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Estimation of Speed Required for Palm Nut Shell Mass-Size Particle Reduction Operation to Enhance Whole Kernels Separation

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ABSTRACT: *The optimum speed required for mass-size reduction of shells to produce most sizes that are small comparable with kernel sizes; coupled with retention of kernel wholeness in cracked palm nut mixture under repeated impact was investigated. This is to enhance whole kernel separation by dry method, reduce maintenance and production cost of palm kernel oil (PK0); and lower the risk of oil rancidity associated with split kernel production and wet method of separation. A static nut cracker and centrifugal nut cracker were used in this study as Test Rigs while sieves were used to grade cracked shells and whole kernels. The data generated were evaluated. A model was developed for energy via speed required to retain kernels wholeness following repeated impact in the crackers. Technical analysis revealed that the maximum allowable speed to retain kernel wholeness is 27.93 m/s; the minimum allowable average speed to fragment cracked shells is 24.95 m/s. Further analysis showed that the optimum speed and energy required for cracked nut mixture under repeated impact to have kernel wholeness retention and production of small sizes of cracked shells relative to kernel sizes are 25.71 m/s and 0.4 J, respectively.*

KEYWORD-*Kernels,Nuts, Separation, Shells, Speed*

I. INTRODUCTION

1.1Theory

When materials are mechanically stressed, the stress would be absorbed internally by the materials as strain energy. The materials would crack when the strain energy exceeds a critical level [1], [2]. The crack propagates to terminal point and results in the reduction of the materials size. When the materials size is reduced, new surfaces are created. The energy applied to create a new surface depends mainly on the hardness of the materials. The magnitude of force and time of application affect the extent of size reduction achieved.

The major models established for predicting energy (E) required for particle size reduction operation are:

$$E = k_k \ln\left[\frac{x_1}{x_2}\right] \tag{1}$$

is Kicks model and for coarse particles sizes

$$\mathrm{E} = \mathrm{K_r}\left[\frac{1}{x_2} - \frac{1}{x_1}\right] \tag{2}$$

is Rittingers model for fine particle sizes

$$E = 2kb\left[\frac{-1}{x_2^{1/2}} - \frac{1}{x_1^{1/2}}\right] \qquad (3)$$

is Bonds model for intermediate particle size

where x_1 and x_2 are initial and final particle sizes, and k_k, k_r and k_b are constants.[3]

For materials of irregular shapes and thickness such as cracked shells of palm nuts, wall nuts, etc; it is difficult to measure their diameters. It is easier to assess or view the energy for shells particle size reduction in terms of mass than size. As the materials size is reduced, the mass of each material size is reduced. The energy model required for the production of small sizes of shells relative to kernel sizes to enhance kernel separation from cracked nut mixture was developed; based on mass-size particle reduction through application of basic energy equation used in particle size reduction operation [4]. When palm nuts are cracked, the cracked nut mixture if subjected to repeat impact to enhance reduction of shell particle sizes has limitations; as the wholeness of kernels released need be retained to promote easy separation. Less percentage of shells in kernels separated encourages (i) high yield of oil as less oil is trapped in the sludge formed from fine crushed shell particles by the oil extractor machine (ii) low maintenance and production cost due to reduction in the rate of wear and tear of the oil milling shaft, cone and basket. More so, high percentage of split kernels encourages rancidity, depending on the duration of exposure of the oily part to environmental influence [5].This study seek to estimate the speed required to retain kernel wholeness during repeated impact for mass-size reduction of palm nut shells in a centrifugal nut cracker; so as to enhance kernels separation and obtain high purity kernels.

1.2 Basic Principles

In size reduction, theoretical considerations suggest that the differential energy (dE) required to produce a small change (dx) in the size of a unit of a material (x) can be expressed as a power function of the size of the material (x).

Thus:

$$\frac{dE}{dx}\,\alpha\, x^{-n} \qquad (4)$$

$$\frac{dE}{dx} = -kx^{-n} \qquad (5)$$

Where k and n are constants.

Different researchers like Kicks, Ritingers and Bond [3] have used [1] as the basic energy equation for calculating size reduction operations. For Kicks, Ritingers and Bonds equations n=1, 2, 3/2 respectively.

1.3Mathematical modeling for palm shell mass-size particle reduction operation [4]

The energy (dE) required to produce a small change (dA) in the area of a unit of crushed shell fragments (A), could be expressed as a power function of the area A of the shell when considering (4).

Hence:

$$\frac{dE}{dA}\,\alpha\, A^{-n} \qquad (6)$$

$$dE = -k\,A^{-n}dA \qquad (7)$$

The area, thickness, mass, density and volume of the shell are denoted as A_S, t_S, M_s, ρ_S *and* V_S, respectively:

$$A_S = \frac{M_S}{\rho_S t_S} \qquad (8)$$

From (7):

$$dE_S = -K\left[\frac{M_S}{\rho_S t_S}\right]^{-n}\left[\frac{1}{\rho_S t_S}\right]dM_S \qquad (9)$$

$$dE_S = -K\left[\frac{1}{\rho_S t_S}\right]^{1-n}[M_S]^{-n}\,dM_S \qquad (10)$$

$$\int dE_S = -K\left[\frac{1}{\rho_S t_S}\right]^{1-n}\int [M_S]^{-n}dM_S \qquad (11)$$

$$E_S = -K\left[\frac{1}{\rho_S t_S}\right]^{1-n}\frac{M_S^{\;1-n}}{1-n} + C \qquad (12)$$

Where:

$$-K\left[\frac{1}{\rho_S t_S}\right]^{1-n} = B = \text{constant; C and K are also constants.}$$

$$E_S = B.\,\frac{M_S^{\;1-n}}{1-n} + C$$

$$E_S - C = \frac{BM_S^{1-n}}{1-n}$$

Lets denote $E_S^* = E_S - C$:

$$E_S^* = \frac{BM_S^{1-n}}{1-n} \qquad (13)$$

It is assumed that E_S^* is the minimum energy required for shell mass-size particle reduction operation following repeated impact load. From (13):

$$Log\ E_S^* = Log\ B + (1-n)Log\ M_S - Log\ (1-n)$$

$$Log\ E_S^* = (1-n)Log\ M_S + [Log\ B - Log\ (1-n)] \qquad (14)$$

The slope of (14) was obtained statistically [6] from the expression:

$$slope = (1-n) = \frac{\hat{N}\sum XY - \sum X \sum Y}{\hat{N}\sum X^2 - \left(\sum X\right)^2} \qquad (15)$$

$$where: X = Log\ M_S$$

$$Y = Log\ E_S^*$$

Experimental procedure to estimate the constant parameters of the derived model was obtained [4] and the values of B and n were 5.75 and ½ respectively. Equation 13 becomes:

$$E_S^* = 11.5 M_S^{\;1/2} \qquad (16)$$

II. METHODOLOGY

Bulk whole kernels and cracked shells obtained from an Oil Mill were categorized into two groups namely: (a) cracked shells and (b) whole kernels. The cracked shells were first introduced into a sieve with aperture size 16 mm. The sieved cracked shells were passed sequentially through aperture sizes as follows: 16, 12, 10, 8, 6, and 4 mm. Each lots of cracked shells retained on the sieve (i.e. those shells bigger than the next sieve size) was kept separately in 5 different groups as follows: 12 to 16 mm; 10 to 12 mm; 8 to 10 mm; 6 to 8 mm; and 4 to 6mm.20 cracked shells were picked randomly from each of the groups and used for experimental studies. The mass of each cracked shell in each group was determined and recorded. For each group, the minimum height drop level of hammer mass (0.575 kg) required to further fragment each shell on application of a maximum number of three (3) cycles of impact in (Test Rig I) static nut cracker [7] shown in Fig. 1 was determined using (17) and Equation given by [2] as:

$$KE_{trans} = \dot{M}gh = \frac{1}{2}\hat{m}v_1^{\;2} \quad (17)$$

Where, KE_{trans} =kinetic Energy, $\dot{M}$ = mass of hammer, g =acceleration due to gravity, h=hammer height drop level, $\hat{m}$ =mass of nut, v_1 =nut velocity

The experiment was replicated three (3) times and the average values taken. A total of 300 cracked shells were used.

The same procedure of grouping cracked shells was applied for bulk whole kernels. In each group of kernels, the minimum height drop level of hammer mass required to further fragment cracked shells was applied to each corresponding group of sieved shells and kernels [8]. A maximum of four cycles of impact were used. Each kernel was visually observed after each impact; and then classified into any of the following three categories.

(a) Percentage of smashed kernel (% FWS)
(b) Percentage of partially split kernel (% SKE), and
(c) Percentage of whole kernel retention (% KEW)

For each set of the experiments three replications were carried out. Based on the data obtained, analyses were carried out to determine energies required to fragment cracked shells without causing objectionable damage to the kernel wholeness.

The energy requirement for little or no objectionable damage to kernel in a centrifugal nut cracker following repeated impact was then modeled.The approach in obtaining the model equation is same as that used for modeling of some related parameters in a centrifugal nut cracker [9]. The model was given as:

$$KE_{trans} = \frac{\pi^2 N^2 \hat{m}}{1800}\left[3r^2 - 2r\left(d_1 + d_2 + d_3\right) + \left(d_1^2 + d_2^2 + d_3^2\right)\right] + \mathrm{E_f} \quad (18)$$

Where r =radius of rotor disc, d_1 =minor diameter of nut or kernel, d_2 = intermediate diameter of nut or kernel, d_3 =major diameter of nut or kernel, N =rotor rpm, $\mathrm{E_f}$ =energy generation due to sound, friction, heat, etc.

A major exception is that the value of nut impact energy obtained is replaced with kernel impact energy value. The kernel impact energy value required to retain wholeness of kernels but fragment the cracked shell under repeated impact load was obtained through experimental studies using static nut cracker (Test Rig I) and various height drop level of hammer mass [4].The model equation developed was tested using various statistical approaches [10], [11]. The model equation was then used in obtaining speed required to guarantee less breakage of whole kernel under repeated impact in a centrifugal nut cracker. The obtained speed was then validated.

III. RESULTS AND DISCUSSION

3.1 Fragmentation of Cracked Nut Cracked Shells Mixture

The graded sizes of cracked shells and their corresponding average mass and energy are presented in Table 1.

Table 1.Average Mass of Kernels and Cracked Shells per Graded Sieve per Applied Energy of Impact Load

Graded Kernels and Cracked Shells (GCS) using Sieves Aperture Sizes.(mm)	M_k Average Mass of Kernel $\times 10^{-3}(kg)$ M_K	M_s Average Mass of Cracked Shells $\times 10^{-3}(kg)$ M_S	Modeled Energy Equation $\hat{E}^*_S = 11.5 M_S^{1/2}$ $(Joules)$	$H = \frac{\hat{E}_S}{\dot{M}g} \times 10^{-3}$ (m)	% of Visual Observation		
					%KEW	%SKE	%FWS
$4 \le GCS < 6$	0.57 (0.26)	0.72 (0.13)	0.31	55	95	5	-
$6 \le GCS < 8$	0.85 (0.28)	1.07 (0.21)	0.38	67	90	5	5
$8 \le GCS < 10$	1.03 (0.32)	1.20 (0.40)	0.40	71	90	10	-
$10 \le GCS < 12$	1.38 (0.27)	2.42 (0.33)	0.57	101	85	15	-
$12 \le GCS < 16$	1.96 (0.48)	3.85 (0.54)	0.71	126	85	15	-
Average	1.16	1.85	0.47	84	89	10	1

* M_S = Mass of cracked shells, $\dot{M}$ = Hammer mass (0.575 kg)

*g = Acceleration due to gravity 9.81 m/s^2.

* H = Height drop level of hammer mass.

* $\%SF = KEW + SKE.$

(KEW=Retention of kernel wholeness. SKE=Kernel wholeness retained but with small crack on its surface. FWS=Kernel smashed. % SF=percentage of whole kernels produced).

The predetermined height drop levels of hammer mass were evaluated from the computed values of energy E_S^*. The effect was evaluated on the basis of percentage retention of kernels wholeness. It was observed that about 95 % of the kernels retained their wholeness. However, out of this percentage, 85 to 90 % retained complete wholeness (% KEW) while 5 – 15 % retained wholeness but sustained small crack (% SKE). 0 – 5 % of kernels were smashed (% FWS) only in one size range of sieve aperture size. This percentage of smashed kernel may be eliminated or reduced drastically if the energy applied is regulated appropriately for the cracked shell obtained from aperture size (6 mm ≤ GCS < 8 mm).Generally, on application of a particular quantity of energy on cracked shells and whole kernels obtained from the same sieve aperture size, it was observed that almost all cracked shells were fragmented to smaller particle sizes. The kernels from the same aperture size retained their wholeness. It is suggested that the observed pattern is because shells are brittle while the kernels have a plastic tendency. The plastic tendencies of the kernels might be due to their biological nature as kernels contain oil and other constituents. These constituents are mostly polymers. This inherent plastic tendency of kernels does not allow the kernel to reach its yield point easily as compared to the fragility of cracked shells.

The value of the constant B varies depending on the type of material subjected to particle size reduction. The value of B seems to contribute to conditions by which different energy levels are required for particle size reduction irrespective of whether the materials have same mass or even higher mass than others. From this study, based on model (16), the minimum range of energies that can effectively fragment cracked nut mixture is 0.31 to 71 Joules with 0.47 Joules as the minimum average energy as shown in TABLE 1.

3.2 Modeling Energy required in achieving little or no Objectionable Damage to Kernel in a Centrifugal Nut Cracker following repeated Impact In order to use (8), the kernel dimensions $d_1^*(\text{minor axis})$, $d_2^*(\text{intermediate axis})$ *and* $d_3^*(\textit{major axis})$ were measured for the Dura and Tenera nut varieties. The values of these dimensions are presented in TABLE 2.

Table 2. Kernel Dimensions for The Dura and The Tenera Nut Varieties

MASS RANGE (g)	NUT VARIETY	KERNEL DIMENSIONS		
		$d_1^*(\text{minor axis})$ (mm)	$d_2^*(\text{intermediate axis})$ (mm)	$d_3^*(\textit{major axis})$ (mm)
$M_K \leq 0.7$	Dura	8.0 (1.8)	9.8 (2.2)	10.9 (3.5)
	Tenera	6.7 (1.5)	7.7 (2.1)	8.6 (3.8)
$0.7 < M_K \leq 1.0$	Dura	8.5 (1.7)	10.4 (1.8)	13.2 (3.9)
	Tenera	7.2 (1.6)	8.2 (1.7)	10.5 (4.1)
$1.0 < M_K \leq 1.3$	Dura	9.2 (1.1)	12.8 (3.9)	15.9 (4.7)
	Tenera	7.8 (1.4)	10.0 (2.8)	12.7 (4.3)
$1.3 < M_K \leq 1.8$	Dura	10.7 (1.8)	13.7 (2.4)	16.1 (4.2)
	Tenera	8.8 (1.6)	10.7 (2.1)	12.9 (4.5)
$M_K > 1.8$	Dura	13.7 (2.1)	15.4 (2.7)	17.4 (5.8)
	Tenera	11.5 (1.9)	12.1 (2.8)	13.9 (4.9)
Average dimensions of kernel for Mixed Variety (Dura and Tenera Nuts)		9.30	11.08	13.21

M_K = Mass of kernel. Values in bracket are standard deviation.

Since bulk nut available to local farmers for cracking are usually of mixed varieties (Dura and Tenera), it is necessary to average each dimension for both varieties. These average values are presented in Table 2. The quantity of energy E_S^* required to fragment the shell and obtain small shell fragments with little or no objectionable damage to the kernel was shown in Table 1. To obtain model equation for kernel subjected to impact with little or no objectionable damage to the kernel, the velocity per mass range of kernel was computed based (17).

$$V_K = \left(\frac{2KE}{M_K}\right)^{1/2} \qquad (19)$$

These velocities were averaged and used as the average velocity of the kernel in the centrifugal nut cracker to achieve little or no objectionable damage to the kernel. From (17) and Table 3 a model equation was obtained.

$$KE = 390.17\,M_K - 0.67 \times 10^{-3} \qquad (20)$$

$$V_K = \sqrt{780.34 - (0.00134 / M_K)} \qquad (21)$$

Since frictional energy loss for kernel wholeness retention in the centrifugal nut cracker is 0.00134 Joules, then dividing the value with the mass of kernel gives a negligible value when compared with the value 780.34 Joules. Hence for all mass range of kernels the approximate maximum speed of kernel is 27.93 m/s to achieve little or no objectionable damage to kernel wholeness while cracked shell will fragment.

Table 3. Velocity to Achieve Little Or No Objectionable Damage to Kernel but Fragmentation of Cracked Shell

Experimental Values of Energy E^*_S.		Average Mass of Kernel $\times 10^{-3}\,kg$	Average Velocity of Kernel $V_K = \left(2KE/M_K\right)^{1/2}$ m/s
0.28		0.57 (0.26)	31.34
0.31		0.85 (0.28)	27.01
0.40		1.03 (0.32)	27.87
0.56		1.38 (0.27)	28.49
0.79		1.96 (0.48)	28.39
Mean Value	0.47	1.16	28.62

- *Values in bracket are standard deviation.*

From Table 3, the low speeds of kernel required for shell fragmentation and retention of kernel wholeness are 27.01 and 27.87 m/s. This corresponds to energy values of 0.31 Joules and 0.40 Joules respectively. Based on model (16) for shell fragmentation minimum energy, these energy values could be used to predict mass of shell as 1.21 and 0.73 g respectively for 0.4 Joules and 0.31 Joules. The speed of these masses of shells is 25.71 and 29.14 m/s for 0.4 Joules and 0.31 Joules respectively using (17). The speed of 29.14 m/s is more than the minimum speed that would likely commence split kernel. Therefore, for energy of 0.4 Joules the shell mass require speed of 25.71 m/s and could be approximated as 26 m/s. This speed is preferred for shell fragmentation as it is less than 27.93 m/s obtained from (21) for kernel splitting to commence. The kernel dimensions used in the equation were determined experimentally and presented in Table 2 as 9.30, 11.08 and 13.21mm respectively for d_1, d_2 and d_3. The minimum average speed for shell mass to commence fragmentation is obtained by equating (16) with (17) and solving for shell mass speed. The speeds obtained were averaged to be 24.95 m/s and is presented in TABLE 4.

Table 4. Determination of Shell Mass Minimum Average Speed for Shell Fragmentation

Mass of Shell, M_S (g)	$Es = 11.5M_S^{\frac{1}{2}} = \frac{1}{2}M_S V_S^2$ Where $V_S{}^2 = \frac{23}{\sqrt{M_S}} m/s$
0.63	30.27
0.72	29.28
1.22	25.66
2.53	21.38
4.89	18.14
Average speed(m/s)	24.95

The summary of the statistical parameters required as pre-requisite for the model equation goodness of fit are presented in TABLE 5.

Table 5: Statistical Parameters for Goodness of Fit for Model (20)for Kernel

Parameters for Goodness of Fit for Model Equation $KE = 390.17\,M_K - 0.67 \times 10^{-3}$ for Kernel of Mixed Varieties(Dura and Tenera)	Values
Coefficient of Correlation, $\dot{r}$	0.9911
Coefficient of Determination, R^2	0.9938
Reduced Chi – Square, $X_C{}^2$	0.00177
Mean Bias Error, MBE	0.0180
Root Mean Square Error, RMSE	0.03256

The coefficient of determination R^2 is approximately equals to coefficient of correlation ($\dot{r}$). The values of R^2 are higher and the reduced chi – square $X_C{}^2$, mean bias error (MBE) and root mean square error (RMSE) values are low. These are attributes of good quality fit. The experimental values and predicted values using test rig and model equation respectively are presented in Fig. 2.

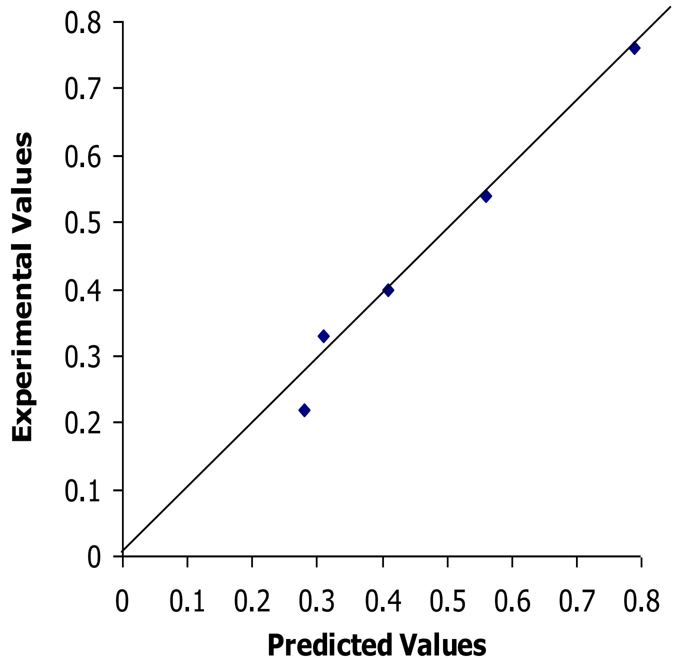

Fig.ure2: Experimental Values of KE against Predicted Values of

$$KE = 390.17\,M_K - 0.67 \times 10^{-3}$$

From Fig. 2 the experimental values and predicted values fall within a line where the slope of the graph is equal to one. This indicates that the predicted values are approximately equal to experimental values. Therefore, the model could be used with reasonable degree of accuracy.

3.3Verification of the Estimated Speed of 25.71 m/s

This speed was tested with cracked nut mixture using a centrifugal nut cracker under repeated impact. The cracked nut mixture moisture content used was 8.5% wb as it falls within the range that can enhance production of whole kernels following palm nut cracking. The cracked nut mixture analysis following cycles of impact is presented in TABLE 6.

Table 6: Analysis of Shell Fragments Product at GCS Speed of 25.71 m/s and Nut Moisture of 8.5 %Wb

% Moisture Content	% Shell out from aperture 4mm	% Shell out from aperture 10mm	% Shell out from aperture 16mm	Cycle of Impact	% FC	%FWS	%FU	% Efficiency
8.5%	29	36	35	1	75.5	0.5	24	75.6
	34	34	32	2	78.8	1.2	20	76.8
	41	30	29	3	84.8	2.2	13	79.3
	48	27	25	4	89	3.0	8.0	82.7
	64	21	15	5	90.5	3.8	5.7	91.3
	73	17	10	6	91.0	4.0	5.0	95.7
	74	17	9	7	90.7	5.0	4.3	95.7
	75	16	9	8	90.3	6.0	3.7	96.3

Table 6 shows that 90 to 91% whole kernels could be achieved with less than 5 % split kernels. This cracked nut mixture can guarantee the production of good marketable quality kernel depending on the method and technique employed for kernel separation. The number of cycles of impacts for shell fragmentation with little or no objectionable damage to kernel is affected by the cracked nut mixture speed and may be by nut the moisture content. At 6 cycles of impact the %FC was 91% while the percentage of shell fragments discharged from 4 mm sieve aperture was 73% leaving the kernels with only 27 % shell fragments for further separation using any suitable technique of separation. The production of split kernels (FWS) was 4 %.

IV. CONCLUSION

1. The energy range of 0.31 to 0.71 Joules can fragment cracked nut mixture. However, the extent of damage on the kernel wholeness depends on the energy applied on the size range of kernels and cracked shells in the cracked nut mixture.

2. A model equation obtained fits the experimental data generated. At a maximum speed of 27.93 m/s, little or no objectionable damage to kernel wholeness in the centrifugal nut cracker was observed. The minimum average speed for shell mass to commence fragmentation was found to be 24.95 m/s. At cracked nut mixture speed of 25.71 m/s and average energy of 0.4 Joules, high percentage of kernel wholeness was retained during repeated impact.

(3) The energy of 0.4 Joules and cracked nut mixture speed of 25.71 m/s were found to cause shell fragmentation that is accompanied with little or no objectionable damage to kernels.

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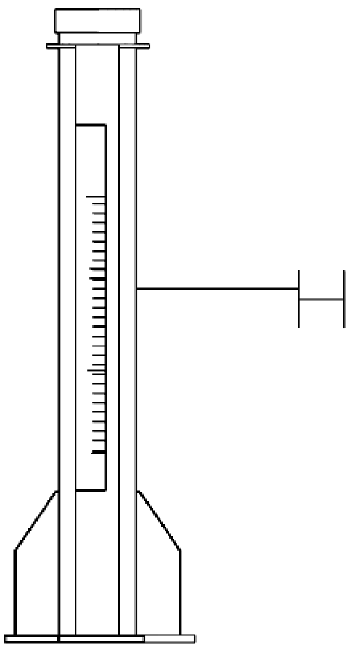

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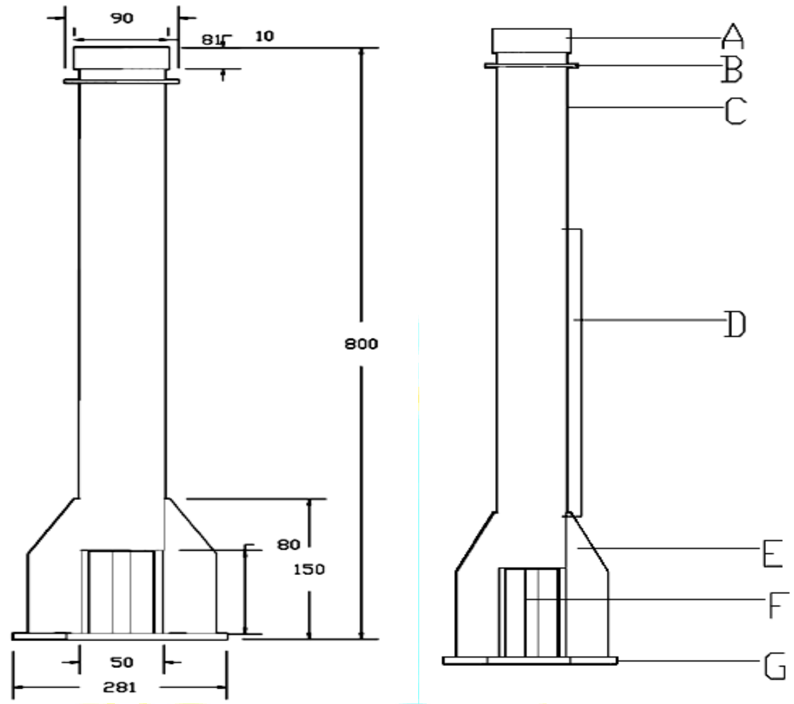

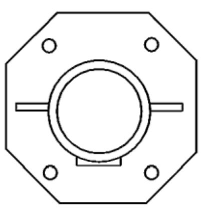

PLAN

PART	DESCRIPTION	FUNCTION
A	Hammer Inlet	Act as entrance to hammer
B	Casing Support	To enforce casing
C	Cylindrical pipe of 3 mm thick and inside diameter of 75 mm	Inside of pipe guide hammer falling to hit nut placed at the centre of base plate
I	Graduated Scale (0-600 mm)	To read off hammer height drop level
E	Base Support	To reinforce casing to base plate
F	Nut Inlet	For ease placement of nut on base plate
G	Base Plate	To withstand cracking force of hammer

Figure. 1.Detailed Views of a Static Nut Cracker