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Behavior and model of grain separation for a small axial flow maize shelling unit

Waree Srison[1)], Khunnithi Doungpueng[2)], Pisal Muenkaew[3)] and Somchai Chuan-Udom*[4)]

[1)]Department of Agricultural Machinery Engineering, Faculty of Engineering and Technology, Rajamangala University of Technology Isan, Nakhon Ratchasima, Thailand
[2)]Department of Farm Mechanics, Faculty of Technical Education, Rajamangala University of Technology Isan, Khon Kaen Campus, Khon Kaen, Thailand
[3)]Faculty of Engineering and Technology, Rajamangala University of Technology Isan, Khon Kaen Campus, Khon Kaen, Thailand
[4)]Department of Agricultural Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen, Thailand

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Abstract

Shelling and grain separation by a small axial flow maize sheller is influenced by the performance of both the maize shelling and cleaning units. For this study, the shelling and grain separation behavior were examined in a mini-maize grain separation unit. Concave rod clearance (CR) had the most impact on the effectiveness of grain separation. Concave rod clearances 10, 20 and 30 mm were selected as test parameters. Cumulative grain separation in a small axial flow maize shelling unit was analyzed in three zones, the feeding zone, the second and third zones, where the last two zones were separated zones. Test results indicated that when CR was increased, cumulative separation of grain, husks and cobs increased along the length of the shelling unit. These parameter relationships were represented using second-degree polynomial equations. An optimal shelling model for a small axial flow maize shelling unit was created. The function, S(l), represented cumulative grain separation as a function of separation length (l). The results from five shelling models indicated that predicted shelling parameters using Caspers's model for both the feed rate and rotor peripheral speeds was the most satisfactory, with lowest root mean square error (RMSE) and highest coefficient of determination (R^2).

Keywords: Axial flow, Maize shelling, Concave, Grain separation

1. Introduction

Maize is a globally important cereal crop [1] that is used for livestock feed [2, 3]. It is an economic export of Thailand. Currently, conflict between Russia and Ukraine, who are major exporters of maize has resulted in higher prices. Maize production facilitates transportation, storage and trading activities [4]. Maize shellers have been used in Thailand since 1929, with continuous development by local manufacturers [5]. There are two types of shelling units, tangential flow and axial flow. For tangential flow machines, materials are fed through a clearance between the rotor and a concave single pass channel which increases grain separation. For axial flow units, materials are fed from the side of the unit into the feeding zone and are axially flowed into a separation zone. The lower concave channel functions as a threshing bed using a rotor and grain separator. Guide vanes control the material flow, which is finally ejected from the outlet [6].

Thai axial flow threshers have been modified to do both rice threshing and maize shelling [4, 7]. Axial flow shelling units are suitable for Thailand and Asian countries. Most customized threshers are large, making them unsuitable for working in small fields [8].

Previous research focused primarily on the operating parameters of axial flow shelling units. Chuan-Udom [4] studied the parameters for Thai threshers that affect losses during maize shelling. Losses result from incomplete shelling where unshelled kernels remain attached to the cob are ejected from the sheller. Shelling losses are impacted by rotor speed (RS), louver inclination (LI), grain moisture content (MC), feed rate (FR) and the grain to materials other than grain ratio (GM). Both LI and MC affect shelling losses. Increasing LI or decreasing MC reduces shelling losses. However, RS, FR, and GM did not show any statistically significant effect on shelling losses. High rotor speeds tend to increase grain breakage [9, 10].

Muenkaew et al. [11] studied the effects of design factors on sunflower threshing performance of a small axial flow threshing unit. Their results showed that peg-tooth clearance had a statistically significant effect on grain purity and grain breakage. Furthermore, reducing peg-tooth clearance and concave clearance did not affect threshing efficiency, grain breakage, and power requirements. Specific energy consumption was higher while losses decreased with reduced peg-tooth and concave clearance.
A study of an axial flow threshing unit for rice threshing indicated that increasing peg tooth spacing resulted in linearly increasing threshing unit losses. Increasing the guide vane inclination yielded linearly decreasing threshing unit losses [12].

Chuan-Udom [13] studied grain separation in a Thai rice axial flow threshing unit. He found that 70-80% of grain was separated in feeding zone with 20-30% of grain removed in the separation zone.

*Corresponding author.
Email address: somchai.chuan@gmail.com
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The performance of a shelling unit and cleaning unit influences grain separation. A grain separation model was developed to study process behavior while estimating grain separation and shelling characteristics, both quantitatively and qualitatively [14, 15].

Maertens and De Baerdemaeker [14] studied a wheat threshing process using combine harvesters. Various feed rates and crop properties were studied to analyze grain separation. Grain separation was a function of feed rate and crop properties. Comparing the results of six different theoretical threshing models, optimal prediction was by Rusanov's exponential model.

Prior research on a 0.9 m long axial flow maize shelling unit primarily focused on the shelling operational parameters. However, there has been no study published on the behavior and modelling of a maize shelling unit.

Models of grain separation are also guidelines for the suitability of various shelling unit design concepts to maximize grain separation in the future. The objective of this research is to study shelling behavior and model grain separation of an axial flow maize shelling unit to predict grain separation and shelling characteristics.

2. Materials and methods

2.1 Maize shelling unit tester

This study was conducted using a small axial flow maize shelling unit provided by the Agricultural Research Development Agency (Public Organisation) of Thailand. It is shown in Figures 1 and 2. The shelling unit was 0.90 m long, with an adjustable speed 0.30 m diameter spike-tooth rotor. The concave portion under the rotor was fabricated of curved steel bars with a concave clearance of 20 mm. The guide vane inclination was set to 85o from the rotor axis. A tray under the shelling unit collected grains, dividing them into nine portions. Each of the nine sections was 10 cm wide. The feed rate into the shelling unit was modulated using an adjustable speed conveyor.

Figure 1 Maize shelling unit

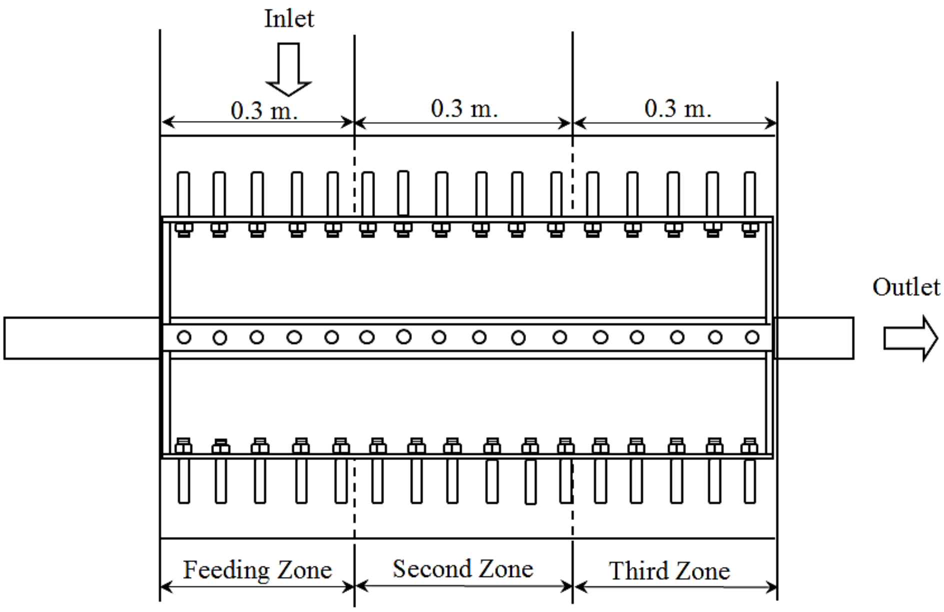

Figure 2 Schematic of the maize shelling unit used in the current study (top view)

2.2 Materials and testing methods

The maize samples used in this study were of the Pioneer B-80 variety. Moisture contents of the grains, husks and cob were 12.4, 15.2 and 15.6% (wb), respectively.

Each test was done in triplicate with 10 kg of maize fed into the inlet by the conveyer. The materials at the husk and cob outlets were collected in bags and separated to determine the remaining maize grain. The output materials that fell through the lower concave were collected in nine portions of the tray (three zones with three portions in each zone). These zones are the feeding zone, second and third zones. The second and third zones were separation zones. Each collecting section had a bag attached for collecting the grains, husks, cobs and other substances for weighing.

2.3 Grain separation behavior

Concave rod clearance (CR), which had the most effect on grain separation [16], was selected as a test parameter. Testing was done at rod clearances of 10, 20 and 30 mm. The test results were used to develop an empirical model for analysis of grain separation by the shelling unit**.**

2.4 Comparison of grain separation models

Grain separation was evaluated at three maize feed rates (FR) 500, 1500 and 2500 kg/h with a 10 m/s rotor peripheral speed (RS). In a second test, various RS values, 8, 10 and 12 m/s, were tested at a 1500 kg/h FR.

For the models of threshing unit separation, Kutzbach [17] presented a cumulative separation function S(l) in terms of threshing unit length (l). The model considered various parameters. Each of these parameters was optimized for all model configurations.

Rusanov [18] proposed an exponent, α = 0.9, for the separation length in Eq. (1).

$$S=1-e^{-\mu l^{\alpha}} \tag{1}$$

where S = grain separation
μ = constant separation coefficient
α = 0.9, based on experimental data
l = separation length (m)

Alferov and Braginec [19] measured grain separation as the difference of two exponential functions that considered the shelling and separation processes as Eq. 2:

$$S=1-e^{-k_1 l}-A\frac{1}{k_1-k_0}\left(e^{-k_0 l}-e^{-k_1 l}\right) \tag{2}$$

where A = mass of unshelled grain
k_0 = a constant shelling coefficient
k_1 = a constant separation coefficient
l = separation length (m)

Caspers [20] developed a third-order polynomial as a single exponential function to describe his experimental results on a tangential threshing unit. The cumulative separated grain was represented by Eq. (3).

$$S=1-e^{-(k_1 l-k_2 l^2-k_3 l^3)} \tag{3}$$

where k_1, k_2, k_3 = coefficients that depend on unit design and material properties
l = separation length (m)

Miu [21] presented mathematic models of shelling and separation processes. His equation describes the percentage of unshelled grain, percentage of shelled grain and cumulative separated grain. The cumulative separated grain in Eq. (4) is

$$S=\frac{1}{\lambda-\beta}\left(\lambda\left(1-e^{-\beta l}\right)-\beta\left(1-e^{-\lambda l}\right)\right) \tag{4}$$

where λ = specific shelling rate
β = specific separation rate
l = separation length (m)

Rusanov, Alferov and Braginec, Caspers and Miu’s model, and an empirical model of the test were chosen to compare grain separation predictions. The models were evaluated using their root mean square error (RMSE) and coefficient of determination (R^2). RMSE is given as Eq. (5).

$$RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(Sh_{exp,\ i}-Sh_{pre,\ i}\right)^2} \tag{5}$$

where N = number of test runs
$Sh_{exp,\ I}$ = experimental grain separation
$Sh_{pre,\ I}$ = predicted grain separation

3. Results and discussion

3.1 Grain separation in a small axial flow maize shelling unit

3.1.1 Cumulative separated grain

From Table 1, for all concave clearances, the quantity of grain passed through the lower concave was maximal in the feeding zone (43.52 – 52.00%) and at a minimum level in the third zone (14.75 - 20.31) of the shelling unit. The maximum and minimum grain quantities were 52.00% at CR 20 mm and 14.75% at CR 30 mm, respectively.

Table 1 Amount of grain passed through the lower concave at rod clearances (CR) of 10, 20 and 30 mm

Shelling unit length (m)	Amount of grain (%)		
	CR=10 mm	CR=20 mm	CR=30 mm
Feeding zone: 0.0-0.3	43.52	52.00	51.80
Second zone: 0.3-0.6	36.17	32.33	33.46
Third zone: 0.6-0.9	20.31	15.67	14.75

The results showed that within the feeding zone, CR had an effect on the cumulative separated grain passing through the bottom concave, which linearly increased with the shelling unit length. As the maize was shelled, grain began to slip out of the feeding zone. In the second and third zones, the amount of separated grain under the lower concave exponentially increased with the length of the shelling unit. In this study, only kernels shelled by the threshing drum were considered. This result agrees with the research of Chuan-Udom [13], Maertens and De Baerdemaeker [14], Butts et al. [22], Zhao et al. [23] and Zhong et al. [24] but differs from the results of Miu and Kutzbach [25] who found that the cumulative separated grain increased rapidly in the feeding zone. The cumulative separated grain in the second and third zones increased slightly, primarily because the shelling unit was longer and the physical properties of the materials were different. The CR showed an increasing trend in the cumulative separated grain and a second-degree polynomial equation was used to describe the shelling behavior (Figure 3). An empirical model of the cumulative separated grain is given as Eq. (6), with R2 values of 0.9992–0.9997 when CR was varied between 10 to 30 mm (Table 2).

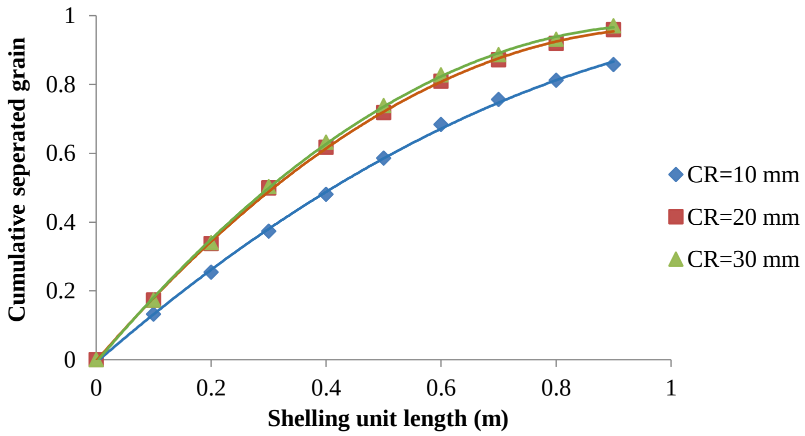

Figure 3 Relationship between shelling unit length and cumulative separated grain

$$CS = Al^2+Bl \tag{6}$$

where CS = cumulative separated grain
l = shelling unit length
A and B = constant coefficients

Table 2 Regression equation representing the cumulative separated grain

Concave rod clearance (mm)	Equation	R^2
10	$CS = -0.5070x^2 + 1.4206x$	$R^2 = 0.9992$
20	$CS = -0.9465x^2 + 1.9128x$	$R^2 = 0.9997$
30	$CS = -0.9655x^2 + 1.9444x$	$R^2 = 0.9996$

3.1.2 Cumulative separated husks and cobs

From Table 3, for all concave clearances, the quantity of husks and cobs in the tray under the lower concave was maximal in the feeding zone (43.09–47.70%) and was reduced to minimum levels in the third zone (19.75–27.31%) of the shelling unit. The maximum and minimum quantity of husks and cobs were 47.70% and 19.75% at CR 20 mm, respectively.

The quantity of husks and cobs in the tray under the lower concave decreased as the length of the shelling unit increased. This is because most of the husks were threshed within 0 to 0.5 m of the shelling unit length. When the materials reached 0.5–0.6 m into the shelling unit, the quantity of husks and cobs increased and then decreased with the shelling unit length. Most of the cobs were threshed within the second and third zones, as shown in Table 3.

Table 3 Quantity of husks and cobs passed through the lower concave at rod clearances (CR) of 10, 20 and 30 mm

Shelling unit length (m)	Quantity of husks and cobs (%)		
	CR= 10 mm	CR=20 mm	CR=30 mm
Feeding zone: 0.0-0.3	43.09	47.70	43.32
Second zone: 0.3-0.6	33.52	32.55	29.36
Third zone: 0.6-0.9	23.39	19.75	27.32

When the CR value was increased, the cumulative separated husks and cobs increased with the shelling unit length (Figure 4). Increasing CR enabled greater husk and cob separation, in agreement with Chuan-Udom [13]. The cumulative separated husks and cobs increased with the length of shelling unit since the husks and cobs were within the feeding zone and less materials passed through the lower concave. When most of the materials were within the second and third zones, the husks and cobs were threshed into slivers that passed easily through the lower concave, in agreement with Chuan-Udom [13]. The quality of husks and cobs under the lower concave influenced the cleaning performance [13]. This is represented by a second-degree polynomial regression, Eq. (7), with R^2 values between 0.9934 and 0.9998 when CR was varied between 10 to 30 mm (Table 4).

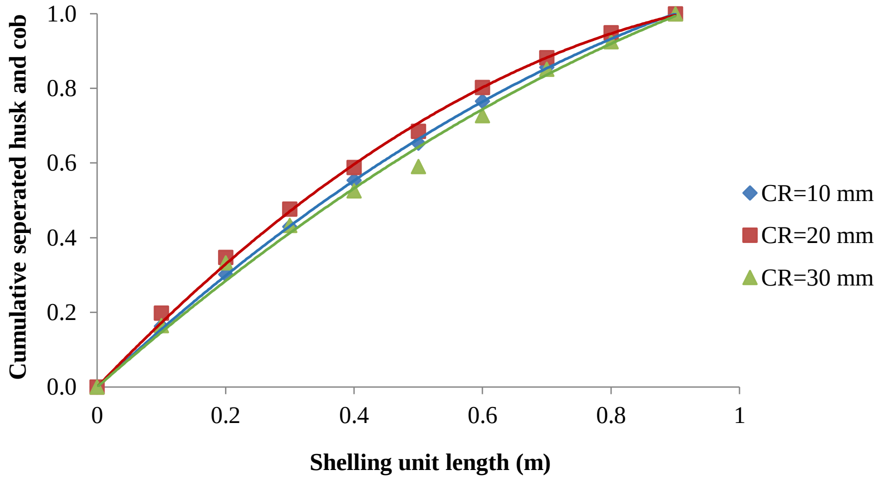

Figure 4 Relationship between shelling unit length and cumulative separated husks and cobs

$$SS = Cx^2+Dx \quad (7)$$

where SS = cumulative separated husks and cobs
x = shelling unit length
C and D = constant coefficients

Table 4 Regression equation representing by the cumulative separated husks and cobs

Concave rod clearance (mm)	Equation	R^2
10	$SS = -0.5417x^2 + 1.599x$	$R^2 = 0.9998$
20	$SS = -0.7699x^2 + 1.7994x$	$R^2 = 0.9984$
30	$SS = -0.4527x^2 + 1.5116x$	$R^2 = 0.9934$

3.1.3 Grain purity

Table 5 demonstrates that with CR values of 10 and 20 mm, the purity of the grain entering the feeding and separation zones through the bottom concave was greater than 95%. A CR of 30 mm was too wide, so the materials other than grain were separated from the grain to a degree less than for CR values 10 and 20 mm. This caused the grain purity under the lower concave of the feeding zone to fall below 95%. For all CR values, grain purity was lowest in the third zone. According to Chuan-Udom [13], grain purity decreased as the length along the shelling unit increased because the husks and cobs were threshed into slivers and then easily passed through the lower concave. This was true when the materials passed into the separation zone before ejection of the husks and cobs at their respective outlets.

Table 5 Purity of grain passed through the lower concave at rod clearances (CR) values of 10, 20 and 30 mm

Shelling unit length (m)	Grain purity (%)		
	CR=10 mm	CR=20 mm	CR=30 mm
Feeding zone: 0.0-0.3	98.30	97.30	93.50
Second zone: 0.3-0.6	98.40	97.00	92.90
Third zone: 0.6-0.9	97.90	96.30	86.80

3.2 Comparison of shelling models for a small axial flow maize shelling unit

3.2.1 Comparison of shelling models by feed rate (FR)

From the tests, cumulative separated grain increased with shelling unit length. Figure 5 shows the cumulative separated grain per length of the shelling unit for three different FRs (500, 1500 and 2500 kg/h) with an RS value of 10 m/s. The cumulative separated grain increased with the shelling unit length. FR 500 kg/h was the most favorable for cumulative separated grain, followed by 1500 and 2500 kg/h. This result agrees with Maertens and De Baerdemaeker [14]. Most of the corn is shelled in the feed zone. As the feed rate increases, the sorting becomes less efficient because the maize in the threshing machine is more densely packed.

Optimization of the shelling model for a small axial flow maize shelling unit was evaluated using RMSE and R^2 values. RMSE and R^2 values correspond to the capability of the shelling models for grain separation. The shelling model results for Rusanov [18], Alferov and Braginec [19], Caspers [20], Miu [21] and the empirical model are shown in Table 6. Five different shelling model predictions at three different maize feed rates are shown in Figures 6, 7, 8, 9 and 10, respectively.

Evaluation of the shelling models at feed rates of 500, 1500 and 2500 kg/h yielded a Caspers's model with RMSE = 0.0058, 0.0046 and 0.0047 with R^2 at 0.9997, 0.9998 and 0.9998, respectively (Table 6). Rusanov's model yielded RMSE = 0.0059, 0.0069 and 0.0067 with R^2 at 0.9997, 0.9996 and 0.9996, respectively. The empirical model presented RMSE = 0.0295, 0.0098 and 0.0193 with R^2 at 0.9919, 0.9994 and 0.9980. respectively. Miu's model yielded RMSE = 0.0249, 0.0239 and 0.0238 with R^2 at 0.9968, 0.9959 and 0.9961, respectively. Alferov and Braginec's model showed RMSE = 0.0296, 0.0286 and 0.0256 with R^2 at 0.9972, 0.9992 and 0.9995, respectively.

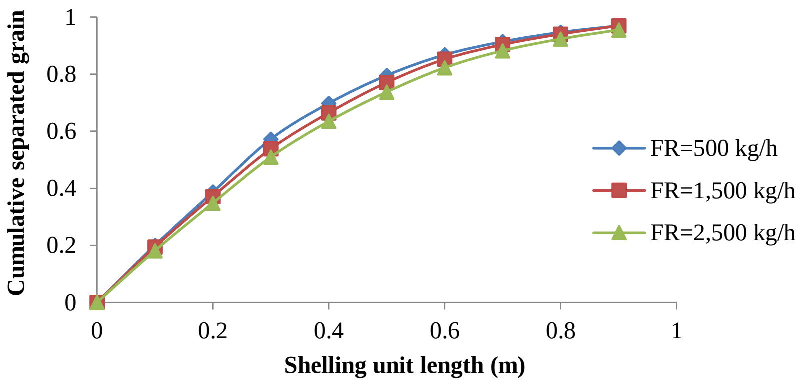

Figure 5 Relationship between shelling unit length and cumulative separated grain

Table 6 Evaluation of shelling models by feed rate

Model	Structure	RMSE	R^2
Caspers	$s=1-e^{-(k_1 l-k_2 l^2-k_3 l^3)}$	0.0046-0.0058	0.9997-0.9998
Rusanov	$s=1-e^{-\mu l^{\alpha}}$	0.0059-0.0069	0.9996-0.9997
Empirical model	$s=al^2+bl$	0.0098-0.0295	0.9919-0.9994
Miu	$s=\frac{1}{\lambda-\beta}\left(\lambda\left(1-e^{-\beta l}\right)-\beta\left(1-e^{-\lambda l}\right)\right)$	0.0238-0.0249	0.9959-0.9968
Alferov and Braginec	$s=1-e^{-k_1 l}-A\frac{1}{k_1-k_0}(e^{-k_0 l}-e^{-k_1 l})$	0.0256-0.0296	0.9972-0.9995

Caspers's model showed the lowest RMSE and the highest R^2 followed by the Rusanov, empirical, Miu and Alferov and Braginec models, respectively (Table 6), when the feed rate was considered. The results were different from Maertens and De Baerdemaeker [14]. Rusanov's model gave a minimal RMSE. These differences should be due to the shelling unit design in the current study (axial flow for maize), but the study of Maertens and De Baerdemaeker [14] used tangential flow for wheat.

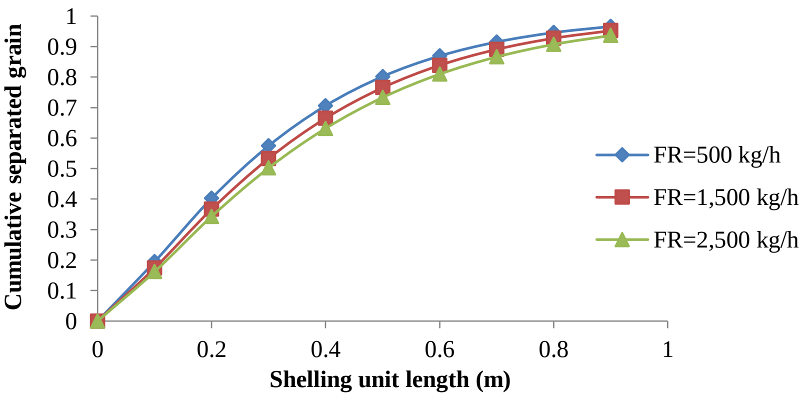

Figure 6 Prediction of Rusanov's optimal shelling model with RS 10 m/s

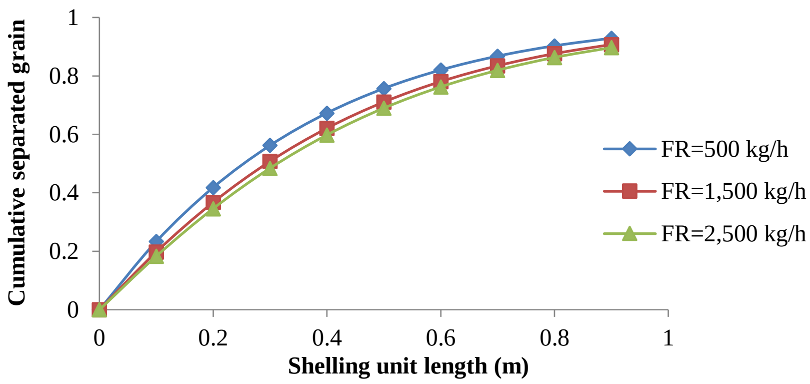

Figure 7 Prediction of Alferov and Braginec's optimal shelling model with RS 10 m/s

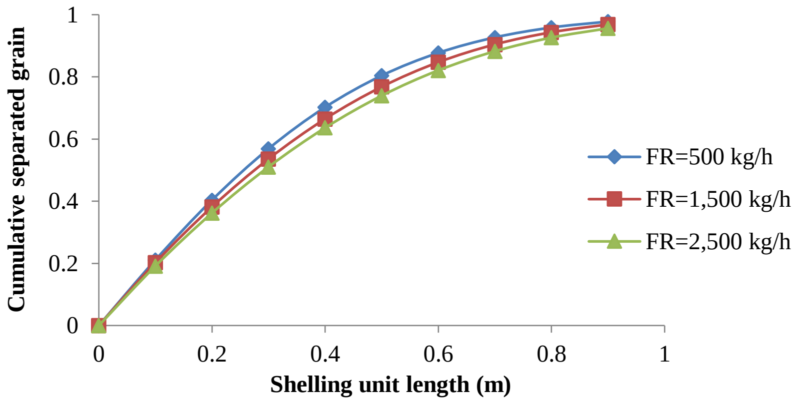

Figure 8 Prediction of Casper's optimal shelling model with RS 10 m/s

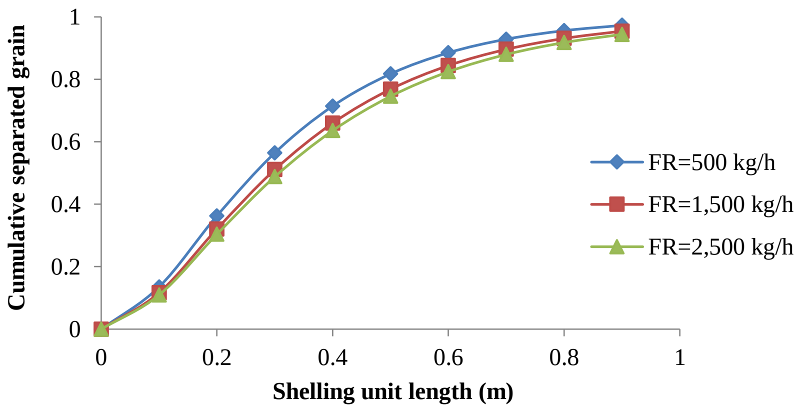

Figure 9 Prediction of Miu's optimal shelling model with RS 10 m/s

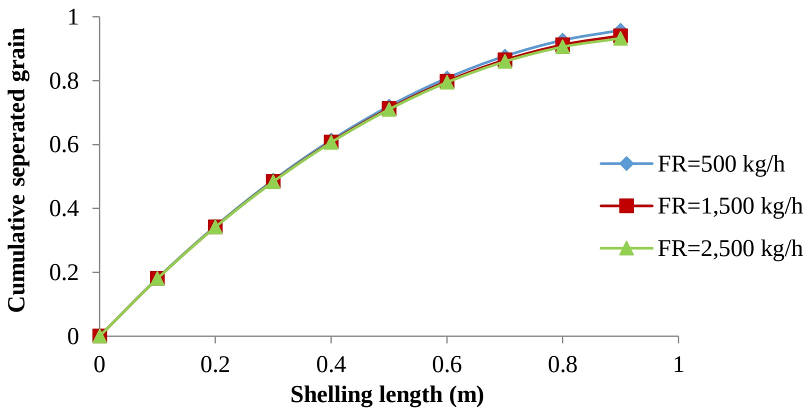

Figure 10 Prediction of the empirical optimal shelling model with RS 10 m/s

3.2.2 Comparison of shelling models by rotor peripheral speed (RS)

Testing determined cumulative grain separation against shelling unit length. Figure 11 shows the cumulative separated grain per length of shelling unit for three different RS values (8, 10 and 12 m/s) with FR at 1500 kg/h. The cumulative separated grain increased with the shelling unit length. Higher impact forces with increasing RS also increased grain separation. This agrees with Chuan-Udom [13].

Table 7 shows the optimization of shelling models for a small axial flow maize shelling unit evaluating RMSE and R^2. RMSE and R^2 values correspond with the capacity of the shelling models for grain separation. The Rusanov [18], Alferov and Braginec [19], Caspers [20], Miu [21] and the empirical model shelling models for the prediction of three different maize feed rates are shown in Figures 12, 13, 14, 15 and 16, respectively.

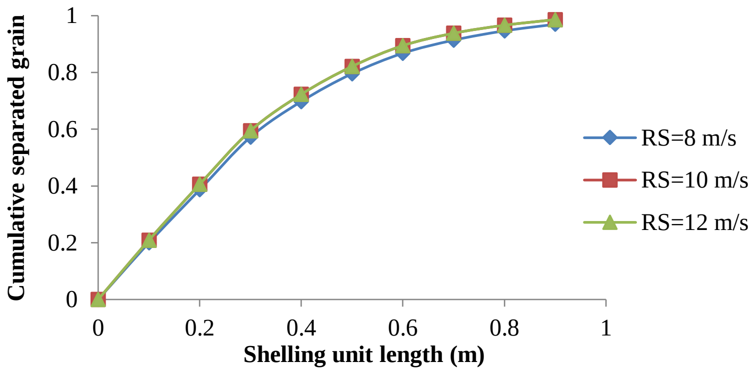

Figure 11 Relationship between shelling unit length and cumulative separated grain at FR 1500 kg/hr

Table 7 Evaluation of shelling models by rotor peripheral speed

Model	Structure	RMSE	R^2
Caspers	$s=1-e^{-(k_1 l-k_2 l^2-k_3 l^3)}$	0.0055-0.0094	0.9993-0.9997
Rusanov	$s=1-e^{-\mu l^{\alpha}}$	0.0052-0.0236	0.9990-0.9998
Alferov and Braginec	$s=1-e^{-k_1 l}-A\frac{1}{k_1-k_0}(e^{-k_0 l}-e^{-k_1 l})$	0.0218-0.0242	0.9989-0.9990
Miu	$s=\frac{1}{\lambda-\beta}(\lambda(1-e^{-\beta l})-\beta(1-e^{-\lambda l}))$	0.0235-0.0273	0.9965-0.9966
Empirical model	$s=al^2+bl$	0.0269-0.0332	0.9910-0.9935

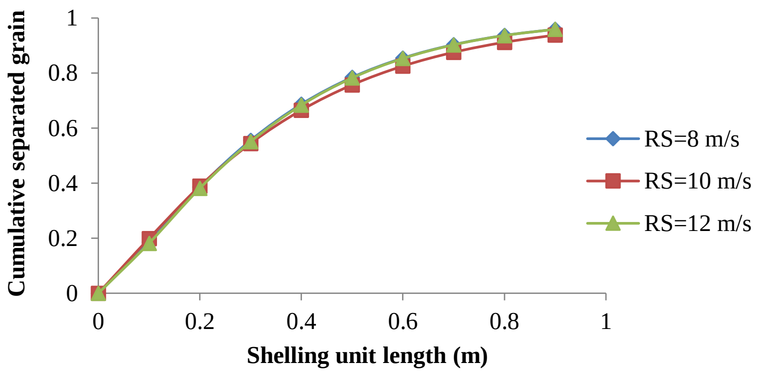

Figure 12 Prediction of optimal shelling for Rusanov's model at a 1500 kg/h FR

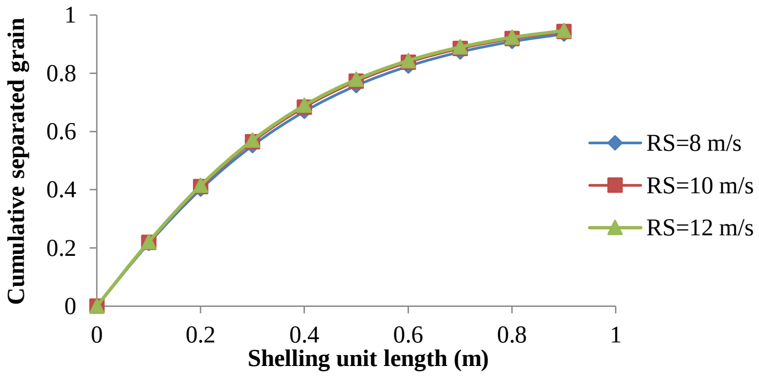

Figure 13 Prediction of optimal shelling for Alferov and Braginec's model at a1500 kg/hr FR

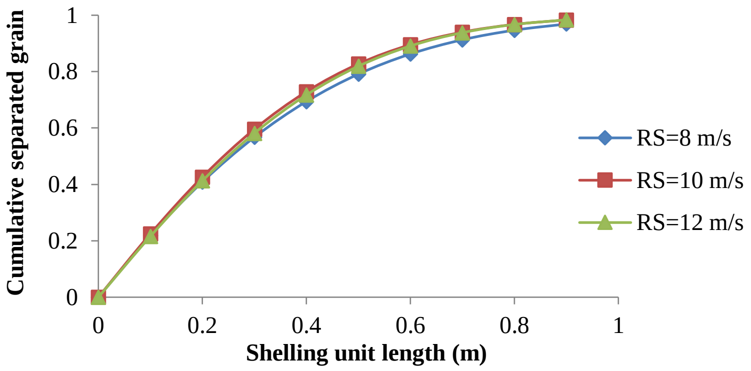

Figure 14 Prediction of optimal shelling for Caspers's model at a 1500 kg/h FR

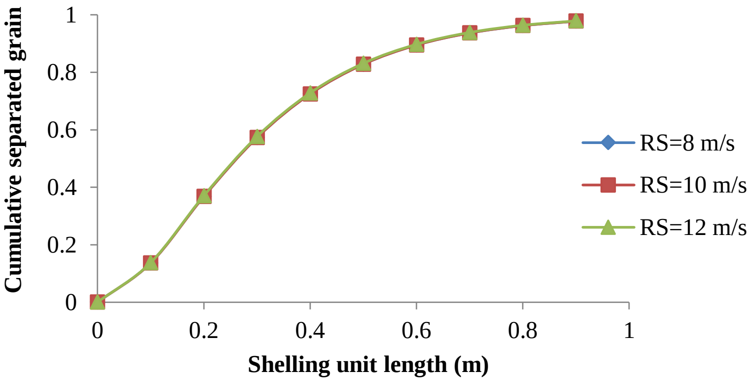

Figure 15 Prediction of optimal shelling for Miu's model at a 1500 kg/h FR

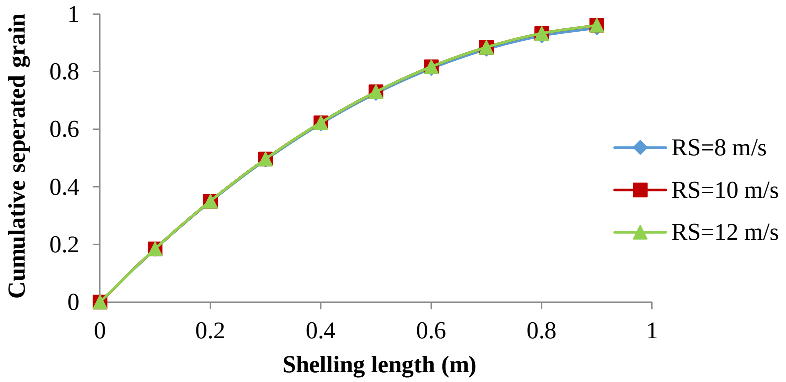

Figure 16 Prediction of optimal shelling for the empirical model at a 1500 kg/h FR

Evaluation of the shelling models by rotor peripheral speeds of 8, 10 and 12 m/s yielded a Caspers's model RMSE = 0.0094, 0.0062 and 0.0055 with R^2 = 0.9993, 0.9996 and 0.9997, respectively (Table 7). Rusanov's model showed RMSE = 0.0052, 0.0236 and 0.0121 with R^2 = 0.9998, 0.9990 and 0.9992, respectively. Alferov and Braginec's model presented RMSE = 0.0218, 0.0242 and 0.0229 with R^2 = 0.9989, 0.9990 and 0.9990, respectively. Miu's model gave RMSE = 0.0273, 0.0235 and 0.0236 with R^2 = 0.9965, 0.9965 and 0.9966, respectively. The empirical model showed RMSE = 0.02688, 0.0332 and 0.0332 with R^2 = 0.9935, 0.9910 and 0.9910, respectively. Caspers's model yielded the lowest RMSE and highest R^2 followed by Rusanov, Alferov and Braginec, Miu and the empirical model, in that order (Table 7) when the rotor peripheral speeds were considered. From FR and RS considerations, the Caspers's model should be selected for an axial flow maize shelling unit.

4. Conclusions

This research evaluated grain separation in a small axial flow maize shelling unit. The following conclusions are drawn:

1) In feeding zone, as the length of shelling unit increased, cumulative separated grain increased linearly. In separation zone, as the length of both the shelling unit and CR increased, cumulative separated grain was greater.

2) Cumulative separated husks and cobs increased rapidly with both the shelling unit length and CR.

3) Increasing the FR decreased cumulative grain separation. As the feed rate increases, sorting becomes less efficient because the maize in the thresher is more densely packed.

4) Greater RS increased cumulative grain separation as a result of higher impact forces.

5) Cumulative grain separation using feed rate and rotor peripheral speeds gave a good fit using Caspers's model, with low RMSE and high R^2 values.

5. Acknowledgements

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6. References

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