Simulation of Tef Seed Broadcasting

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ABSTRACT

In this investigation broadcast seeding of tef seed was considered. In order to predict particle trajectory on and off disc, after developing a mathematical relationship, simulation of particle movement on and off disc of a spinning disc was undertaken. The terminal velocity and coefficient of drag force of tef seed were determined experimentally in laboratory. Projected distance of particle thrown off the disk was calculated by varying different particle property (such as moisture content, coefficient of friction, TGM and particle density) and machine parameters (such as cone angle and angular velocity). The projected distance of a particle increased with increase in moisture content of seed, spreader revolution per minute and inclination of disc with the horizontal. The increase in moisture content was associated with increase in coefficient of friction, which do have effect on-the disc particle motion. The increase in moisture content has influence also on thousand grain mass, particle size, sphericity, particle density and coefficient of drag force which affected off-disc particle trajectory. This investigation showed the possibility of using a spinning disc spreader in order to broadcast tef seed, which could replace broadcasting of tef seed by hand manually. Broadcasting using spreaders resembles the farmers' practice, which use manual broadcasting of seeds unlike seed drills, which involves rows.

Keywords: tef, broadcast seeding, modelling, simulation, particle trajectory, spinning disc

1. INTRODUCTION

Tef (Eragrostis tef (Zucc.) Trotter) is an important cereal crop indigenous to Ethiopia constituting about 20% of cereal production of the country (Bultosa & Taylor, 2004). Countries like USA, Canada, Australia, South Africa and Kenya began the production of tef for different purposes such as forage crop, thickener for soups, stews and gravies (Ketema, 1997). Tef seeds are sown on the surface of the soil and left uncovered or sometimes covered very lightly by pulling woody tree branches over the field by oxen (Ketema, 1997). About 15-55 kg of tef seeds are sown per hectare under different condition such as moisture availability, fertility status of the soil, variety of the crop, mechanisation level and individuals sowing exprience. Additionally, Ketema (1997) commented the seed rate varied due to the fact that evenly hand broadcasting of tef seed is difficult due to smaller weight and size. Tef seeds' equivalent diameter was reported to vary between 0.71 to 0.87 mm and thousand grain mass 0.257 to 0.421 g in the moisture content range 5.6 % to 29.6 % w.b. (Zewdu & Solomon, 2007).

The purpose of the sowing process is the distribution of a certain quantity of seeds over a given area and the placement of seeds at a certain depth in the seedbed. Seeds can be sown by drilling, broadcast sowing and band sowing (Speelman, 1975). Broadcasting is advantageous as area per plant is uniform over other seeding methods. Broadcasting can be applied when soil condition are wet, when seedbeds contain straw and seed distribution is more randomly, covering more of the soil surface, hence reducing machinery costs and soil compaction (Ball, 1986). But it has weakness in applying and control of depth of sowing. Spinning disc type fertiliser spreader can be utilised as a seed broadcaster, and helps in reducing machinery cost, as both operations can be performed with the same spreader.

Broadcasting as one of the seed sowing methods, in combination with reduced cultivation offers the advantage of being up to four times faster than conventional ploughing and drilling and is of particular value for sowing large hectarage of winter cereals (Ball, 1986). Most grass species are small-seeded requiring a shallow seeding depth, from ¼ to ¾ in (6.35 to 19.05 mm) deep. Grass seed fields may be seeded by broadcasting or in rows depending on the available equipment, moisture content and species. Henning and Risner (1993) suggested seeding of orchard grass can be made with broadcast equipment such as fertilizer trucks, buggies or tractor-mounted distribution. Broadcast equipment will not throw orchard grass seed as far as it will throw fertilizer or heavier seeds such as fescue (Henning and Risner, 1993). Similar problem can be encountered for tef seed, too. Broadcasters are less expensive, have high work capacity but hard to calibrate, because of unequal distribution, unequal seed weight and shape, difficulties with wind and uneven soil surface (Hunt, 1983). To help avoid uneven stands, drive the equipment close enough to overlap the previous spread pattern to ensure even seed distribution.

The spread in particles should be symmetrical to the drive direction. To correct the direction of throw, it is possible to alter the release point of the particles from the hopper on the disc, through varying the disc rotational speed, disc radius (Eichhorn, 1995). Orchard grass seed should be covered with about ¼ to ½ inch (6.35 to 12.70 mm) of soil (Henning and Risner, 1993). Spike tooth harrows or "brush type" drags make good tools for covering broadcast seed. The use of a cultipacker or lightweight roller is very important for covering of broadcasted seeds. Schmidt (1995) reported that some farmers in Ohio seeded canola by mixing the seed in water or liquid fertiliser and sprayed it on the soil surface. Prairie grass can be either broadcasted or drilled (Hall, 1992). Broadcast seeding is the best method for seeding grass and alfalfa mix (Peterson, 2006). Broadcasters as used for fertilisers, the fertiliser will be dropped near the centre of the disc, which will be caught by vanes and further accelerated, which finally will be thrown into the air (Eichhorn, 1995). Similarly, tef seed can be broadcasted by the spinning disc. Hence, investigating sowing of tef seed through modelling and simulation of the particle movement with a fertiliser spreader could show strengths and weakness as an alternative method to hand broadcasting undertaken currently by small holder farmers in Ethiopian highlands.

2. MATHEMATICAL MODELLING

The particle motion is affected by physical properties of seeds and disc design (Hofstee, 1995). The coefficient of friction of the seeds with the surface they come in contact affects the particles movement on the disc. The particles' physical and aerodynamical properties affect the particles motion within air, as the size, shape and coefficient of drag force are used in the calculation of particles trajectory within fluid (Mohsenin, 1986, Sitkei, 1986).

Cunningham (1963), Patterson and Reece (1962), Olieslagers et. al. (1996), Dintwa et. al. (2004), Aphale et. al. (2004) and Hofstee (1995) described a mathematical model for a spinning disc fertiliser spreader, using a mechanistic model, which uses laws of physics to follow motion of particles as they fall on to a spinning disc spreader till they leave the spreader. After leaving the spinning disc the motion of the particle in air till it hits the ground was simulated with trajectories of a particle through the air (olieslagers, et. al. 1986; Mennel &Reece, 1963; Reints & Yoerger, 1967; Dobler & Flatow, 1968).

In order to investigate the various parameters which could affect particle trajectories on a disk, mathematical relationships based on the forces acting on the seed, the mass inertia ($m\frac{d^2r}{dt^2}$), the coriolis force ($2m\omega\frac{dr}{dt}$), the centrifugal force ($m\omega^2 r$), the gravity force (mg) and the resulting friction force against the disc surface and the vane $\left(\mu_d (mg\cos\alpha + m\omega^2 r\sin\alpha) + \mu_v m\omega^2\right)$, were discussed by Olieslagers et. al. (1996), Dintwa et. al. (2004) and Hofstee (1995), but pitched vane and only flat disc was considered by Aphale et. al. (2003) and Koya and Faborode (2006). In this investigation a radial vane disc with a cone angle varying from 0 to 20° was considered. The feed radius must have a minimum value, otherwise the particles are not able to start moving because the outward directed forces are not sufficient to overcome the initial friction force.

After the description of the forces involved on a single particle, in order to develop equation describing the state of the particle under these forces, the equilibrium of forces acting on the particle in the direction of motion yields the equation shown below:

$$\frac{d^2r}{dt^2} + 2\mu_v\omega\cos(\alpha)\frac{dr}{dt} - \omega^2 r(\cos(\alpha) - \mu_d\sin(\alpha)) + g(\sin(\alpha) + \mu_d\cos(\alpha)) = 0 \qquad (1)$$

In order to solve Eqn. (1) MATLAB-SIMULINK program was used, which solves numerically using Runge-Kutta method. The equation was written in MATLAB S-Function and the simulation was executed in SIMULINK. The MATLAB S-function simplifies the step to solve the equation by allowing writing the equation directly and save as m-file, which will be later called and executed in SIMULINK. These procedures were used to simulate particle motion on combine harvester cleaning shoe, which works on the principle of oscillating sieves with additional air blowing (Zewdu, 2004). In order to solve the second order differential equations a simplification was used, let $x(1) = \frac{dr}{dt}$, then $\frac{dx(1)}{dt} = \frac{d^2r}{dt^2}$.

With initial conditions r = r_1 and $\frac{dr}{dt}$ = 0 at time zero, the moment the seed reached the disc surface, the numerical solution will be executed. The machine parameters and physical property values are presented in Tables (1) & (2). Depending on the disc radius, the residence time on the disc was determined and the radial velocity and tangential velocity at this moment taken, which will be used to calculate the discharge angle and discharge velocity of the particle just upon leaving the disc. The discharge angle and discharge velocity are used as initial conditions for the particles movement off-disc.

Table 1. Physical and aerodynamic properties of tef seed versus moisture content as used in the models

MC (%)	μ*	d_e (m)*	ρ_t (kg m^{-3})*
5.6	0.29	0.71*1e-3	1361.35
14.9	0.45	0.76*1e-3	1352.65
25.1	0.53	0.87*1e-3	1275.21

* Source: (Zewdu & Solomon, 2007)

Table 2: Other parameters used in the models

$g = 9.81$ m s^{-2}	N =540, 770, 1000 rpm
$\alpha = 0, 5, 10, 20°$	$r_1 = 0.1$ m
$\omega = (2\pi N/60)$ rad/s,	$\rho_A = 1.2$ kg m^{-3}
R = 0.5 m	h = 0.75 m

After leaving the disc, the particles motion in air begins. The fundamental forces involved, as particles are moving in air, are the weight of the particle and the aerodynamic drag. The aerodynamic drag force is a function of the relative velocity of the particle with air (v_r) the density of air (ρ_A) and the size of the particle as expressed by its frontal area (A_f). The drag force is related to properties of the particles and of the fluid through the following relationship (Mohsenin, 1986; West, 1972):

$$F_D = \tfrac{1}{2} C_d \rho_A A_f v_r^2 \tag{2}$$

where F_D is drag force in N, C_d is drag coefficient, ρ_A is density of air in kg m^{-3}, A_f is frontal area m^2 and v_r is relative velocity of air with a seed in m s^{-1}. The net force in the vertical direction on a particle moving in a fluid is the difference between the gravitational force and the resultant drag force and the net force in the horizontal direction is the aerodynamic drag force. As the air is assumed to be still, the relative velocity of the particle with respect to air equals the velocity of the particle. As the particle leaves the disc, the particle discharge velocity (v_d) and discharge angle (φ) are given in eqns. 3 and 4.

$$v_d = \sqrt{(\omega R)^2 + \left(\frac{dr}{dt}\right)^2} \tag{3}$$

$$\varphi = \sin^{-1}\left(\frac{R\omega}{v_d}\right) \tag{4}$$

Where v_d is discharge velocity in m s^{-1}, R is disc radius in m, ω is angular velocity of disc in rad s^{-1}, $\frac{dr}{dt}$ is radial velocity of particle in m s^{-1} and φ is discharge angle of the particle in (°). Mennel and Reece (1963) reported the following relationships as approximate solution in order to solve the particle motion in the air (Eqns. 5 & 6).

$$\frac{d^2 y}{dt^2} = -g - K\frac{dy}{dt}\sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} \tag{5}$$

$$\frac{d^2x}{dt^2} = -K\frac{dx}{dt}\sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} \tag{6}$$

$$K = \frac{3C_D\rho_f}{4\rho_t D_e} \tag{7}$$

Where *m* is mass of the particle in kg, *g* is gravitational acceleration in m s^{-2}, $\frac{d^2y}{dt^2}$ *and* $\frac{d^2x}{dt^2}$ *are* acceleration of the particle in the vertical and in the plane perpendicular to the vertical direction in m s^{-2}, respectively. In order to solve eqns. (5) & (6) the same procedure using MATLAB-SIMULINK as discussed above for on-disc particle motion was followed with the initial conditions, y(0) = h = 0.75 m, x(0) = 0.5 m = R, $\frac{dy}{dt}$ = $v_d\sin(\alpha)$, $\frac{dx}{dt}$ = $v_d\cos(\alpha)$. In order to solve these equations the value of K was essential, while calculating K, C_d was not available for tef seed in literature, and hence C_d was calculated after measuring the terminal velocity experimentally in laboratory as discussed in the following section.

3. DETERMINATION OF AERODYNAMIC PROPERTY OF TEF SEED

3.1 Sample Preparation

Tef grain was procured from Haramaya in Eastern Oromia, in Ethiopia. Tef grains' moisture content was determined using the convective air oven method with 105 °C ±2 (ASAE, 1994). The initial moisture content of tef grain was found to be 6.5%. In order to be able to measure the effect of moisture content on terminal velocity, tef grain was rewetted, by adding a calculated amount of water according to equation (8).

$$Q = \frac{W_i(M_f - M_i)}{100 - M_f} \tag{8}$$

Where, *Q* is the mass of water to be added in kg; W_i is the initial mass of the sample in kg; M_i is the initial moisture content of the sample in % w.b. and M_f is the final moisture content in % w.b. The samples were kept in refrigerator at 5°C (± 1) for 5 days for the moisture to distribute uniformly throughout the sample (Carmen, 1996). The moisture content after equilibration was determined at the time of each experiment using the method mentioned above. Accordingly moisture levels of 6.5, 12.5, 18.0, 24.8 and 30.1% w.b., respectively were obtained.

3.2 Measuring Terminal Velocities

Terminal velocity was measured in laboratory using the suspension air velocity method. A circular duct made of Plexiglas was used to see particles while suspended. A seed cleaner was modified and adopted in order to measure particle's suspension velocities. Air velocity was increased gradually till the particle was suspended. Air was supplied by a centrifugal fan driven by an a.c. motor. At one point just above the suspension point provisions were made in order to allow the digital hot wire anemometer to measure the speed of the air. The anemometer measures at 0.1 ms^{-1} division reading. For each level of moistened grain, ten replicate terminal velocity measurements were taken and the average is reported.

3.3 Calculation of Drag Coefficient

The drag coefficients were calculated using eqn. (9).

$$C_d = \frac{2mg}{\rho_A A_f v_t^2} \tag{9}$$

where $A_f = \pi \frac{LW}{4}$, L is length of particle in m and W is width of particle in m.

Table 3. Seed dimension and thousand grain mass as used in C_d calculation

MC (%)	TGM (g)	L (mm)	W (mm)
6.5	0.2576	1.15	0.59
12.5	0.2990	1.19	0.61
18.0	0.3370	1.22	0.63
24.8	0.3839	1.26	0.65
30.1	0.4205	1.30	0.66

4. RESULTS AND DISCUSSION

4.1 Terminal Velocity and Drag Coefficient of Tef Grain

Terminal velocity of tef grain increased linearly from 3.08 to 3.96 ms^{-1} as shown in *Fig 1* with increase in moisture content from 6.5 to 30.1% w.b. and drag coefficient of tef grain decreased from 0.83 to 0.65 with increase in moisture content from 6.5 to 30.1% *(Fig 2.)*. Both terminal velocity and drag coefficient were linearly related to moisture content as shown in Eqns. (10) & (11):

$$v_t = 0.0363MC + 2.8858 \tag{10}$$

$$C_d = -0.0074MC + 0.8627 \tag{11}$$

with R^2 values of 0.98 and 0.96, respectively. Where v_t is terminal velocity in m s^{-1}, C_d is drag coefficient and *MC* is moisture content % w.b.

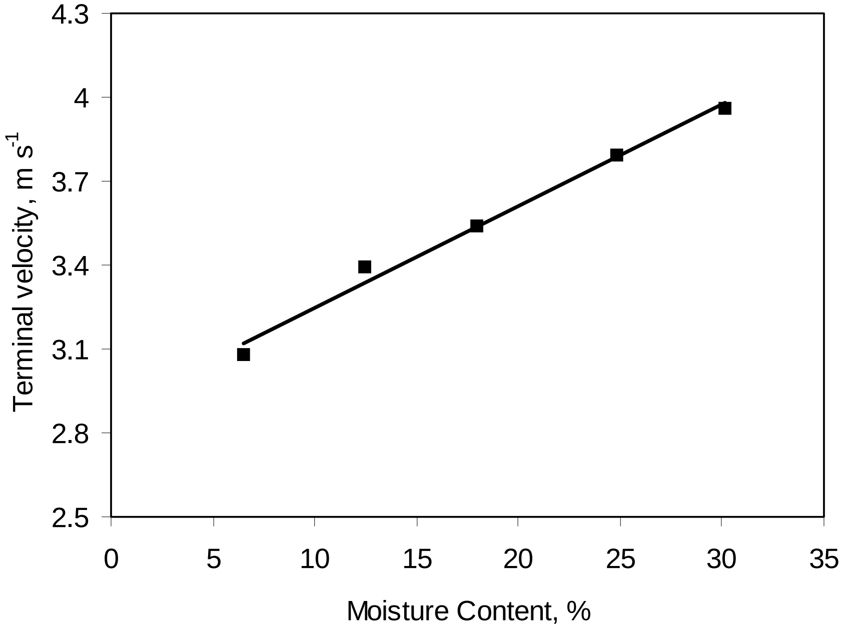

Fig. 1. Effect of moisture content on terminal velocity of tef grain

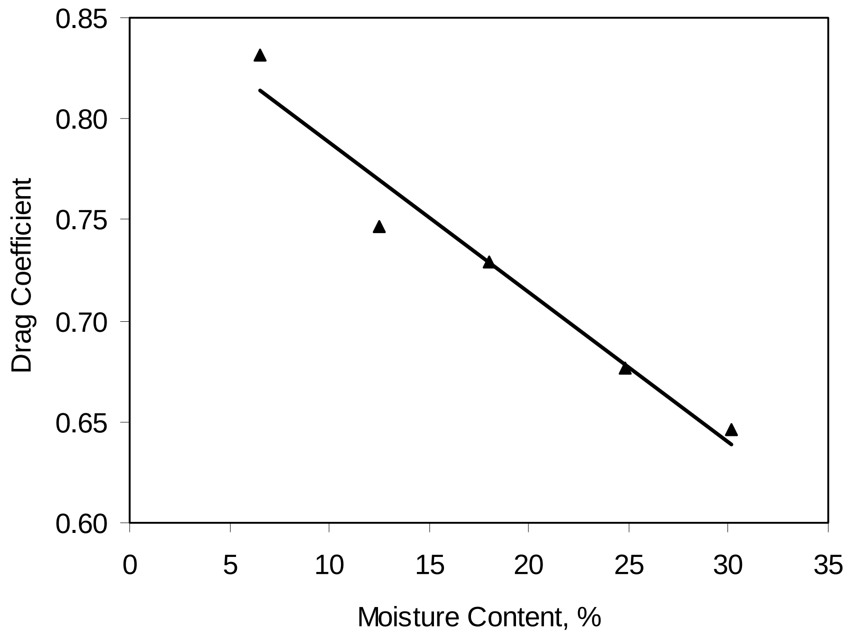

Fig. 2. Effect of moisture content on drag coefficient of tef grain

4.2 On-Disc Simulation of Particle Trajectories

The particle motion on the disc was thoroughly discussed by Hofstee, (1995), Olieslagers et. al., (1996), Aphale et. al., (2003), while working on simulation of fertiliser spreaders performance. Varying the moisture content of tef seed from 5.6 to 25.1% w.b. corresponds to change of coefficient of friction from 0.29 to 0.53. Here it was observed that the seed leaves the disc, considering disc radius of 0.5 m after 156.73 and 182.63 °, respectively, as shown in *fig. 3* which has a delay in the timing of throwing, as well the discharge velocity and discharge angle changes as the moisture content of the seeds change. With increasing coefficient of friction Hofstee, (1995) showed such a delay in time of throwing and having longer residence time. Koya and Faborode (2006) utilised this property of a rotating disc, which depending on varying parameter of particle physical property and settings of different machine parameters to separate palm kernels from shells, in which they found the possibility to throw the shell at delayed timing which could be used to separate it from the palm kernel at different locations around a rotating disc. In order to utilise the application of variable rate of fertiliser to suit the fertiliser demand of the specific site Olieslagers et. al. (1996) and Dintwa et. al. (2004) reported the possibility of varying the discharge point by varying the release point of the fertiliser on the disc and the disc's rotating speed. Hence depending on the physical properties of the seeds and as well on machine parameters the release point and the discharge velocity can be altered to suit demanded coverage and throwing distance.

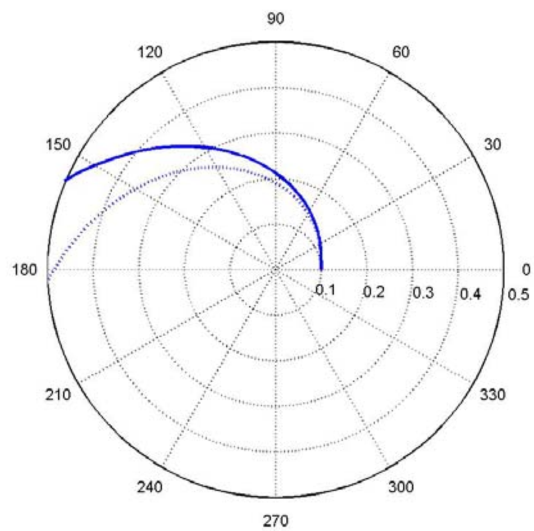

Fig. 3. Particle trajectory on flat disc with a varying moisture content of tef seed,
— MC= 25.1% & …MC=5.6%, N=770 rpm, r_1=0.1, R = 0.5 m

4.3 Off-Disc Simulation of Particle Trajectories

Just at the point of leaving the rotating disc the seed will have certain discharge velocity and discharge direction as well the position of the seed releasing point above ground in the vertical direction and from the disc centre in the radial direction. These release situations are important as initial conditions to begin the motion of the particle in air. The solutions using equations (5) and (6) yields a particle trajectory after leaving the disc up to a point where the height of particle above ground equals zero. Investigations of particle motions in air is mostly investigated in grain cleaning operations in order to predict the particle trajectory and falling point of different crop materials such as grain and material out of grain in order to put demarcation between valuable and less valuable crop products, so that machine design and adoption could follow easily. Particle motion model developments through a moving air was undertaken in order to dimension grain classifier (Adewumi *et al*., 2006), modelling grain cleaning process (Simonyan *et al*., 2006), horizontal trajectory of particles (Gorial & O'Callagan, 1991b), trajectory calculations in vertical ducts (Farran & Macmillan, 1979; Gorial &O'Callaghan, 1991a).

Projected distance and particle trajectory of tef seed with different moisture content after leaving the spinning disc was simulated continuing its motion of on-disc motion is shown in *fig 4*.

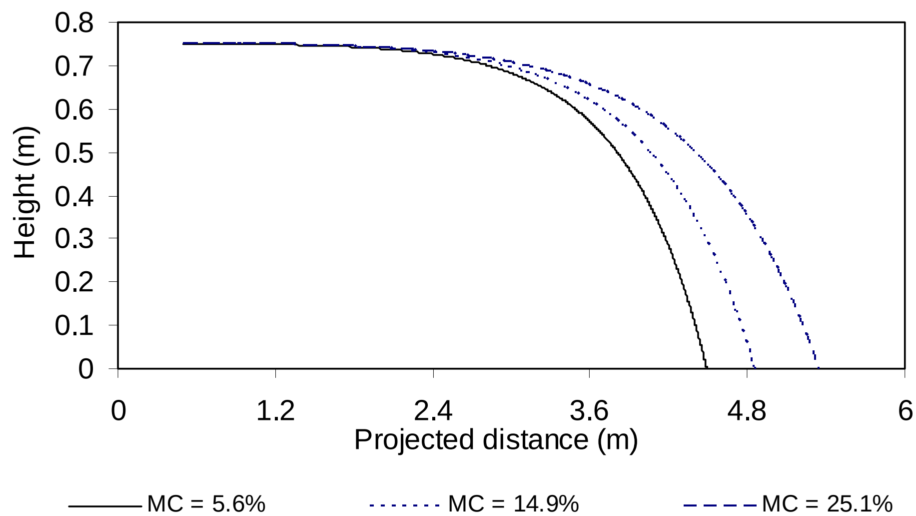

Fig. 4. Height versus projected distance of tef seed off disc with varying moisture content, N =770 rpm, r_1 = 0.1 m, R = 0.5 m h= 0.75 m

The simulated result shows that, even if the discharge velocity upon leaving the disc was higher for a seed with lesser moisture content (lower coefficient of friction), the projected distance was longer for a seed with higher moisture content. This was due to the fact that even if the initial velocity was high at the beginning, the associated change in the physical and aerodynamic property of the seeds, as the seed gets moist, makes the seeds heavier and also the equivalent diameter increases. The increase in weight and equivalent diameter of seeds result in lower coefficient of drag force. As a result particles with higher moisture content travel longer distance.

The effect of increased disc radius, height of disc above ground, feed radius, cone angle of disc and angular velocity of disc are considered to affect the particle trajectory on and off disc and the projected distance a particle can fall (Hofstee, 1995, Aphale, 2003, Olieslagers, 1996). It is shown in fig. 5 and fig. 6 how cone angle (α) and angular velocity (ω) of spinning disc affected particle trajectory and projected distance of tef seed dropping in field.

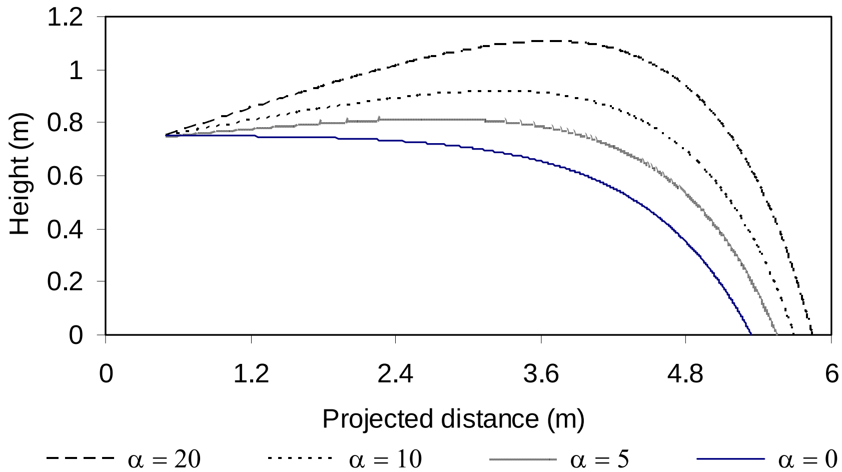

Fig. 5. Height versus projected distance of a tef seed off-disc with varying cone angle, α (°), N = 770 rpm, R = 0.5 m, r_1 = 0.1 m, MC = 25.1%

Increasing cone angle is associated with increase in the time the particle can stay air borne before hitting the ground. Even if a particle can move in the horizontal direction, if it comes in contact with the ground, the particles motion will be forced to halt. The increase in cone angle attributes for a particle stay air borne which results in covering longer distance. But the increase in projected distance will not remain increasing proportionally since the particle will lose its velocity along the throwing projected distance, hence one can see from *fig. 5* the increase in projected distance shrinks with further increase of cone angle from 0 to 10 and further to 20°.

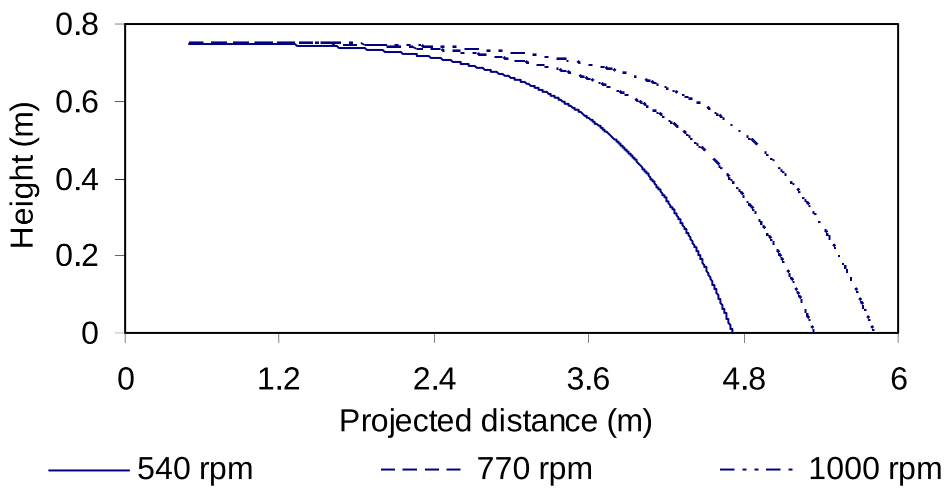

Fig. 6. Height versus projected distance of tef seed as affected by disc revolution per minute (N), α =0°, R = 0.5 m, r_1 = 0.1 m, MC = 25.1 %, h = 0.75 m

In *fig. 6* one can observe the increase in projected distance and the changed particle trajectory. The increase in rotational speed of a rotating disc has a direct effect on the tangential velocity as this is the product of radius of disc and angular velocity of disc. The contribution of the radial velocity to the centrifugal force and the coriolis force is also noticed in their relationships. Hence they do affect the radial velocity to which could have an influence on the discharge parameters.

The result of the above investigation shows the particle distribution on the ground can be altered by adjusting the different machine parameters or employing certain form of a spinning disc. The use of flat or cone shaped discs, the change in coefficient of friction which resulted with a change in moisture content of tef seed and the manipulation of disc rotational speed had effect on broadcast seeding.

Varying the different machine parameters may help the seed distribution to reach from one side of the disc to the other side to cover the needed area to be covered by the broadcaster in one pass. In this study, it was tried how far the small seed of tef can be thrown off a disc by utilising the theory from fertiliser distributor spinning discs depending on some properties of tef seed and through varying the settings of the broadcasting seeder. As a continuation to this theoretical investigation in future, a job of calibration considering rate of seeding and forward speed and practical laboratory tests should be run to compare the match between measured and calculated particle motion and distribution.

5. CONCLUSIONS

Through this investigation of tef seed broadcasting, the following conclusion was reached:

- As drag coefficient of tef seeds was essential in the calculation of particle off-disc motion, terminal velocities were measured for tef (*Eragrostis tef* (Zucc.) Trotter) seed. Tef seeds' terminal velocity increased linearly from 3.08 to 3.96 m s^{-1} with increase in moisture content from 6.50 to 30.1% wet basis (w.b.). The drag coefficients for tef seed were calculated from the experimentally obtained terminal velocities. The drag coefficient of tef seed decreased with increase in moisture content.
- After developing a mathematical relationship, simulation of particle trajectories on and off disc of a spinning disc was undertaken. The projected distance increased with increase in moisture content of seed, spinning disc revolution per minute, inclination of disc with the horizontal.
- The increase in moisture content was associated with increase in coefficient of friction, which do have effect on on-the disc particle motion and the increase in moisture content has influence also on thousand seed mass, particle size, sphericity, particle density and coefficient of drag force which affected off-disc particle trajectory.

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7. REFERENCES

Adewumi, B.A., A.S. Ongolowo and C. O. Ademosun (2006). Investigating particle trajectory as a parameter for selecting the dimensions of cross flow grain classifier. *Agricultural Engineering International*: the CIGR Ejournal. Manuscript FP 06 007 VIII

Aphale, A., N. Bolander, J. Park, L. Shaw, J. Svek and C. Wassgren (2003). Granular fertiliser particle dynamics on and off a spinner spreader. *Biosystems Engineering*, 85(3): 319-329

ASAE (1994). *ASAE Standards* S352.3-moisture measurement-ungrounded grains and seeds. In:ASAE Standards 1994, 469 St. Joseph, MI: ASAE

Ball, B. C. (1986). Cereal production with broadcast seed and reduced tilage: a review of recent experimental and farming exprience. *J. Agri. Eng. Res*. 35(2), 71-95

Bultosa G and J. R. N. Taylor (2004). Tef. In: Wrigley, Corke, H, Walker, C, Encyclopaedia of Grain Science, Elsevier pp 281-289

Carmen K (1996). Some physical properties of lentil seeds. *J. Agri. Eng. Res.*, 63: 87-92.

Cunningham, F. M. (1963). Performance charactorstics of bulk spreaders for granular fertiliser. *Transactions of the ASAE*, 6: 108-114

Dintwa, E., P.V. Liedekerke, R. Olieslagers, E. Tijskend and H. Ramon (2004). Modell for simulation of particle flow on a centrifugal fertiliser spreader. *Biosystems Engineering*. 87(4): 407-415

Dobler, K. and J. Flatow (1968). Berechnung der Wuerfgaenge beim Schleuderduengerstreuer (Calculation of the particle trajectories on spinning fertilser spreader), *Grundlage der Landtechnik* 1968, 18(4): 129-164

Eichhorn, H. (1995). *Landtechnik* (Agricultural Engineering), 7th Edn. Eugen Ulmer.

Farran, I. G. and R. H. Mcmillan (1979). Grain-chaff separation in a vertical air stream, *J. Agric. Engng. Res.* 24: 115-129

Gorial, B. Y. and J. R. O'Callaghan (1990). Aerodynamic Properties of Grain/Straw Materials, *J.Agric. Engng. Res.* 46: 275-290

Gorial, B. Y. and J. R. O'Callaghan (1991a). Separation of grain from straw in a vertical air stream, *J.Agric. Engng. Res.* 49: 111-122

Gorial, B. Y. and J. R. O'Callaghan (1991b). Separation of particles in a horizontal air stream, *J.agric. Engng. Res.* 49: 272-284

Hall, M. H.(1992) Prairie grass, Agrnomy Facts 39. College of Agriculture, cooperative extension http://cropsoil.psu.edu/extension/facts/agfact39.pdf

Henning, J and R. Risner (1993). Orchardgrass. Universitry of Missouri Colombia Extension http://muextension.missouri.edu/explore/agguides/crops/g04511.htm

Hofstee, J.W. (1995). Handling and spreading of fertilisers: Part 5, the spinning disc type fertiliser spreader. *J. Agric. Engng. Res.* 62: 143-162

Hunt, D. (1983). *Farm power and machinery management*, 8th edn, Iowa State University Press, Ames

Ketema, S (1997). Tef *(Eragrostis tef (Zucc.) Trotter). Promoting the Conservation and Use of Under-Utilised Neglected Crops*, 12, IPGRI, Italy

Koya, O.A. and M.O. Faborode (2006). Separation theory for palm kernel and shell mixture on a spinning disc. *Biosystems Engineering* 95(3): 405-412

Mennel, R. M. and A. R. Reece (1963). The theory of the centrifugal distributor. III: Particle trajectories. *J. Agric. Engng. Res*. 7(3): 78-84

Mohsenin N N (1986). *Physical properties of plant and animal materials* (2nd ed.), Gordon and Breach Science Publishers, New York

Olieslagers, R, H. Ramon and J. De Baerdemaeker (1996). Calculation of fertiliser distribution patterns from a spinning disc spreading by means of a simulation model. *J. agric. Engng Res*. 63: 137-152

Patterson, D.E. and Reece, A. R. (1962). The theory of centrifugal distributors. I: motion on the disc, near-center fed*. J . Agric. Engng. Res.* 7(3): 232-240

Peterson, P. (2006). *Seeding grasses with alfalfa: the 'old' idea makes cent$ today*. Minnessota eNews. University of Minnessota Extension Service, http://www.extension.umn.edu/cropEnews/2006/06MNCN13.htm

Reints, R. E. Jr. and R. R. Yoerger (1967). Trajectories of seeds and granular fertilisers. *Transactions of the ASAE*, 10(2): 213-216

Schmidt, W. (1995).Canola production in Ohio, Ohio State University Extension http://ohioline.osu.edu/agf-fact/0109.html

Simonyan, K.; Y. Yiljep, and O. J. Mudiare. 2006. Modelling the cleaning process of a stationary sorghum thresher. *Agricultural Engineering International*: the CIGR Ejournal Manuscript PM 06 012 Vol. VIII.

Sitkei, G. (1986). *Mechanics of agricultural materials*. Akademiai Kiado, Budapest

Speelman, L. (1975). The seed distribution in band sawing of cereals. *J. Agric. Engng. Res*. 20: 25-37

West, N L (1972). Aerodynamic force predictions, *Transactions of the ASAE*, **15** (3), pp 584 - 587

Zewdu, A.D. (2004). *Untersuchungen zur Leistungssteigerung der Reinigungsanlage eines Maehdreschers durch zusaetzlichen Querschwingungen* (Investigations into performance improvement of combine cleaning shoe through additional lateral oscillations), PhD Diss. Technical University of Dresden, Germany. 125 pp.

Zewdu, A D and W. K. Solomon (2007). Moisture-dependent physical properties of tef seed, *Biosystems Engineering*, 96(1): 57-63 doi: 10.1016/j.biosystemseng. 2006.09.008

8 NOMENCLATURE

A_f	frontal area, m^2
C_d	drag coefficient
d_e	equivalent sphere diameter, mm
F_D	drag force, N
g	gravitational acceleration, m s^{-2}
h	height of disc above ground
L	length of grain, mm
m	mass of particle, kg
MC	moisture content of grain sample, % w.b.
M_f	final moisture content, % w.b.
M_i	initial moisture content of the sample, % w.b.
Q	mass of water to be added during rewetting, kg
r	radial direction
r	radial position of a particle
R	radius of disc
r_1	feed radius
R^2	coefficient of determination
t	time, s
TGM	thousand grain mass
v_d	discharge velocity, m s^{-1}
v_r	relative velocity of air with particle, m s^{-1}
v_t	terminal velocity, m s^{-1}
W	width of grain, mm
W_i	initial mass of the sample to be rewetted, kg
x	is a direction perpendicular to vertical direction in the horizontal plane
y	vertical direction
α	cone angle of a disc
φ	discharge angle (deg.)
ρ_A	density of air, kg m^{-3}
ρ_t	density of particle, kg m^{-3}
ω	angular velocity, rad/