Journal of the Nigerian Association of Mathematical Physics
*Volume*23 (March, 2013), pp459 - 466

A Technical Development of an Energy Model for Palm Shell Particle Reduction

[1]Ebunilo, P.O., [2]Orua D.A. and [3]Sadjere E.G.

[1]Department of Mechanical Engineering
University of Benin, Benin City, Nigeria,
[2]Department of Agricultural and Food Engienering,
University of Uyo, Nigeri,
[3]NDDC Port Harcourt,

Abstract

The inefficient separation of cracked palm shells from their nuts has contributed the greatest bottleneck impeding the development of the palm nut cracking industry in Nigeria. The recovery of good quality kernels could be achieved easily if the cracked shells are fragmented to small particle sizes relative to kernel sizes. In this study, the basic energy equations involved in size reduction operation were analyzed based on mass of palm nut shells. This is because the shell size and shape are irregular. Hence, it is difficult to measure precisely the cracked shell dimensions. Therefore, particle size evaluation was considered to be better viewed in terms of mass. The mass of cracked palm nut shells were classified into five groups. The minimum energy required to fragment the cracked shells (SF) were obtained. Mathematical modeling using statistical method was carried out. This showed that the energy required for mass – size reduction is proportional to the square root of the mass of the palm nut. The constant in the equation depends on the density and thickness of the material used in cracking the palm nut.

Keywords: Energy, particle size reduction, palm nut shell, mass

1.0Introduction

The oil palm trees grown in Nigeria are mostly of the Dura, Tenera and Pisifera varieties. Usually, the fruits of the oil palm could be processed into different products that are of economic importance. One of the important products is the nut made up of kernel and shell. The kernel has nutritive value and could be further processed to obtain palm kernel oil and cake .The shell could be processed and used as fuel, activated carbon for water purification, coarse aggregate in road binders courses for asphalt, concrete etc. [1,2]. To obtain kernel for industrial use, the nuts must be cracked in commercial quantities mechanically.

Generally, the unit operation applied for palm nut processing has been mechanized to a reasonable degree of efficiency. An exception to this pattern of technological development relates to kernel and shell separating unit [3-11]. Basically, there are two methods of separating the mixture of kernels and cracked shells, namely: wet and dry. Each method of separation has effect on product quality and quantity [10], [12-13].

Small scale farmers use mostly the dry method involving sieving and/or manual sorting. So far, the design and development of shell and kernel separator by various research workers have yielded only limited improvement in terms of the purity of kernels, the efficiency and capacity of separation achieved. A pre-requisite for good separation of kernels from a mixture of cracked shell fragments is small particle size of the shell fragments relative to kernels following cracking [9],[12]. The efficiency of separation will depend on critical physical properties of the nuts, kernel and shell fragments. Nut cracking energy equipment or test rig have been used by various workers in an effort to discover the perfect operating condition of a nut cracker.

In the test rig, nuts are cracked using potential energy of an elevated weight falling on a stationary nut at a predetermined distance. This is regarded as a mechanism in which the potential energy ultimately converted (translated) into kinetic energy, the momentum of which is destroyed on impact. [8], [14-16]. Thus, it is possible to model the energy requirement for an efficient palm nut shell particle size reduction operation.

Corresponding author:***Ebunilo, P.O.,***E-mail:-, Tel.:+2348037136102

Theory

Palm nut when dried to a certain level of moisture, would crack and release whole kernel if it is subjected to appropriate conditions. The extent of palm shell dryness contributes to its brittleness. The degree of brittleness enhances shell particle fragmentation**.** When palm nut shells are mechanically stressed, the stress would be absorbed internally by the shells as strain energy. The shell would fracture when the strain energy exceeds a critical level – the yield point. The fracture results in reduction of the shell size. When the shell size is reduced, new surfaces are created. The energy applied to create a new surface depends mainly on the hardness of the shell – its friability. The magnitude of force and point of application affect the extent of size reduction achieved. To achieve efficient size reduction, the energy applied to the shells need to be greater than the maximum energy needed to rupture the material by a small margin as possible. As the shell size is reduced, the mass of each shell size is also reduced.

Generally, 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, $$\frac{dE}{dx}\alpha \ x^{-n} = dE = -kx^{-n} \qquad (1)$$

Where x and n are constant accordingly. Different workers like Kicks, Rittingers and Bond have used this equation as the basic energy equation for calculating size reduction [17].

$$E = Kr\left(\frac{1}{x_2} - \frac{1}{x_1}\right) \qquad (2)$$

(Rittingers equation)

$$E = K\ln\left(\frac{x_1}{x_2}\right) \qquad (3)$$

(Kicks equation)

$$E = 2Kb\left(\frac{-1}{x_2^{1/2}} - \frac{1}{x_1^{1/2}}\right) \qquad (4)$$

(Bonds equation)

Where**,** E is the energy required (KJ)
n is the power factor
x_1 is the initial particle size (mm)
x_2 is the final particle size (mm)
K is Kick's constant, n = 1
Kb is the Bonds constant, n = $3/2$
Kr isRittinger's constant, n = 2

Analytical procedure:

In this study, it is considered that it is easier to assess energy for shell size reduction in terms of shell mass than size. This is because the shape, thickness and nature of palm shells vary.

Basically, the energy (dE) required to produce a small change (dA) in the surface area of a unit of a shell surface (A) could be expressed as a power function of the surface area A of the shell when considering equation (1)

$$Hence, \frac{dE}{dA}\alpha \ A^{-n} \qquad (5)$$

$$dE = -k\ A^{-n} dA \qquad (6)$$

Let shell surface area, thickness, mass density and volume be denoted as A_S, t_S, M_s, ρ_S *and* V_S, respectively.

$$A_S = \frac{M_S}{\rho_S t_S} \qquad (7)$$

From equation (5)

$$dE_S = -K\left[\frac{M_S}{\rho_S t_S}\right]^{-n} dM_S \tag{8}$$

Since, the mass of a unit shell changes as new surface area is created for a unit shell size reduced, equation (8) can be written as:

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

$$\int dE_S = -K\left[\frac{1}{\rho_S t_S}\right]^{-n} \int [M_S]^{-n} dM_S \tag{10}$$

$$E_S = -K\left[\frac{1}{\rho_S t_S}\right]^{-n} \frac{{M_S}^{1-n}}{1-n} \tag{11}$$

Let denote $-K\left[\frac{1}{\rho_S t_S}\right]^{-n} = B = \text{constant}$ (12)

$$E_S = B.\ \frac{{M_S}^{1-n}}{1-n} \tag{13}$$

$$LogE_S = LogB + (1-n)LogM_S - Log(1-n)$$

$$LogE_S = (1-n)LogM_S + [LogB - Log(1-n)] \tag{14}$$

The slope of the graphical plot of $LogE_S$ against $LogM_S$ could be obtained statistically through the expression:

$$slope = (1-n) = \frac{N\sum xy - \sum x \sum y}{N\sum x^2 - \left(\sum x\right)^2} \tag{15}$$

$$Where,\ x = LogM_S$$

$$y = LogE_S$$

Experimental procedure

Palm nut shells obtained from nut cracking were used. The shells were classified into five (5) mass ranges as follows:

$M_S < 0.7g$, $0.7g \le M_S < 1.0g$, $1.0g \le M_S < 1.8g$, $1.8g \le M_S < 3.0g$, $M_S \ge 3.0g$.

20 shells in each of the classified mass ranges were randomly picked. These shells were used in experimental studies to determine the minimum effective height drop level of hammer mass required to fragment a high percentage of cracked shells in each classified mass range of shells. Nine (30mm, 50mm, 55mm, 60mm, 70mm, 100mm, 120mm, 140mm, and 150mm) height drop levels and 0.575kg hammer mass were used. The effectiveness of the hammer mass per height drop level was based on the cracked shells that fragmented after experiencing hammer mass impact. The experiment was replicated three (3) times and average values taken where applicable.

For each mass range, the percentage of shells (%SF) that cracked when subjected to impact load was plotted against various height drop levels. The best minimum height drop level (H) of impact load per classified shell mass range that produced the highest %SF was determined based on the peak of each graph plot.

The %SF is given as

$$\%SF = \frac{\text{(number of cracked shells that fragmented when subjected to impact load)}}{\text{Total number of shells used (20)}} \tag{16}$$

The average mass of each classified mass range of shells used in this study were computed as

$$\text{average mass of shells } (M_{s(ave)}) = \frac{\text{(total mass of each of the 20 shells used)}}{20} \tag{17}$$

The energy required to fragment cracked shells (E_s) in each of the classified mass range of shell were computed based on (a) the best minimum height drop level of impact load.

Statistical calculations based on equations (14) and (15) were analyzed to determine the constant (n). Model equation was proposed and validated using various statistical approaches such as reduced chi-square $X_c^{\ 2}$, mean bias error (MBE) and root mean square error (RMSE). Generally for good quality fit, the coefficient of determination R^2 should be higher than $X_c^{\ 2}$, MBE and RMSE should be lower than X_c^2 [18, 19].

Results and Discussion

The minimum energy required to fragment the cracked shell (SF) were obtained from Figures 1 to 5.

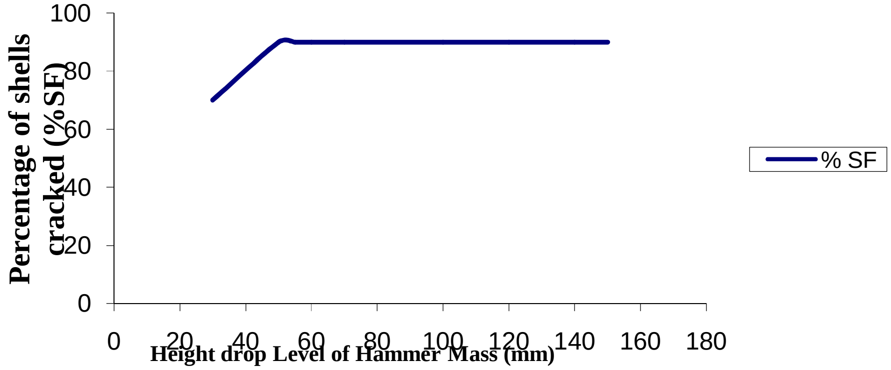

Figure 1: %SF against Height drop level of hammer mass for Cracked Shell mass range $M_S < 0.7g$

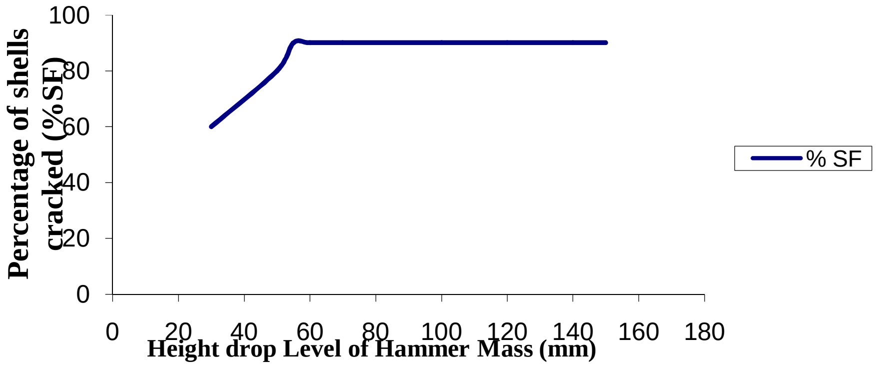

Figure 2: % SF against Height drop level of hammer mass for cracked shell mass range $0.7g \le M_S < 1.0g$

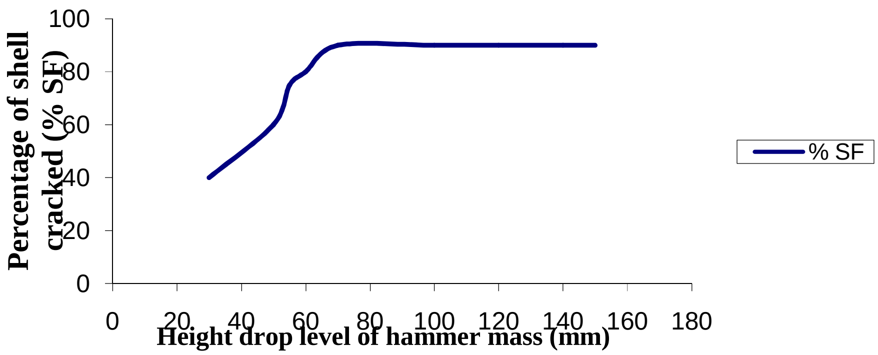

Figure 3: % SF against Height drop level of hammer mass for cracked shell mass range $1.0g \le M_S < 1.8g$

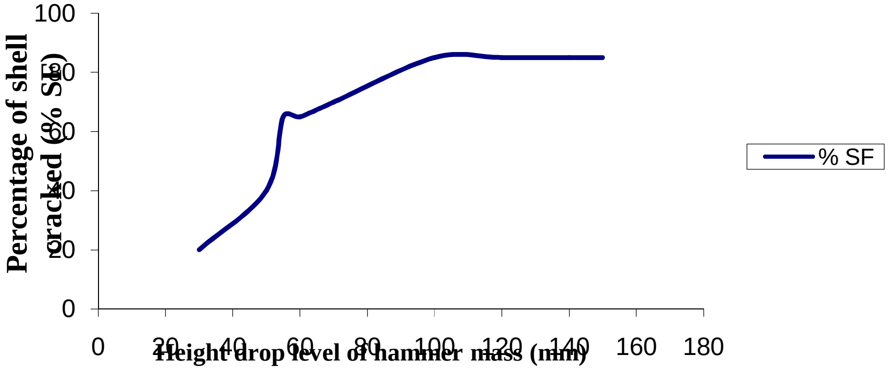

Figure 4: %SF against Height drop level of hammer mass for cracked shell mass range $1.8g < M_S \leq 3.0g$

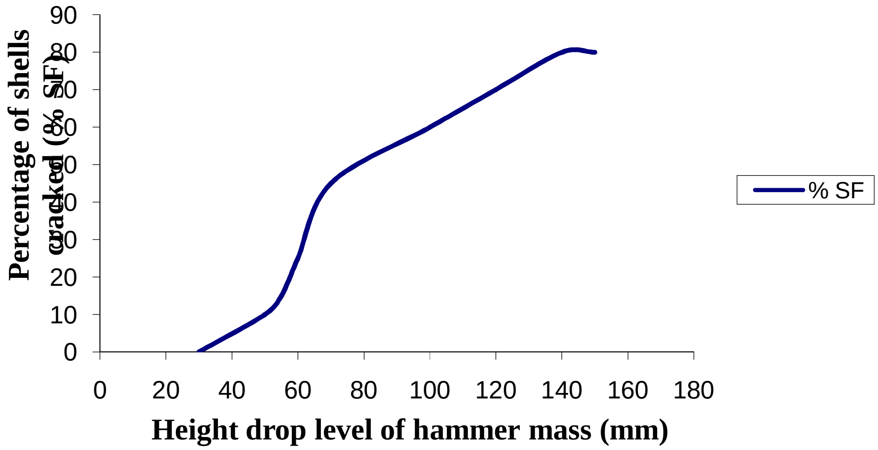

Figure 5: %SF against Height drop level of hammer mass for cracked shell mass range $M_S > 3.0g$

Table 1 shows values of cracked shell mass range, average mass of cracked shells per cracked shell mass range and minimum height drop level of hammer that would commence fragmentation of cracked shells into smaller size particle sizes.

Table 1: Percentage of Cracked Shells That Fragment Per Minimum Best Height Drop Level Of Hammer Mass Per Mass Range Of Cracked Shell

Minimum best height drop level of hammer (mm)	50	55	70	100	140
Percentage of cracked shells that fragment (%SF)	90	90	90	85	80
Average mass of cracked shells per classified mass range (g)	0.63 (0.05)	0.72 (0.10)	1.22 (0.21)	2.53 (0.46)	4.89 (1.20)
Mass range (M_s) of cracked shells (g)	$M_S \leq 0.7$	$0.7 < M_S \leq 1.0$	$1.0 < M_S \leq 1.8$	$1.8 < M_S \leq 3.0$	$M_S > 3.0$

* Values in bracket are standard deviations

The corresponding energies were calculated. Statistical analysis based on equations (14), (15) and (16) was carried out. The values are presented in Table 2.

Table 2: Statistical data for modeling energy requirement for cracked shell fragmentation

Shell mass range (g)	Height drop level (H)	Experimental values of energy (E_S) joules	Mass of cracked shells, $M_S \times 10^{-3} kg$	$Log\ E_S = Y$	$Log\ M_S =$ X	X^2	XY	Y^2	Predicted Values $E_S = M_S^{½}$	Predicted Value of Energy E_S (Joules) $\hat{Y} = \log E_S$	$(Y - \bar{Y})^2$	$(Y - \hat{Y})$	$(\hat{Y} - \bar{Y})^2$	$(Y - \hat{Y})^2$
$M_S \le 0.7$	50	0.28	0.63	-0.55	-3.20	10.24	1.76	0.30	0.29	-0.54	0.0361	–0.01	0.0324	0.0
$0.7 < M_S < 1.0$	55	0.31	0.72	-0.51	-3.14	9.86	1.60	0.26	0.31	-0.51	0.0225	0	0.00225	0.0
$1.0 \le M_S < 1.8$	70	0.40	1.22	-0.40	-2.91	8.47	1.16	0.16	0.40	-0.40	0.0016	0	0.0016	0
$1.8 \le M_S < 3.0$	100	0.56	2.53	-0.25	-2.60	6.76	0.65	0.06	0.58	-0.24	0.0121	–0.01	0.0144	0.0001
$M_S \ge 3.0$	140	0.79	4.89	-0.10	-2.31	5.34	0.23	0.61	0.80	-0.10	0.0676	0	0.00676	0
				$\sum y = -1.81$ $\bar{Y} = -0.36$	$\sum X = -14.16$ $\bar{X} = -2.83$	$\sum x^2 = 40.67$	$\sum XY = 5.40$	$\sum Y^2 = 0.79$			$\sum (Y - \hat{Y})^2 = 0.1399$	$\sum (Y - \hat{Y}) = -0.02$	$\sum (\hat{Y} - \bar{Y})^2 = 0.1385$	$\sum (Y - \hat{Y})^2 = 0.0002$

A model was proposed based on equation (9) as:

$$dE_S = -K\left[\frac{1}{\rho_S t_S}\right]^{-n}\left[M_S\right]^{-n} dM_S \qquad (18)$$

$$where\ n = \tfrac{1}{2}$$

$$-K\left[\frac{1}{\rho_S t_S}\right]^{-1/2} = B = \text{Constant}$$

This equation was further analyzed and could be written as shown in equation (13)

$$E_S = 2BM_S^{1/2}.$$

This equation implies that the energy E_S required for mass- size reduction of any particle is proportional to the square root of the mass of the particle. The constant B depends mainly on the density and thickness of the material for which particle size is to be reduced. For palm nut shell, the value of B is 11.5. Hence,

$$E_S = 11.5M_S^{1/2} \qquad (19)$$

The validity of this model was tested using statistical approaches such as coefficient of determination R^2 and correlation $\dot{r}$, reduced chi-square x_C^2, mean bias error MBE; and mean square error RMSE. The corresponding values of these parameters are 0.99, 0.99, 6.67×10^{-5}, 4.0×10^{-3} and 8.94×10^{-3} respectively. Since R^2 is higher and x_C^2, MBE and RMSE are lower, the data has a good quality fit. The predicted values of E_S and experimental values are presented in Table 2 and represented in Figure 6.

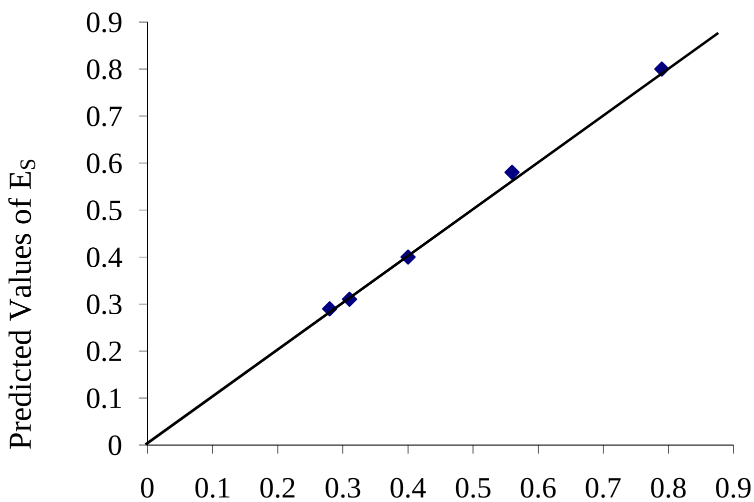

Figure 6: Predicted Values of E_S against Experimental Values of E_S

It is observed that the experimental values and predicted values fall within a line where the slope of the graph is equal to one. This implies that the predicted values are approximately equal to experimental values. Hence the model could be used with reasonable degree of accuracy.

Conclusion

The energy E_S required for mass-size reduction of any particle is proportional to the square root of the mass of the particle

$$E_S = 2BM^{1/2}$$

The value of constant 2B for cracked palm nut shell is 11.5.Generally the value of 2B depends mainly on the density and thickness of the material for which particle size is to be reduced.

References

[1] Nuhu-koko, M. K. (1990): "The Use of Palm Kernel Shell as aggregate for Concrete." *Paper presented at 21st Annual Confernce of Material Testing, Control and Research.* Federal Ministry of Works (FMW), Lagos, Nigeria, Pp. 20.

[2] UNIFEM (1987): *Oil Extraction.* Food Cycle Technology Source Book (1). pp. 34, AIDOS, New York, USA.

[3] Adebayo, A. A. (2004): "Development and performance evaluation of a motorized palm-nut cracking machine". *Proceedings of the annual conference of the Nigerian Institution of Agricultural Engineers*. 26:326 – 330.

[4] Badmus, G.A. (1990): "Design of vertical shaft centrifugal palm nut cracker". *Seminar paper presented to Nigerian society of Agriculture, University of Agriculture, Markudi, Nigeria*. Pp.24-28.

[5] Koya, A. O. and Faborode, M. O. (2006): "Separation Theory for Palm Kernel and Shell Mixture on a Spining disc." *Biosystem Engineering.* Vol.95. 405-412.

[6] Koya, O. A. (2006): "Palm Nut Cracking under repeated impact load". *Journal of Applied Sciences.* 6 (11). 2471 – 2475.

[7] Koya, O. A., Idowu, A. and Faborode, M. O. (2004): "Some Properties of Palm Kernel and Shell Relevant in Nut Cracking and Product Separation". *J. Agric. Eng. Technol, 12: 27-39.*

[8] Oke, P. K. (2007): "Development and Performance Evaluation of Indigenous palm kernel dual processing machine". *Journal of Engineering and applied sciences* 2(4): 701-705.

[9] Rohaya, M. H., Nasrin, A. B., Choo, Y. M., MA, A. N. and Ravi, N. (2006): "A Commercial Scale Implementation of ROLEK™Palm Nut Cracker: techno-Economic Viability Study for Production of Shell-free Kernel". *Journal of Oil Palm Research.* (Special Issue): 153-167.

[10] Rohaya, M. H., Nasrin, A. B., Wahid, M.B., MAY, C.Y., RAMLI, R., NGAN, M. A. and MENON, R. (2009): "Maximizing the recovery of dry kernel and shell via a four-stage winnowing Column" *palmoilis.mpob.gov.my/publications/TOT/TT-427pdf.*Pp 468-471.

[11] Koya, A. O. and Faborode, M. O. (2005): "Mathematical Modelling of Palm Nut Cracking based on Hertz's Theory". *Biosys. Eng.* 91: 471-478.

[12] Akubuo, C. O. and Eje, B. E. (2002): "Palm Kernel and Shell Separator". *Biosystems Engineering*. 81 (2) 193 – 1991.

[13] Sangwichien, C., Ruangmee, A. and Sumanatrakul, P. (2010): Separation efficiency of oil palm shell and kernel mixture by using different types of media. Proceeding of 2010 International Conference on Chemical Engineering and Applications. Singapore, 26 – 28 February 2010.

[14] Babatunde, O. O. and Okoli, J. U. (1988): "Investigation into the effect of nuts sizes on the speed needed for cracking palm nuts in centrifugal nut crackers". *Nig. J. Palm and Oil Seeds.* Vol. 9, 94-108.

[15] Dienagha, A. R. S. and Ibanichuka, O. K. (1991): "Energy Requirement for Palm Nut Cracking". *J. The Nigerian Engineer.* Vol. 26 No.3. 39-46.

[16] Asoegwu, S. N. (1995): "Some Physical Properties and Cracking Energy of Conophor Nuts at different moisture content" .*Int. Agrophysics*, 9. 131-142.

[17] Okoro,C.C.(2001):Unit operations in Food Processing(an integrated Approach).First Edition.Vol.1.New Wave Publishers, London.

[18] Arumuganathan, T., Manikantan, M. R., Rai, R. D., Ananda Kumar, S. and Khare, V. (2009): "Mathematical Modeling of Drying Kinetics of Milky Mush room in a Fluidized Bed Dryer". *Int. Agrophysics*, 23 pp. 1-7.

[19] Torgrul, J.T. and Pehivan, D. (2002): Mathematical modeling of solar drying of apricots in thin layer. J. Food Eng. 55, 209-216 *rspublication.com/ijected/nov12/56pdf*