Analysis of the Impact Forces on Melon Seeds During Shelling.

F. B. Okokon[1*], E. Ekpenyong[1], C. Nwaukwa[1], N. Akpan[1] and F. I. Abam[2]
[1]Agricultural and Food Engineering Department
University of Uyo, P.M.B. 1017, Uyo, Nigeria
[2]Mechanical Engineering Department
Cross River University of Technology, Calabar, Nigeria
Corresponding author's e-mail: fbokokon@yahoo.com

ABSTRACT

Melon seeds are shelled in a rotating impeller – type machine to obtain the cotyledons. The seeds exit the impeller and impact a cylindrical ring shelling the seeds. Because of the force of impact, some of the seeds are broken, which deteriorate in storage and make low market value. An analytical method was used to determine the factors affecting the impact force on the ring. Experimental compression tests were carried out to determine the static forces to break melon seeds. Some seeds were also shelled with an experimental shelling machine and the number of broken seeds was counted.

The analysis showed that the factors affecting the impact force were impeller speed, seed cross- section area at impact and mass ratio. The mean forces to break melon seeds were 13.14×10^{-3}, 19.62×10^{-3} and 19.55×10^{-3} N for orientations breadth wise, lengthwise with tip up and lengthwise with tip down, respectively.

Key words: Impact force, melon seed, shelling, analysis

1. INTRODUCTION

Melon seeds (Citrulus vulgaris) are small, flat and partly oval in shape containing cotyledons. The seed is covered with a thin shell having a thick ring around the edges with a tip (Fig. 1). The cotyledons contain 60% protein and 50% edible oil. The seeds are shelled to obtain the cotyledons by mechanical method where the seeds move between vanes on a rotating impeller and impacting on a fixed cylindrical ring. Makanjuola (1972) studied the bending properties of melon seeds when compressed between two parallel plates under static loading. During loading, the seeds deflected and the shell broke due to bending. On further application of loading, the cotyledon broke. The Depending on the breadth wise and lengthwise orientation under the load, seeds broke longitudinally and transversely, respectively.

During tests on the shelling of melon seeds, Odigboh (1979) found that the percentages of broken seeds were 14.24 – 24.93% for unwetted seeds and 8.64 – 17.05% for wetted seeds. The percent breakages were considered too high since any mechanical damage to shelled melon seeds, predisposes them to deterioration especially rancidification, and are highly susceptible to mould deterioration in storage. The broken seeds also lead to low market value. Egbuta and Uyah (2003) in a 2^3 factorial experiment found that with a high speed and small diameter impeller, the number of shelled but broken seeds was five times greater than with a low speed and large impeller diameter.

Akpan (2004) found that the average forces required to crack melon seed shell of 8.3% wet basis moisture content (mc.w.b) between two parallel plates was 9.9 $\times 10^{-3}$N, 11.6$\times 10^{-3}$ N and 11.3$\times 10^{-3}$ N according to the orientation of breadth wise, lengthwise with tip up and lengthwise with tip down, respectively. The corresponding forces were 9.4$\times 10^{-3}$N, 17.2 $\times 10^{-3}$N and 13.7 $\times 10^{-3}$N at 17.8% mc w.b. and 8.31$\times 0^{-3}$ N, 15.9$\times 10^{-3}$ N and 13.7$\times$ 10^{-3} N at 20.4% (mc w.b), respectively. There was no significant effect of moisture content at 95% confidence level while significant differences were observed in the forces at different orientations. Obot (2005) found that the forces to break whole melon seeds 8.2% mc (w.b) between parallel plates was 12.54$\times 10^{-3}$ N, 18.92$\times 10^{-3}$ N, and 19.58$\times 10^{-3}$ N at breadth wise, lengthwise with tip up and lengthwise with tip down orientations, respectively.

This paper presents an analytical study to determine the factors affecting impact forces between melon seeds and the cylindrical ring of impeller type shelling machine. Experimental data were obtained to verify the result of the analysis.

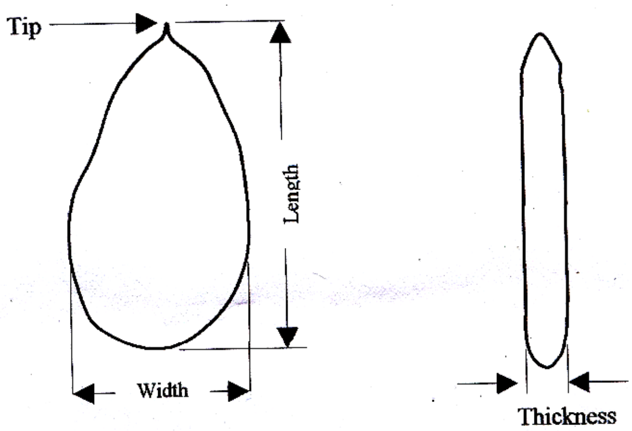

Figure 1. The principal dimensions of melon seed

1. THEORY

2.1 Propagation of Waves in Solid Media

A bar of length ℓ is considered with a fixed end struck by a rigid mass M at the other end. The velocity of the body at the instant of impact is V_0. A uniformly distributed compressive stress is suddenly applied to the free end of the bar. It will produce, in the first instant a uniform compression of an infinitely thin layer at the end of the bar. This compression will be transmitted to the adjacent layer and so on. A wave of compression begins to travel along the bar with a wave-front velocity c (Timoshenko and Goodier, 1970).The instantaneous compressive stress (σ_0) at the free end of the bar is (Juvinall, 1967):

$$\sigma_0 = V_0\sqrt{E\rho} \tag{1}$$

where E is the Young's Modulus of Elasticity of the bar (N/m^2) and ρ the density (kg/m^3) of the bar. Owing to the resistance of the bar, the compressive stress diminishes as it travels along the length of the bar. Denoting by σ the variable compressive stress of the free end of the bar, υ the variable velocity of the body and A the cross-section area of the bar, the equation of motion is in the form:

$$\frac{Mdv}{dt} + A\sigma = 0 \qquad (2)$$

It is found that the variable velocity of the particles is proportional to the variable compressive stress (Timoshenko and Goodier, 1970), hence,

$$V = \frac{\sigma}{\sqrt{E\rho}} \qquad (3)$$

Substituting for V in equation (2)

$$\frac{M}{\sqrt{E\rho}}\frac{d\sigma}{dt} + A\sigma = 0 \qquad (4)$$

The solution for which is

$$\sigma = \sigma_0 \exp\left(-At\sqrt{E\rho}/M\right) \qquad (5)$$

This equation is valid for $0 < t < \frac{2\ell}{c}$, as the compression stress wave reaches the fixed end of the bar where there is no motion, it is reflected as a second wave entirely unchanged. Hence the time for the wave to travel back to the free end of the bar is $t = 2\ell/c$.

At yield point of the bar (Juvinall, 1967):

$$F = \sigma A \qquad (6)$$

where F is the equivalent static force to break the bar.

Substituting equations. (1) and (6) into (5) : ,

$$F = V_0\sqrt{E\rho}\ A \exp\left(-At\sqrt{E\rho}/M\right) \qquad (7)$$

Assuming that the time t for the wave to travel the length of the bar is

$$t = \frac{\ell}{c} \qquad (8)$$

where ℓ is the length of the bar in metres, c is the wave-front velocity in the bar $\left(\sqrt{E/\rho}\right)$

But $\ell \rho A$ = mass of the bar, m kg

$$\therefore F = V_0 \sqrt{E\rho}\ A \exp\left(-\frac{m}{M}\right) \qquad (9)$$

Hence the equivalent static force (F) to break the bar is found to be proportional to the product of the initial velocity of the body at impact (V_0) and the cross-section area of the bar (A), since E, ρ, m are properties of the bar and are deemed constant. M is the mass of the body and is constant.

2.2 Dynamics of the Mechanical Shelling of Melon Seeds

Melon seeds were fed into a rotating impeller with vanes and were confined to move between the vanes predictably flat-down. It is difficult to predict the path of the seeds within the vanes and the orientation of the seeds during impact. A schematic diagram of the motion of a seed in a rotating impeller with vanes is shown in figure. 2. (see Appendix). The seeds emerge from the impeller with a velocity impacting a fixed cylindrical ring, breaking the melon seed shell to release the cotyledon.
The exit velocity of the seed from the impeller (see Appendix for details) $\therefore$

$$V = \omega\sqrt{r^2 - b^2} \quad m/s \qquad (10)$$

2.3 Momentum and Impact of Melon Seed

The total momentum is unchanged (Bull, 1966) and destroyed during impact. The total momentum of the system before impact can be expressed by the mass of the seed (m) and the exit velocity (V).
Let V* represent the equivalent velocity of the ring that would give a momentum equal to the momentum of the system in which the seed is fixed and the cylinder is in motion. Therefore

$$MV^* = mV \qquad (11)$$

where M is the mass of the ring impacting the seed.

$$\therefore V^* = Vm- / -M \qquad (12)$$

hence the velocity of the ring is proportional to the mass ratio (m/M)

2.4 Model Equation

Combination of equations (9), (10) and (12) gives

From equation (9) where V* is substituted for V_0 gives

$$\therefore F = \sqrt{E\rho}\; V * A\exp\left(-\frac{m}{M}\right) \tag{13}$$

Substituting equations. (10) and (12) and b = 0

$$F = \sqrt{E\rho}\;\frac{m}{M}\;\omega\; rA\,\exp\left(-\frac{m}{M}\right) \tag{14}$$

Since the mass ratio m/M is very small, exp (-m/M) ≈ 1

$$\therefore F = \sqrt{E\rho}\;\frac{m}{M}\;\omega rA \tag{15}$$

The equivalent static force to break whole melon seeds in an impeller-type shelling machine is proportional to the product of the impeller rotational speed (ω), impeller radius (r), seed cross-section area (A) at impact and the mass ratio m- / -M. The Young's modulus of elasticity (E) and density (ρ) of the seed are constant and show similar characteristics as other agricultural materials (Lewis, 1987).

3. MATERIALS AND METHODS

Melon seeds were sorted to obtain clean seeds. The moisture content of the sample was determined using the oven drying method as recommended by ASAE, 1982. Fifty seeds were randomly selected and weighted to obtain the average mass of each seed.

3.1 Procedure

3.1.1 Compression Test:

Forty seeds were randomly selected and the length, width and thickness of each seed were measured. Each seed was compressed between two parallel plates in a rig until the seed broke after bending. The force exerted when the seed broke was measured with a sensitive spring gauge (Type, Manufacturer).The seeds were placed breadth wise, lengthwise with tip up and lengthwise with the tip down between the plates.

3.1.2 Experimental Shelling Tests

Two hundred seeds were randomly chosen and fed into an experimental shelling machine to determine the effects of four combinations of the radius and the speed of impeller on the number of broken seeds. The machine consisted of a rotating impeller with vanes centrally positioned on a drive shaft within a cylindrical ring of Ø314 mm internal diameter, 4 mm thickness, 127 mm height and 2.44 kg weight formed from mild steel plate. The shaft is driven by a V belt from a 0.55 kW motor. The parameters were adjusted to 115 mm radius and 1425 min^{-1} speed; 135 mm radius and 1425 min^{-1} speed, 115 mm radius and 2850 min^{-1} speed; and 135 mm radius and 2850 min^{-1} speed. The number of broken seeds was counted and output was classified into groups of shelled but broken and unshelled and broken seeds. The tests were run in three repetitions.

4. RESULTS AND DISCUSSION

The moisture content of the melon seeds during the experiment was 8.7% (w.b.) and the average mass of the seeds was 0.11g with (standard deviation of 0.012g).

4.1 Factors Affecting the Force of Impact

Equation 20 shows the relationship between the static breaking force F, modulus of elasticity of the melon seed E, density of melon seed ρ, mass of the melon seed m, mass of the cylindrical ring M, impeller rotational speed ω, impeller radius r and the seed cross-section area A.

4.2 Equivalent Static Breaking Force

Values of the equivalent static force, the seed cross-sectional areas at three orientations are shown in table 1.

Table 1: The static breaking forces of melon seeds at three orientations.

Orientation	Cross section area, x 10^{-6} m^2			Force, x10^{-3} N		
	Range	Mean	SD	Range	Mean	SD
Breadth wise	19.5-32.0	26.61	2.90	11.30-15.00	13.14	1.10
Lengthwise, tip up	13.4-23.0	16.35	2.56	16.75-22.30	19.62	1.45
Lengthwise, tip down	11.5-20.9	16.41	2.20	17.80-21.50	19.55	1.10

The static breaking forces were in the range of 11.30 –15.00×10^{-3} N with the mean of 13.14× 10^{-3} N for breadth wise orientation. In the lengthwise orientation, with the tip up, the breaking forces were in the range 16.75 – 22.30 × 10^{-3} N with the mean of 19.62 × 10^{-3} N. The breaking forces for the lengthwise orientations with the tip down were in the range of 17.8 – 21.5 × 10^{-3} N with mean of 19.55 × 10^{-3} N. The forces required to break seeds at both lengthwise orientations were found to be about one and a half times greater than at the breadth wise orientation.

4.3 Quality of Broken Melon Seeds.

The amount of shelled but broken seeds and unshelled and broken seeds at different impeller radius and speeds are shown in table 2. Results for three repetitions and mean values are presented.

Table 2: Quantity of broken melon seeds

Impeller Radius, Mm	Speed, min^{-1}	Shelled but broken seeds, % No. 1	No. 2	No. 3	Mean	Unshelled and broken seeds, % No. 1	No. 2	No. 3	Mean
115	1425	6.0	6.0	7.5	6.5	2.0	2.0	2.0	2.0
135	1425	43.0	49.0	46.5	46.2	2.5	4.5	4.5	3.8
115	2850	49.5	51.0	51.0	50.0	7.5	9.0	9.5	8.0
135	2850	82.8	83.5	84.0	83.3	5.5	5.0	4.5	5.0

At the radius of 115 mm and speed of 1425 min^{-1} the mean percentages of shelled but broken seed was 6.5%, unshelled and broken seed was 2.0%. At 135 mm radius and 1425 mm^{-1}, speed, the mean percentages of shelled but broken seed was 46.2%, unshelled and broken seed was 3.8%. At radius 115 mm and speed 2850 mm^{-1}, the values are 50.0 and 8% respectively. A radius 135 mm and speed 2850 mm^{-1}, the mean percentages of shelled but broken seed was 83.3%, unshelled and broken seed was 5.0%.

5. DISCUSSION

The force of impact between the seed and the cylindrical ring was affected by the impeller radius, the impeller rotational speed, the seed cross-section area and the mass ratio. Increasing the impeller radius from 115 to 135 mm at the impeller speed of 1425 mm^{-1}, the observed quantity of shelled but broken seed and unshelled and broken seed also increased from 6.5 to 46.2% and from 2.0 to 3.8%. The amount of shelled but broken seeds increased to seven times higher values while the quantity of unshelled and broken seeds was doubled.

When the speed is doubled to 2850 mm^{-1} and the radius at 115 mm, the amount of shelled but broken seeds increased to eight times higher value while unshelled and broken seeds increased to four times higher value. With an impeller radius of 135 mm and speed 2850, mm^{-1} the quantity of shelled but broken seeds increased by 13 times higher value while unshelled and broken seeds increased to two and a half times higher value. The cross-section area depends on the orientation of the seed during impact. If the seed impacted the ring at breadth wise orientation, the cross-section area during impact is higher than during the lengthwise orientations. The orientation of the seed cannot be determined since it is difficult to predict accurately the path of the seeds within the slot as their motion is bound to be random considering the possibility of multiple impacts (Odigboh, 1979).

The results show that the mean forces required to break seeds at both lengthwise orientations are equal but the values are one and a half times greater than that of at breadth wise orientation. Hence melon seeds impacting the cylindrical ring with the edge or side are more likely to break. The mass ratio, which is the ratio of the mass of the seed to the mass of the cylindrical ring in a machine, was assumed constant. The average mass of the two varieties of melon seed at storage moisture content range from 0.056 to 0.16g (Makanjuola, 1972; Odigboh, 1979; Isiaka et al., 2006). The variation in the average mass of melon seeds is negligible when compared to the mass of the cylindrical ring. Hence the findings show that the main factor affecting the force of impact is the product of the impeller radius and rotational speed.

In an impeller – type shelling machine, seeds break when the impact force between the seed and the cylindrical ring is greater than the range of forces obtained by static loading at a particular orientation, This implies that the percentage of broken seeds during shelling is affected by the product of the impeller radius and speed, while depending on the orientations of the seed during impact.

6. CONCLUSIONS

The model equation obtained through analysis has identified four factors that could affect the quality of broken melon seeds during shelling in an impeller – type shelling machine:

(i) the impeller radius
(ii) the impeller rotational speed
(iii) the seed cross-sectional area
(iv) the mass ratio of the seed mass and cylindrical ring mass

However the product of the impeller radius and the rotational speed was found to be the main factor affecting the percentage of broken seeds.

The analysis was based on the assumption that the stresses throughout the seeds was uniform, although whenever an actual impact occurred, the stress was seldom uniform across the cross-section area (Juvinall, 1967). The full amount of energy was never transmitted because of friction between striking surfaces. Melon seeds were visco-elastic in behaviour, exhibiting both elastic and viscous effects under stress. Hence the actual stresses developed could differ from the analytically developed stress.

7. REFERENCES

Adeniran, M. O. and G. F. Wilson. 1981. Seed type classification of egusi melon in Nigeria. Paper presented at the 6th African Horticultural Symposium, University of Ibadan, 9th – 25th, July.

Ajibola, O. O., S. E. Eniyemo, O. O. Fasina, and, K. A. Adeeko, 1990. Mechanical expression of oil from melon seed. *Journal of Agricultural Engineering Research ,45: 31 -45*.

Akpan, N. A. 2004. Determination of the force required to crack melon seed shell by static loading at different moisture content. B. Eng. Thesis, University of Uyo, Uyo, Nigeria.

Akubuo, C. O. and E. U. Odigboh. 1999. Egusi fruit coring machine *Journal of Agricultural Engineering Research*, 74, 121-126.

ASAE Standard. 1982. S. 352. Moisture measurement – grains and seeds. St. Joseph, Michigan.

Asoegwu, S., S. Ohanyene, O. Kanu, and C. Iwueke. 2006. Physical properties of African oil bean seed (Pentaclethra macrophylla), *CIGR Ejournal, Vol. VIII.*

Atiku, A., N. Aviara and M. Hague. 2004 performance evaluation of a Bambara groundnut sheller *CIGR Ejournal, Vol. VI.*

Audu, I., Oloso and B. Umar. 2004. Development of a concentric cylinder locust bean dehuller *CIGR Ejournal.*

Baryeh, A. E. and B. K. Mangope. 2003. Some physical properties of QP – 38 variety of pigeon pea-*Journal of Food Engineering,* 56 (1), 59 - 65.

Bull, A. J. 1966. *A school course in mechanics – part 1*. Cambridge University Press, London.

Deshpande, S. D., S. Bal, and T. P. Ojha., 1993. Physical properties of soyabean. *Journal of Agricultural Engineering Research,* 39, 259 - 268.

Egbuta, U. and C. G. Uyah, 2003. Design, fabrication and testing of the melon impact sheller. B. Eng. Thesis, of the University of Uyo, Uyo, Nigeria.

Fayoriju, M. F. and F. B. Okokon, 1974. An evaluation of a mechanical method of shelling and separating of melon seeds by centrifugal impaction device and pneumatic centrifugal fan device. B.Sc. Thesis, University of Ife, IIe-Ife.

Fung, Y. C. 1965. *Foundations of solid mechanics*. Pentice-Hall, Inc, New Jersey.

Gupta, R. K. and S. K. Das. 1997. Physical properties of sunflower seeds. *Journal of Agricultural Engineering Research,* 66, 1 - 8.

Isiaka, M., A. M. I. Elokere and T. A. Oyedele, 2006. Determination of physical properties of melon seeds. In Proc. NIAE Conference, Zaria, Nigeria, 6^{th} – 10^{th} November.

Juvinall, R. C. 1967. *Stress, Strain and strength*. McGraw-Hill Book Company New York.

Lewis, M. S. 1987. Physical properties of foods and food processing systems. Ellis Horwoord Ltd, Chichester.

Makanjuola, G. A. 1972. A study of some of the physical properties of melon seeds. *Journal of Agricultural Engineering Research,* 17 (1), 128 – 137.

Mamman, E., B. Umar and N. Aivara. 2005. Effect of moisture content and loading orientation on the mechanical properties of Balanites aegyptiaca nuts. *CIGR Ejournal, 7, FB 04 – 015.*

McLean, W. G. and E. W. Nelson. 1997. *Schaum's outline of engineering mechanics – staticand dynamics*. 2^{nd} edition. McGraw Hill Book Company, New York.

Mohsenin, N. N. 1986. *Physical properties of plant and animal materials*, Gordon and Breach Science Publisher, New York.

Montgomery, D. C. and G.C. Runger. 1994. *Applied statistics and probability for engineers*. John Wiley and Sons, Inc, New York.

Nauhouot-Ohara, N., B. R. Criner, G. H Brusewitw, and J. B. Soki. 2000 Selected physical characteristics and aerodynamic properties of cheat seed for separation from wheat *CIGR Ejournal, 2,#82/1 – 14.*

Nwosu, R. C. 1988. Engineering properties of egusi fruit and the design of egusi seeds extraction equipment. B. Eng Project Report, Department of Agricultural Engineering, University of Nigeria.

Obot, V. W. 2005. Determination of the force required to break melon seed in static loading. B. Eng. Thesis, of the University of Uyo, Uyo, Nigeria.

Odigboh, E. U. 1979. Impact egusi shelling machine. *Transactions of the ASAE* 22 (5), 1264 – 1269.

Okokon, F. B., E. Ekpenyong, and A. U. Ukpoho, 2005. A study of the shelling characteristics of melon seeds in a factorial experimental design. *Journal of Food, Agriculture and Environment, Finland,* 3 (1): 110-114.

Oloko, S. A., B. J. Agun and A. A. Jimoh. 2002. Design and Fabrication of melon washing machine. *World Journal of Biotechnology, 3 (2), 481-486.*

Oloko, S. and Agbetoye. 2006. Development and performance evaluation of a melon depodding machine. *CIGR Ejournal, 8, PM 06-018.*

Schlack, A. L. and P. G. Kessel. 1977. Lecture notes on dynamics. Madison, Wisconsin.

8. NOMENCLATURE

ℓ	length of bar, m	ρ	density of the bar, kg/m^3
A	Cross section area of the bar, m^2	M	Rigid mass, kg
σ_o	instant comprehensive stress, N/m^2	σ	Variable compressive stress N/m^2
E	Young’s modulus of elasticity, N/m^2	c	wave-front velocity, m/s
v	variable velocity of the body, m/s	V_0	initial velocity of rigid mass, m/s
V*	equivalent velocity of the ring, m/s	V	exit velocity of the seed, m/s
a	acceleration of the particle, m/s^2	a_0	acceleration of the disc, m/s^2
ω	angular velocity of the disc, rad/s	S	distant of the seed, m
r	radius of the disc, m	q	force acting on the particle, N
F	equivalent static force, N	m	mass of the seed, kg
t	compressive wave travel time, s		

9. APPENDIX

Velocity of the Melon Seeds at Impact (Schlack and Kessel, Lecture Notes on Dynamics, Mad. Wisc., 1977).

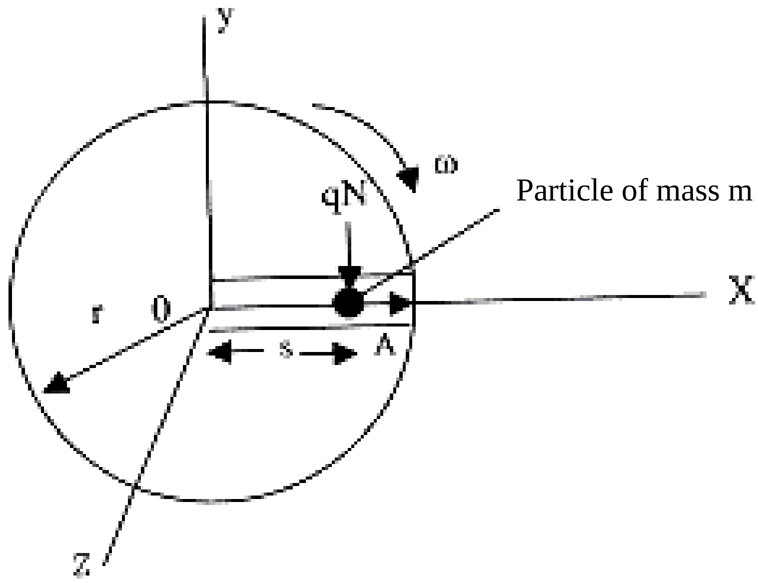

Figure 2. Schematic diagram of the motion of a particle on a slotted disc

Assume a particle of mass m moving along the slot OA in a rotating disc of radius r at ω radians/sec (Fig. 2). The only force acting on the particle by the walls of the slot is q N. Let the particle be a distance s from the center of the disc. The acceleration $\vec{a}$ of the particle is:

$$\vec{a} = \vec{a}_0 + \vec{\omega} \times \left(\vec{\omega} \times \vec{s}\right) + \dot{\vec{\omega}} \times \vec{s} + \ddot{\vec{s}} + 2\vec{\omega} \times \dot{\vec{s}} \qquad (1)$$

since the disc is fixed,

$$\vec{a}_0 = \dot{\vec{\omega}} = 0$$

and expressing in unit vectors, $\vec{i}$, $\vec{j}$, $\vec{k}$

$$\vec{\omega} = -\omega\,\vec{k}\ ;\ \ddot{\vec{s}} = \ddot{s}\vec{i}\ \ and\ \ \dot{\vec{s}} = \dot{s}\vec{i}$$

and noting that,

$$\vec{\omega} \times \left(\vec{\omega} \times \vec{s}\right) = -\omega\vec{k} \times \left(-\omega\vec{k} \times s\vec{i}\right) = -\,s\omega^2\vec{i}$$

and

$$2\vec{\omega} \times \vec{\dot{s}} = -2\omega\vec{k} \times \dot{s}\vec{i} = -2\omega\dot{s}\vec{j}$$

then equation (A.1) becomes

$$\vec{a} = -s\omega^2\vec{i} + \ddot{s}\vec{i} - 2\omega\dot{s}\vec{j} \quad (2)$$

Since force = m × $\vec{a}$

$$-q\ \vec{j} = m\left[\left(\ddot{s} - s\omega^2\right)\vec{i} - 2\omega\ \dot{s}\ \vec{j}\right] \quad (3)$$

equating forces on the system

$$\ddot{s} - s\omega^2 = 0 \quad (4)$$

But $\ddot{s} = \dot{s}\dfrac{d\dot{s}}{ds}$

$$\therefore \dot{s}\frac{d\dot{s}}{ds} = s\omega^2 \quad (5)$$

Integrating equation (A.5) and assuming that the seeds are released at a distance b from the center with negligible initial velocity,

$$\int \dot{s}d\dot{s} = \omega^2\int_b^r sds$$

$$\frac{1}{2}\dot{s}^2 = \frac{\omega^2}{2}\left(r^2 - b^2\right)$$

$$\dot{s} = \omega\sqrt{r^2 - b^2} \quad (6)$$

From equation (A.6), the exit velocity of the seed from the impeller is

$$V = \omega\sqrt{r^2 - b^2} \quad m/s \quad (7)$$