DISCRETE ELEMENT MODELLING OF THE ABRASIVE DEHULLING PROCESS OF SORGHUM AND MILLET

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The abrasive dehulling process of sorghum and millet was modelled using a three-dimensional discrete element model. The model was validated by comparison between experimental and simulation results. Good correlation between experimental and simulation results was obtained. Several numerical experiments were also carried out using the developed model to investigate the influence of mill and grain parameters on dehulling of sorghum and millet. The simulated results correlated well with experimental results from literature. The developed model therefore provides a simple and cheap tool, which can be used to study the dehulling process in more detail than, is currently possible using the available experimental methods.

Keywords: *Sorghum, millet, abrasive dehulling, discrete element, modelling*

INTRODUCTION

Dehulling represent a key step in the final processing of sorghum and millet for human consumption. Efficient mechanical dehulling of these two grains is a major problem hindering their use as human food. The need for an efficient mechanical dehulling system to replace the slow and laborious traditional hand pounding method has led to a lot of activity in this area for the last 20 years (Munck, 1995). Despite the effort to improve the efficiency of the current mechanical dehulling systems, the quality of the product from these systems is still not good enough to compete with products from other cereal grains or from traditional dehulling system.

Although empirical studies can provide useful information in the design and operation of the dehulling process, they do not address the more fundamental problem of understanding the mechanical behaviour of the grain kernels with respect to their interaction with each other and the machinery. The major thrust in sorghum and millet dehulling research today lies in understanding of the dehulling mechanism which in turn could lead to the design and development of more efficient mechanical dehulling equipment. The practical significance of an accurate understanding of what is really happening inside a dehulling mill cannot be over-emphasised. Such knowledge, if established, would be a basic step towards the determination of important parameters such as force distribution inside the mill and the breakage of grain kernels during the dehulling process, which cause the high losses and poor dehulling efficiency experienced in current systems.

Studies so far conducted on the dehulling process of sorghum and millet have mainly been through experimental and analytical methods. The data gathered by these methods is still inadequate to provide quantitative

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[§] Author to whom correspondence should be directed. E-mail address: lazaroel@suanet.ac.tz information about what actually happens to individual grain particles inside the mill. Hence detailed understanding of the dynamic behaviour of the grain kernels inside the mill and the interaction between grain and mill is severely hampered by the deficiencies of methods so far used. The alternative to the experimental approach to this problem is the computational approach. Computational methods, provided the physical models are accurate, could enable prediction of forces and stress-strain responses at both the microscopic and macroscopic scale during the dehulling process.

Discrete Element Method approach to the dehulling process

The discrete element method (DEM) is a numerical method for modelling the mechanical behaviour of granular materials. The method was developed by Cundal (1971) for the analysis of rock mechanics problems and later extended by Cundal and Strack (1979) to granular media such as sand. It has since been successfully used for numerical modelling of the mechanical behaviour of a wide range of granular materials. Unlike conventional numerical techniques such as finite element, boundary element or finite difference methods that are suited to modelling continua, DEM treats granular material as an assemblage of distinct particles, whose dynamic behaviour is modelled at particle scale. Each particle interacts with its neighbours through particle-to-particle contacts which can be formed or broken at each time step, it also keep track of the motion of individual particles and monitors or updates any contact with neighbouring particles.

Although, DEM was originally devised in the Geotechnical engineering field as a tool for modelling discontinua, it has found increasing application in diverse range of fields such as, deformation in granular media (Cundal *et al.*, 1982), flow of powders and grain (Campbell and Brennen, 1983), mechanical behaviour of granular soil under monotonic loading (Ng, 1989), large deformation flow of arbitrarily shaped particles (Walton, 1982), constitutive behaviour of granular soils (Dobry and Ng., 1989; Issa and Nelson, 1989), flow phenomenon in silos and hoppers (Rong *et al.*, 1995; Sakaguchi *et al.*, 1994)and failure of bio-materials under impact loading (Schembri and Harris, 1996).

A number of computer programs based on the DEM have been developed for different fields of study. Researchers have either used programs developed by Cundal and his co-workers such as BALL and TRUBAL (Cundal and Strack, 1979) or have modified these programs to suit their own needs such as CONBAL (Ng and Dobry, 1990), DISC (Ting *et al*, 1989) and CONBAL 3.4 (Raji, 1999, Abbaspour *et al.*, 1998). Other researchers, however, have developed their own programs, such as MASOM (Issa and Nelson, 1989), and GLUE (Bathrst and Rotenburg, 1990)

Despite the many advantages offered by DEM, there are also some disadvantages associated with it. The main disadvantage of DEM, as pointed out by Ting *et al.* (1989), is its enormous computational expense. The explicit nature of the algorithm in which each element has to be treated individually and the necessity to use a very small time step of simulation to guarantee numerical stability and accuracy imposes limitations on its capabilities, and hence, any realistic simulation becomes very time intensive. So far, with the available computer facilities only a limited number (say hundreds to few thousands) of particles can be dealt with at the same time, which is far from the scale required for practical engineering problems. However, despite this setback, the advantages weigh significantly in favour of the DEM over physical simulation as long as the DEM models are scaled appropriately with the physical system.

The study of the mechanics of dehulling process is a complex multi-body interaction problem, and hence quite suitable for DEM analysis. However, at the moment there is no

DEM program available that fits the requirement for the study of the dehulling process. The objective of this paper was to develop a DEM program tailored to the study of the abrasive dehulling process of sorghum and millet by modifying one of the existing DEM programs. Such a tool could be very useful in providing more insight on how the current mechanical dehulling system can be improved for higher dehulling efficiency and less loss.

The DEM algorithm

The numerical scheme adopted in DEM formulation computes incrementally the movement of each particle in the system in two or three dimensions by applying Newton's second law to the particles in motion and a force-displacement law to particles in contact. Newton's second law gives the motion of the particles resulting from the forces acting on them while the force-displacement law gives the current inter-particle contact force. Each cycle is carried out over a time step, the length of which is chosen such that during a single time step disturbance cannot propagate from any particle further than its immediate neighbours. Each particle in the assembly is identified separately, by its radius, mass, moment of inertia and contact properties. The co-ordinates of the centre of mass and the radius of the particle define the geometry and the position of the particles. For all particles, a list of particles that are in immediate contact and in the near-neighbourhood is maintained. Thus to find which other particles are in contact with a given particle, only the particle's contact list is checked instead of checking every particle in the assembly. This procedure drastically reduces the number of searching steps at the expense of computer memory space and time. Once there is overlap between two particles, the normal and shear forces at the contact point are determined from the magnitude and rate of overlap. Finally, all the contact forces on the particle are summed to get the net out-of-balance force acting on the particle. From this force the acceleration, velocity, and displacement of the particle are calculated. As this procedure is carried out for every particle, an entire set of the particle positions emerges at the next instant of time.

The equations for computing the incremental contact forces between particles were developed by Cundal and Strack (1979). The model equations are summarised below for a particle characterised by position x, mass m, and moment of inertia I:

$$F_i = m\ddot{x}_i + \sum_n \left(c\dot{x}_i + kx_i\right) \qquad i=1,2,3 \qquad (1)$$

$$M_i = I\ddot{\theta}_i + \sum_{i=1}^{3} \left(kx_i + c\dot{x}_i\right)s_i \qquad i=1,2,3 \qquad (2)$$

where F_i is the force acting on the particle, M_i is the moment about the centroid of the particle, and m is the mass of the particle, $\ddot{x}$ is the acceleration of the particle, I is the moment of inertia of the particle, $\ddot{\theta}$ is the angular acceleration, s_i is the perpendicular distance from the line of action of the force to the centroid of the particle, and the directions i = 1,2,3 refers to the x, y, z co-ordinates respectively. New velocities and positions of the particles are obtained by numerical integration of equation (1) and (2) over a short time interval Δt (time step) from $t_{N-\frac{1}{2}}$ to $t_{N+\frac{1}{2}}$ assuming that $\ddot{x}$ and $\ddot{\theta}$ remain constant over the time interval Δt:

$$\left(\dot{x}_i\right)_{N+\frac{1}{2}} = \left(\dot{x}_i\right)_{N-\frac{1}{2}} + \ddot{x}_i \Delta t \qquad (3)$$

$$\left(\dot{\theta}_i\right)_{N+\frac{1}{2}} = \left(\dot{\theta}_i\right)_{N-\frac{1}{2}} + \ddot{\theta}_i \Delta t \qquad (4)$$

These equations are applied to each particle in turn. Further numerical integration of the new velocities leads to new displacements and rotational increments, which are used to update the position and rotations of each particle as follows:

$$\left(x_i\right)_{N+1} = \left(x_i\right)_N + \left(\dot{x}_i\right)_{N+\frac{1}{2}} \Delta t \qquad (5)$$

$$\left(\theta_i\right)_{N+1} = \left(\theta\right)_N + \left(\dot{\theta}_i\right)_{N+\frac{1}{2}} \Delta t \qquad (6)$$

The new values for the displacements are used in a force displacement law to find new force increments at contact points, and the cycle is repeated for the next time step. Thus by repeating these calculations, which alternate between application of force-displacement law at contact points and Newton's law of motion to particles in motion, new positions of all the particles in the system can be determined, and the time evolution of all the particles motion in the *x, y* and *z* co-ordinates is given by repeating the entire set of calculations at successive time steps until equilibrium is achieved.

Both contact and frictional damping are used as energy dissipation mechanism in the program. Frictional damping occurs during sliding when the absolute value of the shear force at any contact is greater than a maximum value which is equal to the frictional force between two particles or particle and mill wall or dehulling surface. This is given as:

$$F_{s\max} = F_n \tan\phi + C \qquad (7)$$

where F_n *is the normal force,* ϕ is the inter-particle friction angle and C is the cohesion between the particles

THE THEORY OF ABRASIVE DEHULLING

Abrasive dehulling is the most commonly used mechanical dehulling method for sorghum and millet. The method employs carborundum or other abrasive disks or drums mounted on a vertical or horizontal rotor to progressively abrade the outer layers of the grain. To investigate the mechanics of the abrasive dehulling process, the Tangential Abrasive Dehulling Device (TADD) was used as a model mill. TADD was used in this particular modelling exercise because of its ability to closely simulate the abrasive dehulling action of commercial abrasive dehullers together with the fact that this mill can effectively dehull grain samples as small as one grain (Reichert *et al.*, 1986). These features together with its ability to process multiple samples at a time made it very useful experimental model for the DE model validation. Details of the mill design and operation of TADD are described in Reichert *et al.* (1986).

The abrasive system in TADD is very similar to the classical physical model for the determination of coefficient of dynamic friction. In the classical system there is a friction force that opposes the movement of the surface, abrading the object and the surface. In the mill, the interlocking of the grain particles and the friction force between the grain and the dehulling disk opposes the movement of the abrasive surface, this result in abrasion of the grain and hence the removal of the grain portion in contact with the dehulling disk. The amount of material removed depends on the normal force acting on the grain particle in contact with the abrasive disk. Grain to grain friction also occur as the grain particles come into contact and rub against each other due to the constant mixing action provided by the rotation of the abrasive disk. This also contributes to the dehulling process although to a much lesser extent compared to the abrasive disk. The friction force between the grain particles and the dehulling surface can be related to the normal force acting on the surface of the grain by the Coulomb law of friction.

$$F = \mu F_n + C \qquad (8)$$

where F is the friction force, μ is the coefficient of dynamic friction, and F_n is the normal force, which in this case equivalent to the weight of the grain in the cup and C is the cohesion between the grain and the surface.

Determination of contact area and volume of materials removed

The amount of materials sheared off depends on the magnitude of the normal force and the mechanical properties of the grain. Assuming the mechanical properties of the grain to be similar, their deformation should therefore be proportional to the normal force acting on them. The amount of material sheared off by the abrasion between grain and grain or between grain and the abrasive disk due to this deformation will be proportional to the normal force. Assuming the grain particles to be perfect elastic spheres, the deformation of the grain kernel due to the normal force F_n can be deduced from Hertz contact theory for elastic spheres. For two-grain particles in contact or for a grain particle in contact with a rigid plate such as a wall or the dehulling disk, the following relationship between the normal force and material properties can be derived. The normal force F_n acting on a particle is given by (Peleg, 1984):

$$F_n = \frac{8\alpha^{\frac{3}{2}}}{3}\left(\frac{R_1R_2}{R_1+R_2}\right)^{\frac{1}{2}}\left[\frac{1-\nu_1}{G_1}+\frac{1-\nu_2}{G_2}\right]^{-1} \qquad (9)$$

where α is the total deformation of both particles at contact area, R_1 is the particle radius (m) and R_2 is the radius of curvature of the contact surface (m), G is the modulus of rigidity (MPa) and ν is the Poisson's ratio.

The deformation at contact area can be determined from:

$$\alpha = \left\{\frac{3}{8}F_n\left[\frac{1-\nu_1}{G_1}+\frac{1-\nu_2}{G_2}\right]\left(\frac{R_1+R_2}{R_1R_2}\right)^{\frac{1}{2}}\right\}^{\frac{2}{3}} \qquad (10)$$

The contact area of the deformed grain particles in these cases is to a good approximation circular in shape. The radius of the contact circle for a given normal force F_n, is given by:

$$a = \left\{\frac{3}{8}F_n\left[\frac{1-\nu_1}{G_1}+\frac{1-\nu_2}{G_2}\right]\left(\frac{R_1R_2}{R_1+R_2}\right)\right\}^{\frac{1}{3}} \qquad (11)$$

Which for two-grain particles in contact or grain particle in contact with a flat wall (assuming $R_2 = \infty$) is given by:

$$a = \left[\frac{3F_nR}{8G}(1-\nu)\right]^{\frac{1}{3}} \qquad (12)$$

From which the contact area A_c can be calculated from the following equation:

$$A_c = \pi\left[\frac{3F_nR}{8G}(1-\nu)\right]^{\frac{2}{3}} \qquad (13)$$

For contact between a grain particle of radius R_1 and a curved wall of radius R_2, the radius of the contact circle is given by:

$$a = \left\{\frac{3}{8}F_n\left(\frac{1-\nu_1}{G_1}+\frac{1-\nu_2}{G_2}\right)\left[\frac{R_1R_2}{R_1-R_2}\right]\right\}^{\frac{1}{3}} \qquad (14)$$

where G_1, G_2 and ν_1, ν_2 are moduli of rigidity and Poisson's ratios of the grain and wall materials respectively. The contact area in this case will be equal to:

$$A_c = \pi\left\{\frac{3}{8}F_n\left(\frac{1-\nu_1}{G_1}+\frac{1-\nu_2}{G_2}\right)\left[\frac{R_1R_2}{R_1-R_2}\right]\right\}^{\frac{2}{3}} \qquad (15)$$

Assuming G_2 to be very large compared to G_1, equation (15) can be simplified to:

$$A_c = \pi\left[\frac{3F_nR_1R_2(1-\nu)}{8G_1(R_2-R_1)}\right]^{\frac{2}{3}} \qquad (16)$$

The volume of deformed area can be determined from the deformation and radius of the particle using the following equation (Arzt, 1982):

$$V = \alpha^2\pi\left(R-\frac{\alpha}{3}\right) \qquad (17)$$

where α is the deformation (m) and R is the radius of the particle (m)

Dehulling occurs only when grain particles slide over each other or on the dehulling disk or the mill walls. The force component responsible for the sliding of the grain particles is the shear or tangential force F_s the magnitude of which depends on the friction force between the two surfaces in contact. Sliding of the grain particles take place only when the maximum possible shear force is greater than or equal to the absolute value of the limiting friction force at the point of sliding

$$F_{s(\max)} \geq |F_n|\tan\phi \qquad (18)$$

$F_{s(max)}$ is therefore the force responsible for the removal or shearing off the seed coat from the endosperm during the dehulling process. The maximum shear force per unit area is obtained by dividing the maximum tangential force $F_{s(max)}$, by the contact area for a given normal force as determined from equation (15) or (16) depending on the contact conditions. The volume of material removed is obtained from equation (17).

Model Implementation

The dehulling process described above was implemented as part of the DEM program CONBALL 3-4. This is a well documented three dimension program based on two programs, TRUBAL, which was developed by Cundal and Strack (1979) and CONTACT, which was incorporated in TRUBAL by Ng and Dobry (1990) to take account of the non linear force-deformation relationship at inter-particle contacts based on Mindlin's solution. While the structure of the parent code was kept the same, a number of important features unique to dehulling process were introduced. Also some of the features in the code pertaining to problems in flow and compression were discarded. The major changes included:

i) Modification of the program to simulate both straight and curved or circular walls
ii) The original code was meant for simulation of multi-particle irregular bodies, it was therefore modified to simulate spherical particulate bodies.
iii) The program was changed from the simulation of gravity flow to a combination of flow and abrasion between particle/ particle and particle and wall.
iv) Particle - wall contact detection was modified to include both particle contacts with both straight and curved walls.

Simulation steps

Simulation using the modified CONBAL3-4 essentially consists of three major steps: Detection of contacts, computation of contact forces and computation of particle motion. This cycle of dynamic calculations is repeated thousands of times as the simulation proceeds. Briefly stated, this three dimensional DEM algorithm proceed as follows:

Initialisation

(i) Each physical entity in the system (grain particle or wall) is identified separately by a set of geometrical properties, physical properties, Initial *x*, *y*, and z co-ordinates, and velocities.
(ii) A computational scheme termed boxing is implemented to reduce the number of elements that have to be tested for potential contact with each entity. To do so the entire space is divided into small boxes, and a set of pointers is used to store all elements inside each box in a linked list called the contact list. Hence test for potential contacts is done only between elements in the same or neighbouring boxes.

Iteration for each time step

(i) For each particle, forces and moments at all contact points are calculated, and reduced in their resultant *x*, *y*, and *z* components.
(ii) Newton's second law of motion is applied to find translational and rotational accelerations. These accelerations are integrated to update velocities, which are in turn integrated to update particle position.
(iii) For those particles in contact with others or mill wall, the incremental force at each contact during the time step is calculated.
(iv) For each box, pointers to the elements/particles that has moved out of the box are dropped and new pointers are assigned for incoming entries.
(v) For each particle, new contacts are formed while some old contacts are broken, and a new iteration cycle is launched.

Input Parameters

The input parameters that must be specified to run numerical tests with the current DEM program may be divided into two main groups:
(i) The geometrical and other physical property data: The geometrical data that describes the position and orientation of the rigid boundaries (the walls) and the positions and radii of the particles with respect to global co-ordinate system. The

physical properties, which include; particle radius, density, friction coefficients, number and types of the particles to be used.

(ii) Other parameters, which apply to the field as a whole which include, damping ratio, the fraction of the critical time step (frac) and the number of cycles required

Model validation

To validate the model, comparison was made between simulation results and experimental results using TADD. To ensure that experimental and numerical results are comparable, the properties of experimental materials and the simulation were made as similar as possible.

EXPERIMENTAL SET-UP AND PROCEDURES

One sorghum variety (*Dionje*) and one millet variety (*IM*) was used in the validation of the model. The physical properties of the grain used are given in Table 1.

Dehulling tests were carried out in a tangential abrasive-dehulling device (TADD) using a 6-cup cover-plate and an 80-grit resin bounded abrasive cloth fixed to a 250 mm diameter aluminium disk as the abrasive disk. The dimensions of the sample cups were 50 mm diameter and 35 mm in height; same dimensions were used for the working space in the simulation.

The effect of operating variables, such as the retention time of the grain in the dehuller on the amount of materials removed as bran from the grain were investigated using a 2 g, grain sample. After dehulling for pre-determined time intervals of 15, 30, 45, and 60 seconds, the dehulled grain was removed from the sample cups using a vacuum device and weighed to determine the weight loss. A 2 g sample was also dehulled for a total time of 240 seconds which was the time required to remove material equivalent to the seed coat content of the grain (i.e. 8.3% of the grain by weight) as bran. The weight loss (%) was designated as materials removed.

The simulation was run for 15, 30, 45, 60 and 240 seconds, the same as in the experiment. The proportion of material removed in the simulation was recorded and compared with results obtained from the experiment. The parameters used in the simulation are summarised in Table 2. Apart from direct comparison with experimental results, the effect of different grain and mill parameters such as grain hardness, disk speed, and disk roughness on the rate of material removal predicted by the model was investigated by varying these parameters.

Table 1. Physical properties of the grain

Grain Type	Moisture (%db)	P/radius (m)	P/density (kg/m^3)	Coefficient of friction			M/Rigidity (MPa)
				Grain/grain	Grain/wall	Grain/disk	
Sorghum	12	0.00179	1265	0.4	0.3	0.65	1000
Millet	12	0.00125	1035	0.4	0.33	0.65	900

Table 2. Parameters used in the simulation

Grain Type	D/speed (rpm)	No of Particles	Time step (sec)	Work space dimensions		Damping ratio	
				Diameter(mm)	Height(mm)	g/g	g/w
Sorghum	1500	63	1.0×10^{-5}	5.0	3.5	0.33	0.3
Millet	1500	120	4.5×10^{-6}	5.0	3.5	0.23	0.25

g/g – grain to grain collision, g/w – grain to wall collision

RESULTS AND DISCUSSION.

Simulation tests

Figures 1(a) to 1(f) show the results of the simulation of the abrasive dehulling process of 1000 sorghum grain particles (approximately 30g of grain) in TADD using the modified program. Figure 1(a) shows the particle generation stage where particles are being generated systematically in the dehulling cup. There is no contact between particle and particle or particle and the cup walls or dehulling disk at this stage. Figure 1(b) shows the consolidation stage where the grain particles are consolidating under gravity until they come into contact with the rotating dehulling disk. As the first layer of particle touched the dehulling disk, it is pulled towards the cup wall by the rotating dehulling disk. Figure 1(c) show the grain particles as they hit the dehulling cup wall and bounce back, colliding with the particles behind them and those, which are still at consolidation stage. Figure 1(d) show the grain particles after reaching the cup wall are forced to go up the cup wall by the force exerted by the rotating disk and the push from the grain particles following behind. Figures 1(e) and 1(f) shows the particles having reached the top of the grain mass roll down to the rotating disk. The process is repeated until the pre-set retention time is reached.

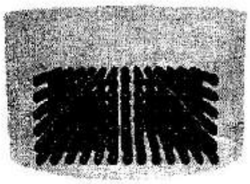

Figure 1(a) Particle generation stage

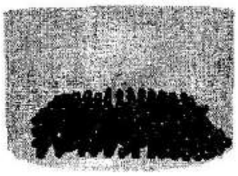

Figure 1(b) Particle consolidation (first layer of particles just touching the dehulling disk

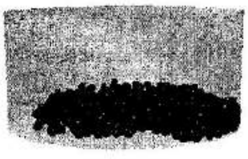

Figure 1(c) Particles in contact with the dehulling disk are pulled to the cup wall

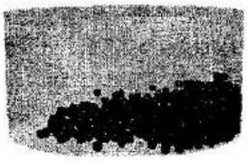

Figure 1(d) Particles reach the cup wall and are forced up the wall by particles following behind

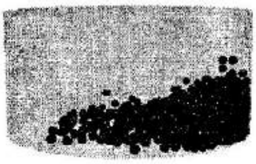

Figure 1(e) Particles forced up the cup wall reach the top of grain mass and roll/slide back to the dehulling disk

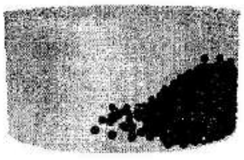

Figure 1(f) The cycle is repeated until the required retention time is reached

Figure1 Simulation of the tangential dehulling process in TADD

The effect of retention time on the amount of materials removed.

The comparison between experimental and simulation results on the amount of material removed as bran for a given retention time is shown in Figure 5 for a 60 seconds retention period and in figure 6 for 240 seconds retention period. 240 seconds retention in the dehuller was required to remove 8.5% of the grain sample, which was equivalent to the grain seed coat content as determined from hand peeling tests (8.3±0.2% for *Dionje*). The short and long retention periods were used for both experiment and simulation. In the current study the term 'material removed' refers to the amount of the material removed from the grain sample as bran and was determined from the following equation:

$$\%\ \text{materials removed} = \frac{\text{Initial sample weight - final sample weight}}{\text{Initial sample weight}} \times 100 \qquad (19)$$

In both experiment and simulation the amount of material removed from the grain increased with increase in dehulling time (i.e. retention time in the dehuller). There was a good agreement between the predicted and the experimental results in short and long retention periods for both sorghum and millet. Figure 2(a) and (b) show the results for short time retention (60 seconds retention) for sorghum and millet respectively while Figure 3(a) and (b) show the results for long time (240 seconds) retention. For both short and long time retention periods, the amount of material removed in the experiment was slightly higher than the amount predicted by the model for both grain types. For short time retention the difference between the rate of material removal from the grain sample as predicted by the simulation and from actual experiment was constant as evidenced by the closeness of the slopes for the experimental and predicted curves. The difference between experimental and predicted material removed after 60 seconds retention was approximately 0.1% for sorghum while for millet was 0.13%. However, as the retention time in the dehuller increased, the difference between the rate of material removal predicted by the simulation and the experimental increased for both sorghum and millet as shown in figure 3(a) and (b). The mean difference between simulated and experimental results after 240 seconds retention was 0.5% for sorghum and 0.4% for millet. Statistical analysis (t-test) showed that the difference between material removed predicted by the model and experimental results was not significant (P<0.05) for short time (60 seconds) retention while for long time retention (240 seconds) was significant at P<0.05).

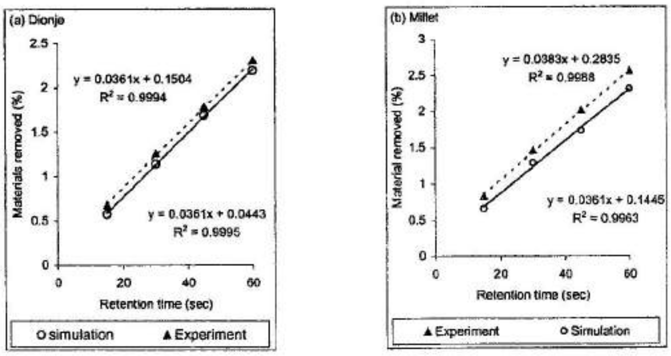

Figure 2: Effect of retention time on the amount of materials removed from sorghum *(Dionje)* and millet (*IM*) after 60 seconds for experiment and simulation

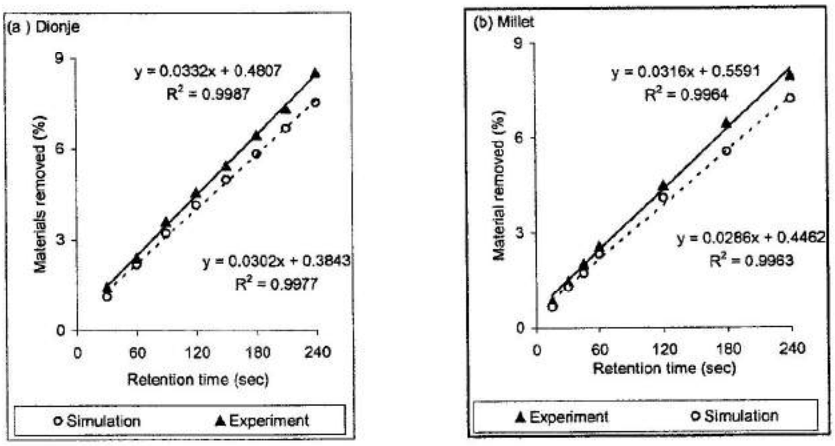

Figure 3. Effect of retention time on the amount of materials removed from sorghum (*Dionje*) and millet (*IM*) after 240 seconds for Experiment and simulation

The difference could be explained by the fact that, the longer the retention time in the dehuller, the higher the chance of kernel breakage. This explanation is supported by experimental evidence from literature that kernel breakage is positively correlated with retention time in the dehuller (Deshpande, 1981). The broken particles small enough to pass out of the sample cup were thus lost with the bran leading to the increase in the rate of material removed in the experiment as the retention time increased. On the other hand the model assume that no grain is broken during the dehulling process and only the materials removed are shear off.

The relationship between the material removed (%) and retention time in the experiment and simulation could be represented by the following empirical equation

$$Y_{removed} = at + b \qquad (20)$$

where, $Y_{removed}$ is the material removed (%), a and b are constants and t is the retention time in the dehuller (sec). The values of the constants and the respective R^2 values for short and long time retention periods are given in Table 3 for both sorghum and millet.

The influence of grain properties and machine operating variables on the rate of material removal from the grain sample.

Effect of grain strength properties

The effect of grain strength or kernel hardness on the rate of materials removed was investigated by varying the modulus of rigidity of the grain. The rate of material removal from the grain decreased with increase in the modulus of rigidity (or hardness) of the grain as indicated in figure 4(a) and (b) for sorghum and millet respectively. The model predicted that, the softer the grain the more the amount of materials which will be removed as bran from the grain sample for a given retention time in the dehuller. These results are in good agreement with experimental results reported in literature that for the same retention time in the dehuller, more materials were lost as bran from soft grain than in hard grain (Reichert *et al.*, 1988).

The relationship between the grain modulus of rigidity or hardness and the rate of material removal from the grain as illustrated in figure 4(a) and (b) could be represented by the following equations for sorghum and millet respectively:

$$\ln(S_{removed}) = 2.9 - 0.002Gs \quad (R^2 = 0.994) \quad (21)$$

and

$$\ln(M_{removed}) = 1.9 - 0.001Gs \quad (R^2 = 0.994) \quad (22)$$

where, $S_{removed}$ and $M_{removed}$ is the material removed per second (%) for sorghum and millet respectively, and G_s is modulus of rigidity of the grain (MPa)

Table 3. Values for the constants and R^2 for the relationship between retention time and material removed (equation 20)

Grain Type	Retention Time (sec)	Experiment a	Experiment b	Experiment R^2	Simulation a	Simulation b	Simulation R^2
Dionje	60	0.04	0.15	0.999	0.04	0.04	0.999
	240	0.03	0.48	0.998	0.03	0.38	0.998
Millet	60	0.04	0.28	0.999	0.04	0.14	0.996
	240	0.03	0.56	0.996	0.03	0.45	0.996

Effect of the dehulling disk speed

The effect of the speed of rotation of the dehulling disk on the rate of material removal was studied by varying the disk speed from 500 rpm to 2000 rpm for a retention time of 60 seconds. The results predicted by the model are summarised in figure 5(a) and (b) for sorghum and millet respectively. The rate of removal of materials from both sorghum and millet increased with increase in disk rotation speed, reaching a peak at 1500-rpm (157 rad/sec). For speed of revolution above 1500 rpm there was no significant increase in the rate of material removal from the grain. This may have been caused by the fact that, as the speed of rotation of the disk increased above 1500 rpm the number of contacts between grain and grain and between grain and the dehulling disk decreased. The mean number of contacts between particles and the dehulling disc was 20, 22 and 21 for sorghum and 25, 27, 26 for millet at 1000, 1500 and 2000 rpm respectively indicating that there on average there was higher number of contacts with the dehulling disk at 1500 rpm than at 2000 rpm.

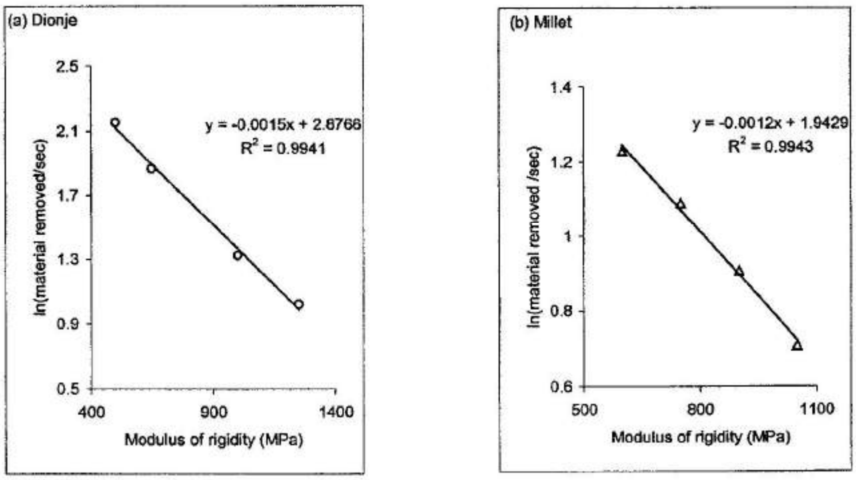

Figure 4. Effect of modulus of rigidity on the rate of material removed after 60 seconds retention as predicted by the model

The relationship between the disk speed (radians/sec) and the rate of material removal (%) from the grain sample as shown in figure 5 could be represented by the following polynomial equations for sorghum and millet respectively:

$$S_{removed}=7x10^{-09}\,r^3-5x10^{-06}\,r^2+0.0013r+1.22, \quad (R^2=1) \qquad (23)$$

$$M_{removed}=-10^{-08}\,r^3+4x10^{-06}\,r^2-0.002r+0.85, \quad (R^2=1) \qquad (24)$$

where, $S_{removed}$ and $M_{removed}$ are the material removed per second for sorghum and millet respectively, and r is the disk rotation (rad/sec)

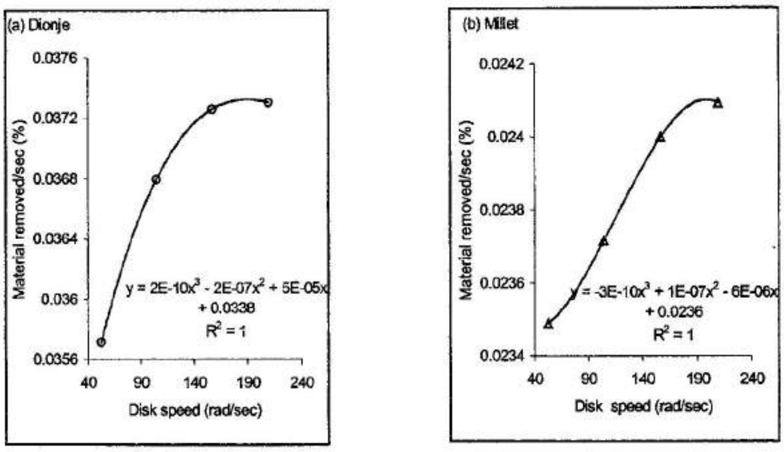

Figure 5. The effect of dehulling disk speed on the rate of material removed per second as predicted by the simulation after 60 seconds retention

Effect of the dehulling disk roughness

The effect of the dehulling disk roughness was simulated by varying the coefficient of friction between the grain and the dehulling disk. Figure 6 summarise the results on the effects of varying the coefficient of friction of the disk on the rate of material removal from the grain. The rate of material removal predicted by the model increased with increase in friction coefficient between grain and dehulling disk for all retention time investigated for both sorghum and millet. These results agreed well with experimental results from literature. Deshpande (1981), found that all other factors being similar, the rougher the abrasive disk the higher the amount of materials removed as bran for a given retention time.

The relationship between the coefficient of friction between disk and grain particles and the rate of material removal from the grain could be represented by the following equation:

$$ln(S_{removed})=4.7\mu+0.6 \quad (R^2=0.999) \qquad (25)$$

$$ln(M_{removed})=10.1\mu-2.7 \quad (R^2=0.988) \qquad (26)$$

Where, $S_{removed}$ and $M_{removed}$ is material removed per second for sorghum and millet respectively, and μ is the coefficient of friction between grain and dehulling disk

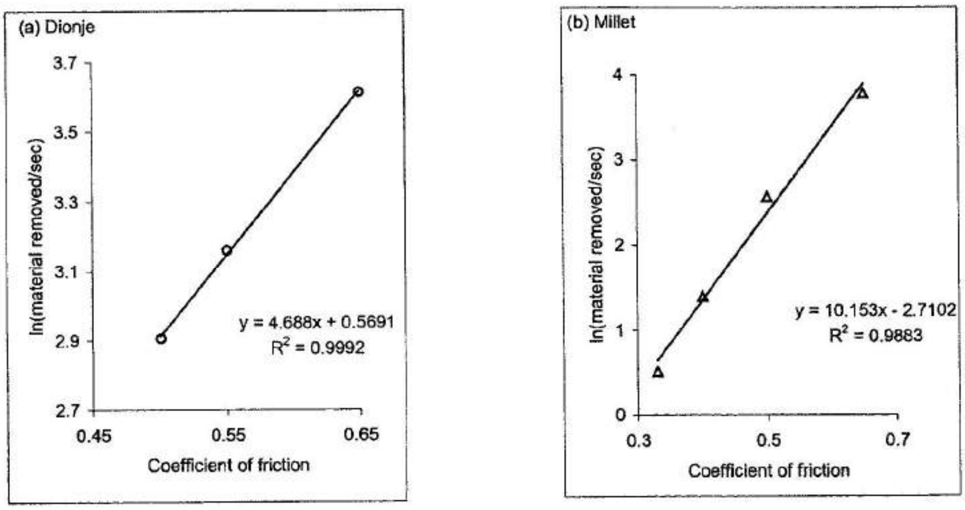

Figure 6. The effect of dehulling disk friction on the rate of material removed as predicted by the simulation for 60 seconds retention.

SUMMARY AND CONCLUSIONS

The dehulling process inside a tangential dehulling device (TADD) was successfully simulated using a 3-D DEM program based on CONBAL 3-4. The program was able to simulate the movement of the grain particles inside the mill from which important parameters such as the velocity, displacement and force experienced by individual grain particles inside the mill could be obtained at any stage of the process if required. Comparison between the effect of retention time in the dehuller on the rate of material removal as bran from the grain sample was carried out and it was found that result from simulation and experiment were well correlated.

This is the first time that the dynamic events taking place inside the dehulling mill have been successfully simulated by considering individual grain particle velocity, contact force and displacement. This made it possible to study the effect of changing different mill parameters such as rotational speed of the dehulling disk, retention time in the mill, the roughness of the dehulling disk, or grain properties such as grain hardness, on rate of material removal from the grain sample without performing the actual experiments. This means that in future such simulations will save time, money and labour for performing such experiments in laboratory. Also practically any information required such as frequency, distribution and intensity of impacts of grain kernel inside the mill could be obtained from the simulation. Such information, given the harsh conditions existing inside the dehulling mill and current capability of experimental methods available would be difficult to obtain. The results shown here although in no way exhaustive are quite fundamental in nature and point towards possible new method for studying the dehulling process. This new tool could therefore be very useful in design of new dehulling mills or improvement of existing ones for higher dehulling efficiency and lower losses.

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NOMENCLATURE

C	Cohesion between particles
DEM	Discrete Element Method
F	Friction force, N
F_i	Force acting on a particle, N
F_n	Normal force, N
G_1	Modulus of rigidity of grain, MPa
G_2	Modulus of rigidity of retaining wall material, MPa
I	Moment of inertia of particle, kg/m^2
m	Mass of the particle, kg
M_i	Moment about the centroid, N.m
$M_{removed}$	Percent material removed per second for millet
N	Normal force, N
R_1	Radius of the particle, m
R_2	Radius of curvature of contact surface, m
s_i	Perpendicular distance from line of action of force, m
$S_{removed}$	Percent material removed per second for sorghum
TADD	Tangential Abrasive Dehulling Device
V	Volume of deformed area
$Y_{removed}$	Material removed, %
	Greek Symbols
α	Total deformation of particles in contact, m
$\dot{x}$	Particle velocity, m/sec
$\ddot{x}$	Particle acceleration, m/sec^2
Δt	Time step, sec
ϕ	Inter-particle friction angle
μ	Coefficient of friction
ν	Poisson's ratio
$\ddot{\theta}$	Angular acceleration of the particle, rad/sec

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