisture content. The embryo adherence ratio increased by 10·3 and 11·0%, respectively, when brown rice at samples 16·2% and 15·5% MC were milled by the vertical mill, improved by using a shaft speed of 900 min^{-1} and the emery stone mesh no. 50 instead of mesh size size no. 35.

The conditions recommended for the vertical mill in producing embryo rice were about 15% MC, 2·3 $t\,h^{-1}$ milling rate, a shaft speed of 900 min^{-1}, emery stone mesh size no. 50, and zero outlet resistance, considering the embryo adherence ratio, broken rice ratio, and whiteness of milled rice.

References

Chung J H (1995). Development of rice mill machinery for production of the clean and enriched rice. Ministry of Agriculture and Forestry, Korea

Chung J H; Lee Y B (2003). Simulation of a rice mill process. Biosystems Engineering, **86**(2), 145–150

Erdman A G; Sandor G N; Kota S (2001). Mechanism Design: Analysis and Synthesis. Prentice Hall, USA

Hong M C; Song S (1990). Studies on the quality of embryoed rice III–the effect of different milling machines on the quality of embryoed rice. Crop Improvement Division of Taichung, District Agricultural Improvement Station, Chaughua, Taiwan

Hosokawa A; Ban T; Yokosawa I; Yanase H; Chikubu S (1995). Rice Post-Harvest Technology. The Food Agency, Ministry of Agriculture, Forestry and Fisheries, Japan pp. 351–379

Koh H K (1993). Post-harvest Processing Machinery. Hyangmun. Publisher, Korea

Mohapatra D; Bal S (2004). Wear of rice in an abrasive milling operation—part 1: prediction of degree of milling. Biosystems Engineering, **88**(3), 337–342

Shitanda D; Nishiyama Y; Koide S (2001). Postharvest technology performance analysis of an impeller husker considering the physical and mechanical properties of paddy rice. Journal of Agricultural Engineering Research, **79**(2), 195–203

Yan T Y; Chung J H (2002). Effects of milling conditions on the adherence of rice germs. Proceedings of the Korean Society for Agricultural Machinery (KSAM) 2002 Winter Conference, Korean Society for Agricultural Machinery, Suwon, Korea.