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Determination of Rotor Operating Factor (Efficiency) Required for the Design of Rotor Speed in a Centrifugal Nut Cracker

Olosunde William Adebisi^{1*}, Assian Ubong Edet¹, Antia Okon Orua¹

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ABSTRACT

The rotor of a palm nut cracker must be designed in such a way as to overcome friction, wears, the collision of nuts, etc. during nut cracking. Thus, there is a need to find the efficiency (rotor operating factor) K_f of the rotor and then used it to obtain the actual operating rotor speed in revolution per minute (rpm) for effective operation. In this study, masses of palm nuts (\bar{m}), its exit velocity from the rotor disc (v), rotor radius (r), axial dimensions, and energy generated due to friction, sound, heat, etc. (E_p), palm nut translational kinetic energy (KE_{trans}), energy released per unit nut (Q) and inverse of theoretical rotor speed (N_t^{-1}) were used based on some existing models. Plots of r against N_t^{-1} to determine the slope and thereafter evaluate K_f were carried out. The effect of \bar{m} on K_f was assessed using Analysis of Variance at 5% level probability. The results showed that the mean K_f was 0.76 and was not affected by varying \bar{m} since the calculated probability was 0.002 and r-squared was 0.324. The actual rotor speed could be found as the product of K_f and N_t .

INTRODUCTION

The palm nut cracking process is one of the major operations in palm nut processing because it liberates kernels from the nuts. The process may be tasking due to certain factors e.g., nut moisture content, nut impinging velocity, nut size/variety, cracker rotor speed, rotor to drum diameters ratio, cracker rotor, feeding rates, force, energy, power required for cracking, clearance between the rotor and the cracking wall, etc. (Okokon *et al.*, 2007; Esua *et al.*, 2015; Antia *et al.*, 2013; Antia *et al.*, 2014b; Eric *et al.*, 2009; Antia *et al.*, 2014b; Umani, 2014; Umani *et al.*, 2020; Antia *et al.*, 2017; Oke, 2007; Antia and Aluyor, 2017, Antia, 2011; Jimoh and Olukunle, 2013). Configuration of palm nut cracker plays a very vital role in the efficiency of the cracker. Well-designed components would enhance the effective operation of the cracker. One of the major components that requires effective design is the rotor. The rotor with its nuts inlet and outlet is shown in Figure 1.

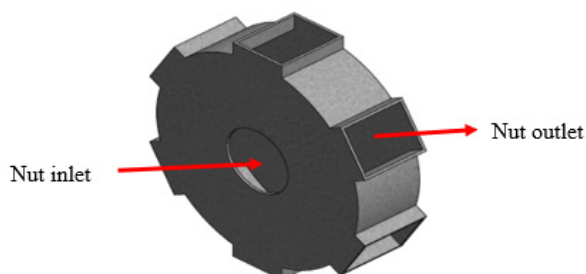


Figure 1: Rotor

The rotor is housed in the cracker chamber. It receives nuts from the hopper and impinges them at a certain velocity against the cracking wall (drum). Below the

threshold range of impinging velocity, the nuts would not crack but discharge whole uncracked nuts, and above this would result in smashed or broken kernels. During the design stage, machine components, and operating factors must be considered to guarantee, durability, safety and smooth-running operation (Antia *et al.*, 2013). Therefore, rotating rotor must be designed to overcome obstacle such as friction, wears, etc. during nut cracking operation. These challenges may likely affect its initial designed speed. Hence, there is a need to evaluate its efficiency and incorporate as correction factor known as rotor operating factor (Antia, 2019). However, several work studies have been done to enhance the development of improve palm nut processing system (Antia *et al.*, 2015; 2017; Antia and Aluyor, 2017; 2018). Therefore, the major objective of this study was to determine rotor operating factor. This factor (efficiency) would find application in predicting actual rotor speed required for effective nut impinging velocity.

Theory

Based on some studies conducted by some researchers, the following models were formulated for effective nut cracking to release whole kernels in a centrifugal nut palm cracker:

Palm nut translational kinetic energy (KE_{trans}) depends on the average mass of the nut (\bar{m}) in kg and its exit velocity from the rotor disc (v) in $m.s^{-1}$. It is given as: $KE_{trans} = \frac{1}{2}\bar{m}v^2$ (1)

The range of speed necessary to crack the nut without objectionable damage to the kernel(s) was found to be 25.71 to 31 $m.s^{-1}$ by Antia and Aluyor (2018). However, in this study, the range (24 $m.s^{-1}$ to 32 $m.s^{-1}$) was extended.

Theoretical rotor speed (N) in revolution per minute is computed as (Antia *et al.*, 2013): $N_t = [(1800(KE_{trans} - E_p))] /$

¹ Department of Agricultural and Food Engineering, Faculty of Engineering, University of Uyo, Uyo, Akwa Ibom State, Nigeria
* Corresponding author's e-mail: williamolosunde@uniuyo.edu.ng

$$(\pi^2 \dot{m} [3r^2 - 2r(d_1 + d_2 + d_3) + (d_1^2 + d_2^2 + d_3^2)])^{(1/2)} \quad (2)$$

$$Q = ((KE_{trans} - E_f) / (\dot{m})) \quad (3)$$

$$N_t = [(1800 Q) / (\pi^2 \dot{m} [3r^2 - 2r(d_1 + d_2 + d_3) + (d_1^2 + d_2^2 + d_3^2)])^{(1/2)}] \quad (4)$$

Where, r = selected rotor disc radius based on cracking drum diameter (m); d_1 = nut minor diameter (m), d_2 = nut intermediate diameter (m), d_3 = nut major diameter (m); Q = energy released per unit nut ($J.kg^{-1}$) and has constant value determined for the Dura, Tenera and Pisifera; E_f = energy generated due to friction, sound, heat, etc and a constant value already determined. Only \dot{m} and v vary based on KE_{trans} .

In an attempt to find the rotor operating factor (efficiency) and then, actual rotor revolution per minute (rpm), the following were considered:

(i) The nut velocity in relation with rotor disc radius and rotor disc revolution is generally given in Equation 5 (Khurmi and Gupta, 2012).

$$V = 2\pi r N / 60 \quad (5)$$

(ii) Introducing the actual nut velocity (V_a) in $m.s^{-1}$ and actual rotor revolution per minute (N_a), we have

$$(iii) V_a = (2\pi r N_a) / 60 \quad (6)$$

(iv) Theoretical nut velocity (V_t) in $m.s^{-1}$ and theoretical rotor revolution per minute (N_t) may be given as:

$$(v) V_t = (2\pi r N_t) / 60 \quad (7)$$

(vi) The theoretical rotor revolution per minute (N_t) is proportional to the actual rotor revolution per minute (N_a).

$$N_t \propto N_a \quad (8)$$

$$N_t = K_a N_a \quad (9)$$

Where, K_a is proportionality constant that takes care of various factors that may affect the movement of the component(s) during operation.

Equations 7 and 9 may be written as:

$$V_t = (2\pi r K_a N_a) / 60 \quad (10)$$

Therefore,

$$r = (60 V_t) / (2\pi K_a N_a) \quad (11)$$

Ideally, from Equation 9, if $K_a = 1$, $N_a = N_t$, otherwise, K_a value may deviate. Hence to evaluate K_a , Equation 11 could be expressed as:

$$r = ((60 V_t) / (2\pi K_a)) \cdot 1 / N_t \quad (12)$$

The values of K_a could be assessed from the slope of curve obtained by plotting various values of N_t against r - values based on their corresponding V_t

Thus,

$$\text{slope} = ((60 V_t) / (2\pi K_a)) \quad (13)$$

and intercept = 0.

(vii) Generally, the efficiency of the operation may be given as:

$$\text{Efficiency}(\eta) = \text{output} / (\text{input}) = N_a / (N_t) \quad (14)$$

$$N_a = \eta N_t \quad (15)$$

From Equations 9 and 14, we have

$$\text{Efficiency}(\eta) = N_a / (N_t) = 1 / K_a = \text{rotor operating factor} (K_p) \quad (16)$$

Therefore, Equation 15 may also be expressed as:

$$N_a = \eta N_t = 1 / K_a N_t = K_p N_t \quad (17)$$

METHODS

Sample Collection and Preparation

Computation of Dependent Variables using Customized M236 Machine Design Spreadsheet

The dependent / independent variables and constants were identified from Equations 1 to 17. With the aid of the Customized M236 Machine Design Spreadsheet, power by Microsoft Excel®, columns were created for parameter, symbol, variables (both dependent/ independent variables) and unit. The Equations were encrypted, in the forms of syntaxes, into the Customized M236 Machine Design Spreadsheet, and the steps followed:

First, the row representing rotor disc radius (r) to display its selected dimensions from 0.082 m to 0.104 m at an interval of 0.002 was created.

Value of energy generated due to friction, sound, heat, etc. ($E_f = -0.0282 J$) was keyed across.

Average mass of palm nut ($\dot{m} = 0.0006 kg$) as the least nut mass and theoretical nut exit velocity ($v_t = 24 m.s^{-1}$) were also inputted across.

Palm nut translational kinetic energy (KE_{trans}) and energy released per unit nut (Q in $J.kg^{-1}$) were simulated.

Nut minor diameter ($d_1 = 0.01592 m$), nut intermediate diameter ($d_2 = 0.02069 m$) and nut major diameter ($d_3 = 0.02846 m$) were entered across

Theoretical rotor speed (N_t) in revolution per minute and its reciprocal (N_t^{-1}) were automatically generated.

Step (c) was repeated with $v_t = 25, 26, 27, 28, 29, 30, 31$ and $32 m.s^{-1}$ and the corresponding values of N_t^{-1} were noted.

Finally, the whole experiment was repeated with $\dot{m} = 0.001, 0.003, 0.006, 0.009$ and $0.012 kg$.

Computation of Rotor Operating Factor

Based on Equation 12, multiple plots of r vs N_t^{-1} at constant \dot{m} but varying v_t were made starting at 0-0 origin using Microsoft Excel® application.

The slope of each plot was generated and mean K_a over the range of v was calculated based on Equation 13 as:

$$K_a = (60 V_t) / (2\pi \text{slope}) \quad (14)$$

Then, the mean values of K_a obtained at various masses were evaluated using Analysis of Variance (ANOVA) to ascertain the influence of varying nut masses (\dot{m}) on K_a .

The rotor operating factor (K_p) was found as inverse of K_a based on Equations 16 and 17.

RESULTS

Plots of rotor disc radius (r) in metres against reciprocals of its theoretical speed (N_t^{-1}) at various nut masses (\dot{m}) are shown in Figures 2 to Figures 7.

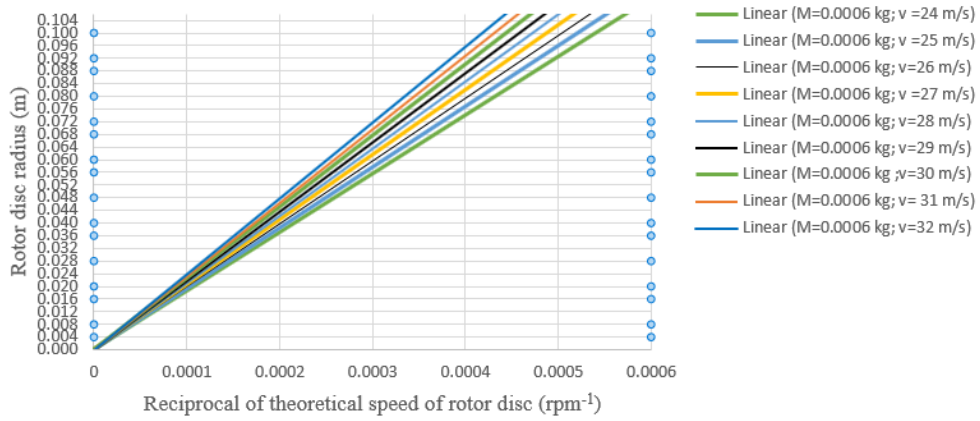


Figure 2: Rotor disc radius versus its reciprocal of theoretical speed at nut mass= 0.0006 kg.

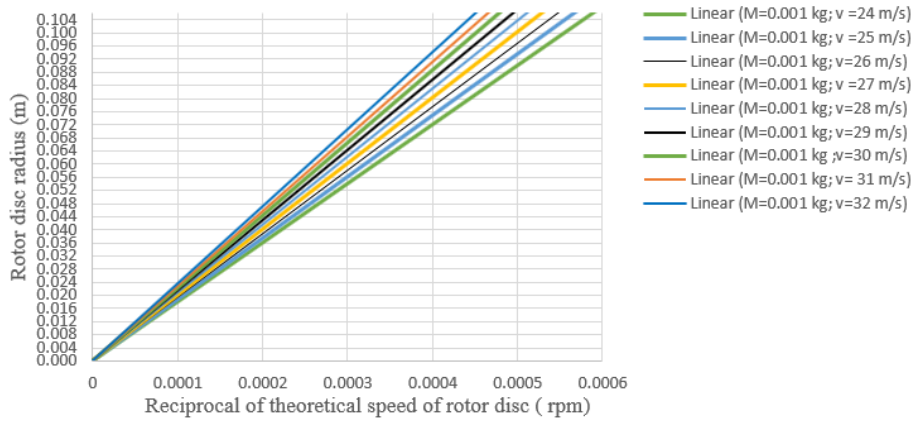


Figure 3: Rotor disc radius versus its reciprocal of theoretical speed at nut mass= 0.001 kg.

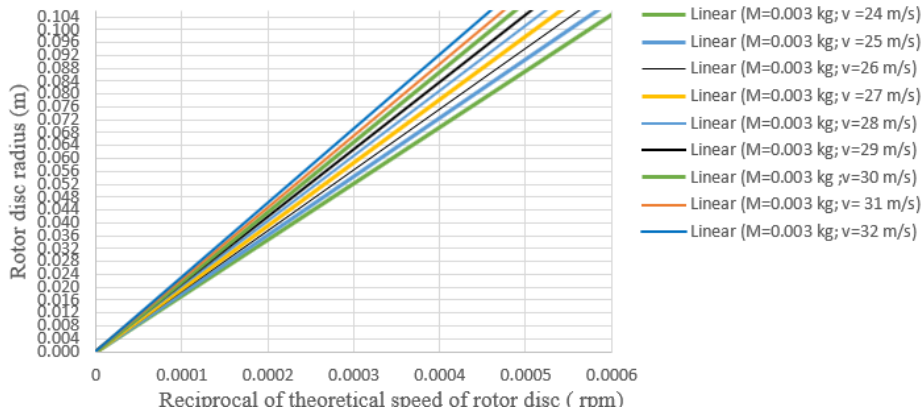


Figure 4: Rotor disc radius versus its reciprocal of theoretical speed at nut mass= 0.003 kg.

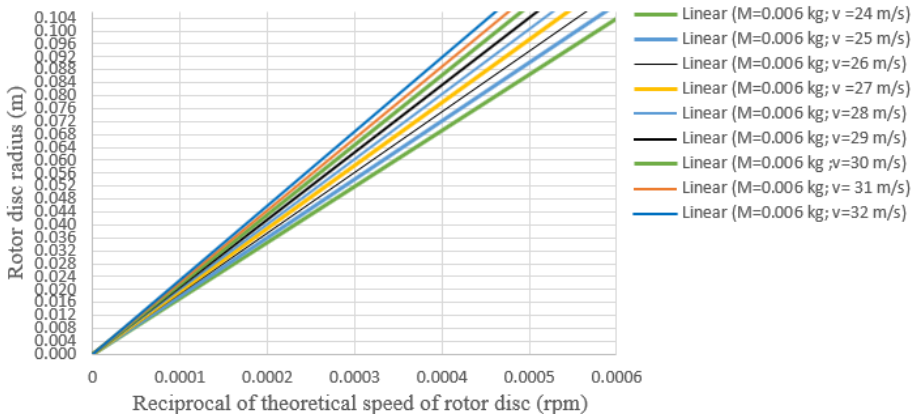


Figure 5: Rotor disc radius versus its reciprocal of theoretical speed at nut mass= 0.006 kg.

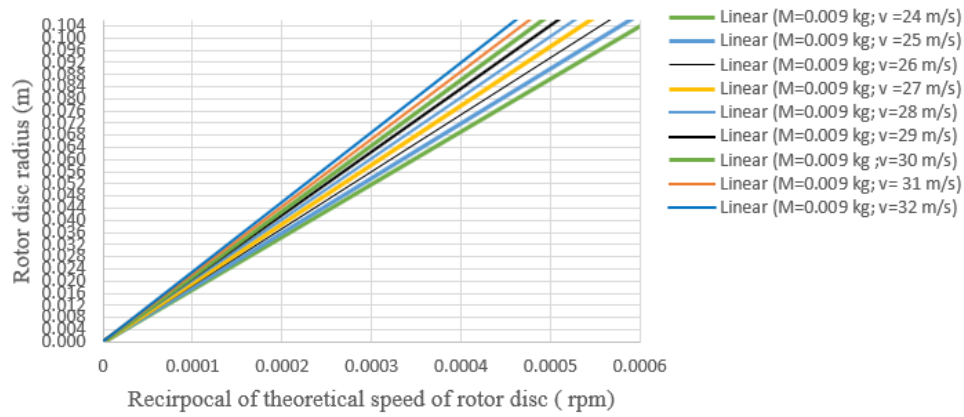


Figure 6: Rotor disc radius versus its reciprocal of theoretical speed at nut mass= 0.009 kg.

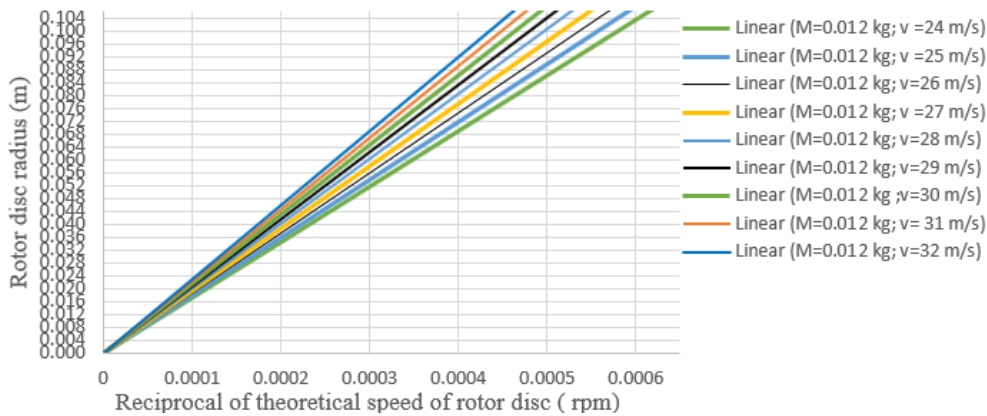


Figure 7: Rotor disc radius versus its reciprocal of theoretical speed at nut mass= 0.012 kg.

The plots in Figures 2 to Figures 7 showed positive correlated linear relationship. As rotor disc radius (r) increased at constants theoretical nut exit velocity (v_t) and nut mass (\dot{m}), the reciprocal of theoretical rotor

disc speed ($N_t^{(-1)}$) also increased. Besides, v_t increased with decrease in $N_t^{(-1)}$. Furthermore, mean of K_a at various nut masses is presented in Table 1.

Table 1: Mean K_a and K_f at various nut masses

v_t	Slope at Various Nut Masses						K_a at Various Nut Masses					
	\dot{m}_1	\dot{m}_2	\dot{m}_3	\dot{m}_4	\dot{m}_5	\dot{m}_6	\dot{m}_1	\dot{m}_2	\dot{m}_3	\dot{m}_4	\dot{m}_5	\dot{m}_6
24	185.21	179.94	174.51	173.12	172.66	172.42	1.24	1.27	1.31	1.32	1.33	1.33
25	191.86	191.86	191.86	180.22	179.78	191.86	1.24	1.24	1.24	1.32	1.33	1.24
26	198.55	193.64	188.60	187.32	186.90	186.68	1.25	1.28	1.32	1.33	1.33	1.33
27	194.43	194.43	194.43	194.43	194.02	194.43	1.33	1.33	1.33	1.33	1.33	1.33
28	201.54	201.54	201.54	201.54	201.15	201.54	1.33	1.33	1.33	1.33	1.33	1.33
29	208.66	208.66	208.66	208.66	208.27	208.66	1.33	1.33	1.33	1.33	1.33	1.33
30	225.59	221.28	216.89	215.77	215.40	215.22	1.27	1.29	1.32	1.33	1.33	1.33
31	232.41	228.23	223.97	222.89	222.53	222.35	1.27	1.30	1.32	1.33	1.33	1.33
32	239.25	235.19	231.06	230.02	229.67	229.49	1.28	1.30	1.32	1.33	1.33	1.33
Mean							1.28	1.30	1.31	1.33	1.33	1.32
Average	K_a						1.31					
Average	K_f						0.76					

Note: K_a =constant; $\dot{m}_1 = 0.0006$ kg, $\dot{m}_2 = 0.001$, $\dot{m}_3 = 0.003$, $\dot{m}_4 = 0.006$, $\dot{m}_5 = 0.009$ and $\dot{m}_6 = 0.012$

From Table 1, slope obtained as $(60 V_t)/(2\pi K_a)$ at various nut masses increased as the nut exit velocity (v_t) from the rotor also increased. The minimum value of slope, considering the nut masses, was 172.42 at 24 m.s⁽⁻¹⁾ whereas its maximum at 32 m.s⁽⁻¹⁾ was 239.25. Similarly,

within this nut mass range (0.0006 kg – 0.012 kg), the minimum, maximum mean and overall average rotor operating proportionality constant (K_a) were 1.28, 1.33 and 1.31, respectively. Nevertheless, the influence of nut masses on K_a is given in Table 2.

Table 2: ANOVA effect of nut mass on rotor operating proportionality constant (K_r)

Source of Variance	Type III Sum of Squares	df	Mean Square	F	P
Nut Mass	0.016	5	0.003	4.592	0.002
Error	0.033	48	0.001		
Total	0.049	53			

$R\text{-Squared} = 0.324$, $P = \text{probability level at } 5\%$, hence, $P_{\text{tab}} = \text{table probability} = 0.05$ and $P_c = \text{calculated probability}$

CONCLUSION

Generally, there was no statistically significant influence of nut mass on rotor operating proportionality constant since $R^2 = 0.324$, F-value = 4.592 and the calculated probability, P_c (0.002) was less at 5% level probability ($P_{\text{tab}} = 0.05$). It could be deduced that variation in nut mass does not influence K_a and K_r . Hence, the actual rotor disc revolution per minute could be obtained as the product of rotor operating factor ($K_r = 0.76$) and the theoretical rotor disc speed (N_t).

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