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Original Article

Effects of operating factors for an axial-flow corn shelling unit on losses and power consumption

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ABSTRACT

The operating factors were studied for an axial-flow corn shelling unit that affected losses and power consumption. The shelling unit was 0.90 m long, with a diameter toward the end of the peg tooth of 0.30 m. The factors comprised three levels of moisture content (MC), three levels of feed rate (FR), and three levels of rotor speed (RS). The experiments were conducted based on response surface methodology and 2^3 factorial designs. The results of this study indicated that the MC significantly affected grain breakage and power consumption, but did not affect shelling unit losses. Increasing the MC increased both the grain breakage and power consumption. The FR affected the power consumption but did not affect shelling unit losses and grain breakage. Increasing the FR increased the power consumption. The RS had a significant impact on the shelling unit losses, grain breakage and power consumption. Increasing the RS increased the grain breakage and power consumption, but decreased the shelling unit losses. Empirical models were formulated based on multiple linear models.

Introduction

Corn is a feed raw material and is important for the livestock industry (Farjam et al., 2014). Corn production is based on its variety and, additionally, the harvesting mechanism is one of the most important components in corn production processes (Reference) (Chuan-Udom, 2013).

Kunjara et al. (1998) discussed corn shelling in Thailand from which the following information is sourced. Corn shelling has been used and modified since 1929. The development of corn sheller equipment was mostly conducted by local manufacturers, with the most corn shellers used for de-husking being the rasp bar sheller and peg-tooth sheller. These shellers have been tested and evaluated to determine their best operational performance until the accumulative losses (grain losses and grain breakage) were less than 1.5%. Nevertheless, with a rasp bar sheller, it was found that broken crop components remaining on the concave surfaces reduced the effectiveness of grain separation, while the power consumption and shelling drum speed of the peg-teeth sheller were double that of the rasp bar sheller (Kunjara et al., 1998).

A shelling unit for corn husker shelling was originally developed based on a wheat threshing unit, which was efficient but the grain breakage was relatively high (Department of Agriculture, 1996). Chuan-Udom (2013) studied the operating factors of Thai threshers affecting corn shelling losses and found that an axial flow rice thresher was highly efficient and easy to clean, with little grain breakage, with the adjustment to shell corns being economical and requiring only easy modification. Moreover, the principle of an axial flow shelling unit is suitable for Thailand and conditions in Asian countries (Singhal and Thierstein, 1987; Chuan-Udom, 2011).

The study of the operations and adjustments of the Thai, axial flow, rice combine harvester by Chuan-Udom and Chinsuwan (2009) showed that the rotor speed, guide vane inclination, grain moisture content, feed rate and grain material other than grain had significant effects on the threshing unit losses. Chinsuwan et al. (2003) studied the effects of the rotor tangential speed and feed rate on threshing unit losses and rice grain damage. The data obtained showed that the threshing unit losses decreased and the damage increased when the rotor tangential speed was increased. Andrews et al. (1993) studied the effects of combine operating parameters on the harvest loss in rice and reported that the feed rate, the ratio of material other than grain to that of grain, grain moisture content, rotor speed and concave clearance affected threshing unit losses. Gummert et al. (1992) reported that the rotor

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speed, feed rate and louver inclination affected threshing unit losses and that the rotor speed affected grain damage.

The appropriate axial flow sheller for shelling corn requires the study of important factors that affect losses and the power consumption, namely, the rotor speed, feed rate and grain moisture content Therefore, the aim of this research was to study the effects of operating factors of an axial-flow corn shelling unit on losses and the power consumption.

Materials and methods

Corn shelling unit

This study was conducted using an axial flow corn shelling unit provided by the Agricultural Research Development Agency (Public Organization), Thailand as shown in Fig. 1. The shelling unit was 0.90 m long, with a diameter toward the end of the peg tooth of 0.30 m, with a controllable rotor speed. There was a power measuring device as shown in Fig. 2. The axial flow corn shelling unit consisted of a spike-toothed cylinder. The concave portion located under the cylinder was made of curved steel bar. The guide vane inclination was adjustable. The chute for grain under the shelling unit was divided into nine slots. The feed rate was adjustable by controlling the conveyer belt speed of the materials into the shelling unit. The experiments were performed at the laboratory scale.

This study was performed with Pioneer B-80 corn variety.

Fig. 1. Corn shelling unit.

Fig. 2. Power measuring device.

Factors studied and experimental design

The range of operating factors affecting losses and the power consumption of an axial flow corn shelling unit were the moisture content (MC), feed rate (FR) and rotor speed (RS), as shown in Table 1. Following a factorial experimental design, a large number of factors and degrees were required to determine the quantity of materials and the experimental unit. Thus, a 2^3 factorial experimental design was applied, as shown in Table 2, to reduce the use of materials and the time for testing (Berger and Maurer, 2002).

Testing method

Each test used 10 kg of corn. The corn was fed into the inlet of the shelling unit on a conveyor belt. The samples taken from the husks and cobs outlet was screened until only corn grain remained and the grain was weighed and subtracted from the original 10 kg of corn and the result was considered as the shelling unit loss (TL). To obtain the percentage of grain breakage (GB), two 1 kg samples were randomly taken from the chute, the GB was separated by hand and the weight of the GB was recorded. In this experiment, a torque transducer with a strain gauge (KFG-2-350-D2-11L1M3R; Sokki Kenyujo Co. Ltd.; Tokyo, Japan) was used. The torque meter was installed on the cylinder shaft to measure the torque and to calculate the power consumption (P).

Data analysis

From the obtained parameters, the terms TL, GB and P were used to construct multiple line models. Then, the models were

Table 1
Independent variables and their factor levels.

Variable	Range and Levels (coded)		
	–	0	+
X_1; Moisture content (% wet basis)	14	21	28
X_2; Feed rate (t/hr)	0.5	1.5	2.5
X_3; Rotor speed (m/s)	8	10	12

Table 2
Experimental units based on a 2^3 factorial design for losses and power consumption of an axial flow corn shelling unit for the variables moisture content (X_1), feed rate (X_2) and rotor speed (X_3).

Experiment number	X_1	X_2	X_3
1	−	−	−
2	+	−	−
3	−	+	−
4	+	+	−
5	−	−	+
6	+	−	+
7	−	+	+
8	+	+	+
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0

Table 3
Effects of moisture content (MC), feed rate (FR) and rotor speed (RS) on shelling unit losses, grain breakage and power consumption.

Experiment number	MC (% wet basis)	FR (t/hr)	RS (m/s)	Shelling unit losses (%)	Grain breakage (%)	Power consumption (W)
1	14 (−)[a]	0.5 (−)	8 (−)	2.32	0.61	1529.73
2	14 (−)	0.5 (−)	8 (−)	2.93	0.37	1439.82
3	14 (−)	0.5 (−)	8 (−)	3.24	0.18	1417.35
4	28 (+)	0.5 (−)	8 (−)	2.43	2.26	1979.24
5	28 (+)	0.5 (−)	8 (−)	2.89	2.22	2046.66
6	28 (+)	0.5 (−)	8 (−)	3.33	2.47	2024.19
7	14 (−)	2.5 (+)	8 (−)	2.60	0.18	2271.42
8	14 (−)	2.5 (+)	8 (−)	2.88	0.19	2316.37
9	14 (−)	2.5 (+)	8 (−)	3.06	0.25	2316.37
10	28 (+)	2.5 (+)	8 (−)	2.90	2.20	3058.06
11	28 (+)	2.5 (+)	8 (−)	2.89	2.13	2990.63
12	28 (+)	2.5 (+)	8 (−)	2.65	2.68	3058.06
13	14 (−)	0.5 (−)	12 (+)	1.60	0.94	2069.14
14	14 (−)	0.5 (−)	12 (+)	1.57	0.71	2046.66
15	14 (−)	0.5 (−)	12 (+)	1.52	1.30	2091.61
16	28 (+)	0.5 (−)	12 (+)	1.11	2.20	2361.32
17	28 (+)	0.5 (−)	12 (+)	1.90	2.36	2338.84
18	28 (+)	0.5 (−)	12 (+)	1.60	2.47	2428.74
19	14 (−)	2.5 (+)	12 (+)	1.54	0.49	2653.50
20	14 (−)	2.5 (+)	12 (+)	1.53	1.06	2541.12
21	14 (−)	2.5 (+)	12 (+)	1.57	0.79	2631.02
22	28 (+)	2.5 (+)	12 (+)	1.58	2.22	3215.39
23	28 (+)	2.5 (+)	12 (+)	1.54	2.68	3215.39
24	28 (+)	2.5 (+)	12 (+)	1.47	2.20	3215.39
25	21 (0)	1.5 (0)	10 (0)	2.36	1.06	2586.07
26	21 (0)	1.5 (0)	10 (0)	2.22	1.26	2653.50
27	21 (0)	1.5 (0)	10 (0)	2.03	1.52	2563.60
28	21 (0)	1.5 (0)	10 (0)	2.56	1.61	2586.07

[a] Figures in parentheses indicate code of range and levels; − = low, 0 = medium, + = high.

applied in the analysis of the effects of parameters on losses and the power consumption based on response surface methodology and 2^3 factorial designs, determining the effects of each parameter on the coefficient of determination (R^2) using the Design Expert software package (version 7; Stat-Ease Inc; Minneapolis, MN, USA.). ANOVA was used for regression analysis of the design factors affecting TL, GB and P. Significance was tested at $p < 0.05$.

Indicator values

The indicator values, TL, GB and P, were computed based on the procedure for evaluation of corn shellers (Economic and Social Commission for Asia and the Pacific Regional Network for Agricultural Machinery, 1995).

Results and discussion

The effects of MC, FR and RS on TL, GB and P are shown in Table 3.

Operating parameters affecting the shelling unit losses

The results of ANOVA of the operating parameters affecting shelling unit losses are shown in Table 4. The results indicated that RS had a significant impact on shelling unit losses, whereas MC, FR, MC*FR, MC*RS, FR*RS and MC*FR*RS did not have a significant impact on shelling unit losses.

The regression equation that determined the effect of the operating parameters on shelling unit loss is shown in Eq. (1):

$$TL = 5.44 - 0.32RS \qquad (1)$$

where TL is the threshing loss (percentage) and RS (meters per second) is the rotor speed and the R^2 and adjusted R^2 values for Eq. (1) were 0.87 and 0.87, respectively.

Based on Eq. (1), the response surface plot showing the effect of MC and RS on TL is provided in Fig. 3.

From Fig. 3, increasing the rotor speed (RS) reduced the shelling unit loss (TL) which is related to the research of Simonyan (2009), where increasing beating resulted in an increase in the shelling capacity and reduced the shelling unit loss.

Operating parameters affecting the grain breakage

Table 5 shows the ANOVA results for the operating parameters affecting GB. The results indicate that MC, RS and MC*RS had a significant impact on the grain breakage, whereas FR, MC*FR, FR*RS and MC*FR*RS did not statistically affect GB.

The regression equation for determining the effect of operating parameters on grain breakage is shown in Eq. (2).

$$GB = -3.40 + 0.22MC + 0.28RS - 9.85 \times 10^{-3} MC * RS \qquad (2)$$

where GB is the grain breakage (percentage), MC is the moisture content (percentage), Rs is the rotor speed (meters per second) and the R^2 and the adjusted R^2 values are 0.96 and 0.94, respectively.

Based on Eq. (2), response surface plots were developed showing the effect of MC and RS (Fig. 4) and of MC and FR (Fig. 5) on GB.

From Figs. 4 and 5, increasing RS tended to increase GB which was related to the research of Rostami et al. (2009) where increased beating resulted in increased grain breakage.

Increasing MC resulted in a tendency for GB to increase (Chuan-Udom, 2013; Mahmoud and Buchele, 1975) because the high

Table 4
Analysis of variance operating parameters affecting shelling unit loss.

Source	Sum of squares	DF	Mean square	F value	*p*-value Prob > F	
Model	10.15	7	1.45	18.77	<0.0001	Model is significant
MC	$1.93 \times 10^{-0.005}$	1	$1.93 \times 10^{-0.005}$	$2.49 \times 10^{-0.004}$	0.9876	
FR	$1.82 \times 10^{-0.003}$	1	$1.82 \times 10^{-0.003}$	0.024	0.8796	
RS	9.57	1	9.57	123.93	<0.0001	
MC*FR	$1.95 \times 10^{-0.003}$	1	$1.95 \times 10^{-0.003}$	0.025	0.8754	
MC*RS	$2.51 \times 10^{-0.003}$	1	$2.51 \times 10^{-0.003}$	0.032	0.8589	
FR*RS	$3.77 \times 10^{-0.004}$	1	$3.77 \times 10^{-0.004}$	$4.89 \times 10^{-0.003}$	0.9450	
MC*FR*RS	$3.13 \times 10^{-0.003}$	1	$3.13 \times 10^{-0.003}$	0.040	0.8426	
Pure error	1.47	19	0.077			
Correlation total	11.65	27				

MC = moisture content, FR = feed rate, RS = rotor speed; DF = degrees of freedom.

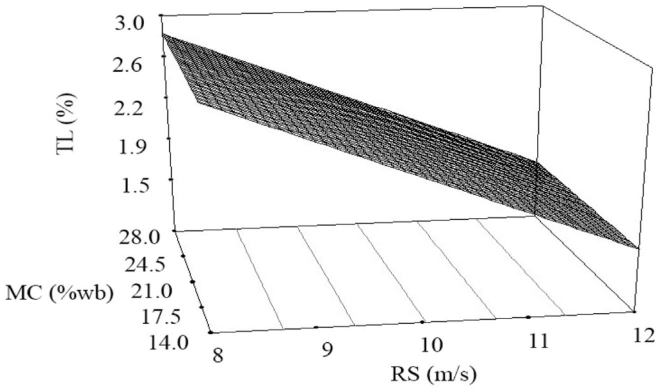

Fig. 3. Response surface plot of shelling unit loss (TL) showing the effect of moisture content (MC, measured on a weight basis, %wb) and rotor speed (RS), when feed rate was 1.5 t/hr.

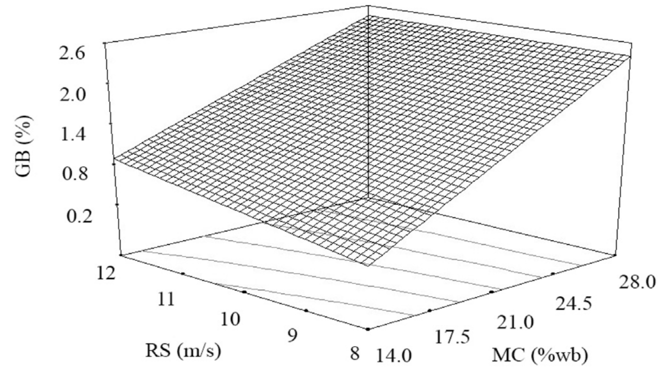

Fig. 4. Response surface plot of grain breakage (GB) showing the effect of moisture content (MC, measured on a weight basis, %wb) and rotor speed (RS), when feed rate was 1.5 t/hr.

moisture content of the grain was more flexible, making the grain more prone to breaking when it was beaten.

Operating parameters affecting the power consumption

Table 6 shows the results of ANOVA for the operating parameters affecting the power consumption. The results indicated that MC, FR, RS, MC*FR, MC*RS and FR*RS had a significant impact on shelling unit losses, whereas MC*FR*RS did not statistically affect shelling unit losses.

The regression equation for determining the effect of operating parameters on power consumption is shown in Eq. (3):

$$\begin{aligned} \mathrm{P} = & -925.096 + 58.508\mathrm{MC} + 699.237\mathrm{FR} + 211.020\mathrm{RS} \\ & + 11.416\mathrm{MC} * \mathrm{FR} - 3.345\mathrm{MC} * \mathrm{RS} - 39.956\mathrm{FR} * \mathrm{RS} \end{aligned} \quad (3)$$

where P is the power consumption (watts), MC is the moisture content (percentage), FR is the feed rate (meters per second) RS is the rotor speed (meters per second) and the R^2 and the adjusted R^2 values are 0.99 and 0.99, respectively.

Based on Eq. (2), response surface plots were developed showing the effect of MC and FR (Fig. 6), MC and RS (Fig. 7) and FR and RS (Fig. 8) on P.

From Figs. 4 and 5, increasing MC increased P, because the grain with high moisture content was stickier. Increasing FR tended to increase P, as loading more material into the shelling unit resulted in increased beating (Saeng-Ong et al., 2015) as shown in Figs. 6 and 8. From Figs. 7 and 8, increasing RS tended to increase P, as there was increased beating (Saeng-Ong et al., 2015).

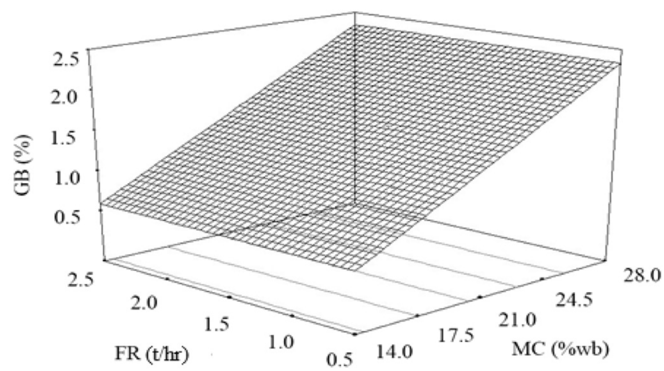

Fig. 5. Response surface plot of grain breakage (GB) showing the effect of feed rate (FR) and moisture content (MC, measured on a weight basis, %wb), when rotor speed was 10 m/s.

The main conclusions for the study were: 1) the rotor speed (RS) significantly affected shelling unit loss (TL), with increased RS reducing TL; 2) the moisture content (MC) and rotor speed (RS) significantly impacted on the grain breakage, with increased MC and RS resulting in an increased tendency for grain breakage; 3) the moisture content (MC), feed rate (FR) and rotor speed (RS) significantly affected power consumption (P), with increased MC, FR and RS increasing consumption; 4) the optimal linear model of the operating factors affecting shelling unit loss (TL) was 5.44318−0.32501RS with an R^2 value of 0.87; 5) the optimal model of the operating factors affecting grain breakage (GB) was $-3.40 + 0.22\mathrm{MC} + 0.28\mathrm{RS} - 9.85 \times 10^{-003}\mathrm{MC}^*\mathrm{RS}$ with an R^2 value of 0.96; 6) the optimal model of the operating factors

Table 5
ANOVA for operating parameters affecting grain breakage.

Source	Sum of squares	DF	Mean square	F value	*p*-value Prob > F	
Model	19.54	7	1.45	51.62	<0.0001	Model is significant
MC	16.80	1	16.80	310.70	<0.0001	
FR	0.045	1	0.045	0.83	0.3728	
RS	0.56	1	0.56	9.86	0.0054	
MC*FR	0.068	1	0.068	1.26	0.2752	
MC*RS	0.44	1	0.44	8.05	0.0105	
FR*RS	$2.04 \times 10^{-0.004}$	1	$3.77 \times 10^{-0.004}$	$3.77 \times 10^{-0.003}$	0.9516	
MC*FR*RS	$3.37 \times 10^{-0.004}$	1	$3.13 \times 10^{-0.003}$	$6.24 \times 10^{-0.003}$	0.9379	
Pure error	1.03	19	0.077			
Correlation total	20.61	27				

MC = moisture content, FR = feed rate, RS rotor speed (RS); DF = degrees of freedom.

Table 6
ANOVA of operating parameters affecting power consumption.

Source	Sum of squares	DF	Mean square	F value	*p*-value Prob >F	
Model	$6.59 \times 10^{0.006}$	7	$9.42 \times 10^{0.005}$	580.58	<0.0001	Model is significant
MC	$1.53 \times 10^{0.006}$	1	$1.53 \times 10^{0.006}$	944.00	<0.0001	
FR	$3.93 \times 10^{0.006}$	1	$3.93 \times 10^{0.006}$	2422.03	<0.0001	
RS	$8.74 \times 10^{0.005}$	1	$8.74 \times 10^{0.005}$	535.67	<0.0001	
MC*FR	86,211.76	1	86,211.76	53.16	<0.0001	
MC*RS	57,765.05	1	57,765.05	35.62	<0.0001	
FR*RS	86,211.76	1	86,211.76	53.16	<0.0001	
MC*FR*RS	$1.54 \times 10^{0.005}$	1	5388.24	3.32	0.0841	
Pure error	36,202.20	19	1621.79			
Correlation total	$6.95 \times 10^{0.006}$	27				

MC = moisture content, FR = feed rate, RS rotor speed (RS); DF = degrees of freedom.

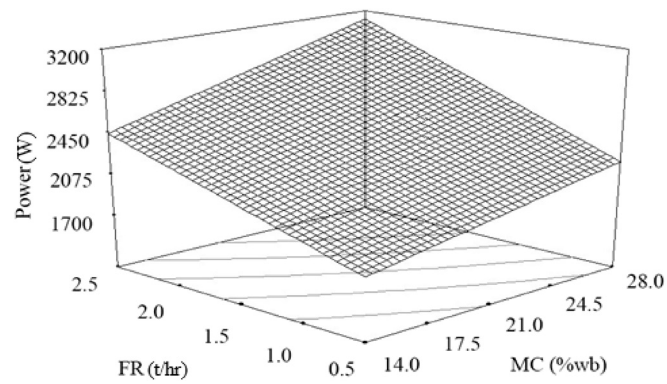

Fig. 6. Response surface plot of power consumption (P) showing the effect of feed rate (FR) and moisture content (MC, measured on a weight basis, %wb), when rotor speed (RS) was 10 m/s.

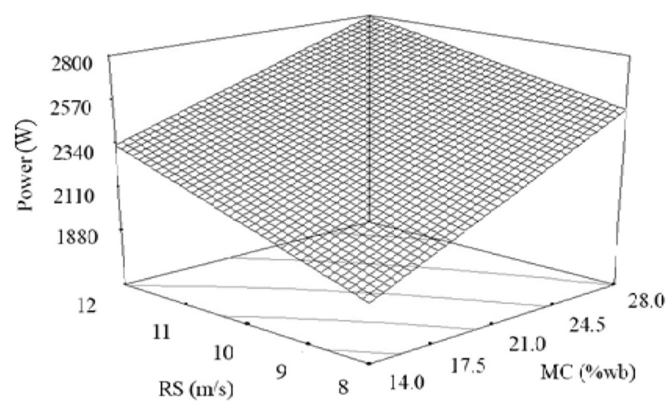

Fig. 7. Response surface plot of power consumption (P) showing the effect of moisture content (MC, measured on a weight basis, %wb) and rotor speed (RS), when feed rate was 1.5 t/hr.

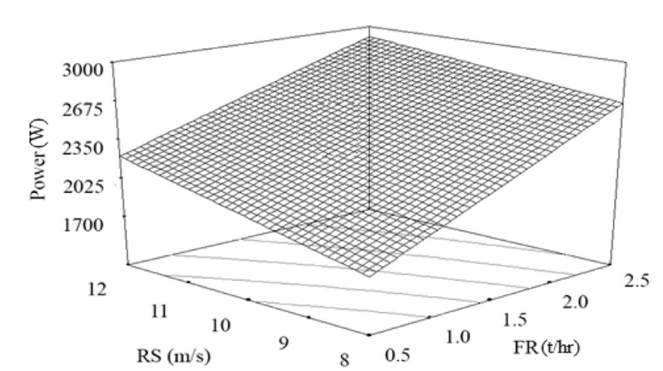

Fig. 8. Response surface plot of power consumption (P) showing the effect of feed rate (FR) and rotor speed (RS), when moisture content was 14% on a wet basis.

affecting power consumption (P) was −925.096 + 58.508MC + 699.237FR + 211.02RS + 11.416MC*FR − 3.345MC*RS − 39.956FR*RS with an R^2 value of 0.99.

Conflict of interest

There is no conflict of interest.

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