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A simulation of the influence of spinning on the ballistic flight of spherical fertiliser grains

S. Cool [a,b,*], J. Pieters [b], K.C. Mertens [a], B. Hijazi [a], J. Vangeyte [a]

[a] Technology and Food Science Unit, Institute of Agricultural and Fisheries Research (ILVO), Burg. Van Gansberghelaan 115 bus 1, 9820 Merelbeke, Belgium
[b] Ghent University, Department of Biosystems Engineering, Faculty of Bioscience Engineering, Coupure Links 653, 9000 Ghent, Belgium

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A B S T R A C T

A three dimensional ballistic model was developed to investigate the effect of spin on the trajectory of fertiliser grains in the air and their subsequent landing position. In addition to the gravitational- and drag force, also the Magnus force and drag torque were included in the model. Because of the considerable uncertainty regarding the spinning velocity of the grains, initial conditions for the ballistic model were simulated using a newly derived analytical model that describes motion on a concave disc. In both models, grains were presumed to be perfectly spherical. Simulations indicated a major effect on the landing positions of individual grains although the magnitude was dependent on fertiliser- and spreader characteristics. Deviations up to 33% of the total travelled distance in the direction of the initial horizontal velocity vector were found. Furthermore, the Magnus force clearly causes a deflection of the trajectory in the horizontal plane.

1. Introduction

In Europe, most mineral fertiliser spreading is performed using centrifugal spreaders (Van Liedekerke et al., 2009; Hijazi et al., 2011). This type of spreader is generally equipped with two rotating discs upon which two or more vanes are mounted. During spreading, fertiliser grains fall from the hopper through an adjustable orifice onto the disc, come into contact with the vanes and are accelerated before being ejected into the air. Various parameters influence the spread pattern of a centrifugal spreader (Olieslagers et al., 1996; Cointault and Vangeyte, 2005). As a result, this type of spreader must be calibrated to assure a homogeneous distribution in the field which is important to maximise profit for the farmer, but also to reduce negative ecological effects such as eutrophication (Tissot et al., 2002; Hijazi et al., 2010). In the past, collection methods have been used to determine the spread pattern of centrifugal spreaders (Lawrence and Yule, 2005). Standardised testing protocols describe how the tests should be performed and interpreted. Because the spatial distribution on the ground is measured manually using collection trays, the tests are complex and very labour intensive and are therefore not widely used in practice (Grift et al., 1997; Cointault et al., 2002; Vangeyte et al., 2007).

Recently "predict rather than collect" systems have been developed. By using an analytical model or a numerical solution of differential equations that describe motion of individual fertiliser particles on the disc (Inns and Reece, 1962; Patterson and Reece, 1962; Cunningham, 1963; Hofstee, 1995; Olieslagers et al., 1996; Aphale et al., 2003; Dintwa et al., 2004; Villette et al., 2005), Discrete Element Method (DEM) models (Van Liedekerke et al., 2006; Van Liedekerke et al., 2009) or using a hybrid approach in which ejection parameters such as speed, direction and size are measured (Cointault et al., 2002; Reumers et al., 2003; Hijazi et al., 2011; Vangeyte, 2013), the landing positions of the grains and corresponding spread patterns can be simulated using a ballistic model.

Until now, two-dimensional ballistic models have been used to simulate the trajectory in the air. Because only the gravitational- and drag force are considered in these models, the horizontal projection of the predicted trajectory is a straight line. The gravitational force $\vec{F}_g$ [N] is calculated as follows:

$$\vec{F}_g = m\vec{g} \tag{1}$$

With: m the mass of the grain [kg], $\vec{g}$ the gravitational acceleration [m s^{-2}].

* Corresponding author at: Burg. Van Gansberghelaan 115 bus 1, 9820 Merelbeke, Belgium. Tel.: +32 9 272 28 21.

E-mail addresses: simon.cool@ilvo.vlaanderen.be (S. Cool), jurgen.vangeyte@ilvo.vlaanderen.be (J. Pieters), koen.mertens@ilvo.vlaanderen.be (K.C. Mertens), bilal.hijazi@ilvo.vlaanderen.be (B. Hijazi), jan.pieters@ugent.be (J. Vangeyte).

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Nomenclature

Symbol	Explanation SI unit
A	projected surface area [m^2]
C_d	drag coefficient [–]
C_m	Magnus coefficient [–]
$C_{d,r}$	drag coefficient corrected for spin [–]
$C_{d,nr}$	drag coefficient not corrected for spin [–]
C_ω	drag torque coefficient [–]
d	diameter of particle [m]
$\vec{F}_c$	centrifugal force [N]
$\vec{F}_d$	drag force [N]
$\vec{F}_{fd}$	friction force exerted by the disc [N]
$\vec{F}_{fv}$	friction force exerted by the vane [N]
$\vec{F}_g$	gravitational force [N]
$\vec{F}_m$	Magnus force [N]
F_t	force exerted by the vane [N]
$\vec{g}$	gravitational acceleration [ms^{-2}]
m	mass of particle [kg]
r	grain radius [m]
r_0	initial radial starting distance of particle from disc centre [m]
R	radius of the disc [m]
Re	Reynolds number [–]
Re_ω	rotational Reynolds number [–]
T	drag torque [N m]
$\vec{v}$	translational velocity vector of particle [m s^{-1}]
V	volume of particle [m^3]
(u, v, w)	coordinates of fertilizer particle in original coordinate system [m]
(x,y,z)	coordinates of fertilizer particle in rotated coordinate system [m]
α	horizontal angle at which the particle leaves the disc [°]
β	cone angle of the disc [°]
μ	friction coefficient [–]
μ'	dynamic viscosity of air [kg m^{-1} s^{-1}]
ρ	true density of particle [kg m^{-3}]
ρ_{air}	density of air [kg m^{-3}]
ρ_{medium}	density of a medium [kg m^{-3}]
$\vec{\omega}$	spinning velocity vector of particle [rad s^{-1}]
ω_{disc}	rotational speed of disc [rad s^{-1}]

The following formula is used to calculate the drag force $\vec{F}_d$ [N] working on a particle in translational motion in the air:

$$\vec{F}_d = -C_d \frac{A\rho_{air}}{2} |\vec{v}|\vec{v} \tag{2}$$

With: C_d the drag coefficient [–], A the projected surface area [m^2], ρ_{air} the density of air [kg m^{-3}], $\vec{v}$ the velocity vector of the grain [m s^{-1}].

The dimensionless drag coefficient is often expressed as a function of the Reynolds number because the drag force depends on the velocity of the particle relative to the fluid flow, the size of the particle, the fluid density and the fluid viscosity. Furthermore, the drag coefficient also accounts for the effect of the shape of the particle on the drag force. Some authors assume fertiliser grains to be spherical and therefore make use of well-established empirical equations (Olieslagers et al., 1996; Villette et al., 2010; Grift and Hofstee, 2002), while others use experimental methods to calculate this coefficient. The drag coefficient can be determined by measuring the terminal velocity of individual particles in a fluid (Aphale et al., 2003; Gindert-Kele, 2005) or in an elutriator, i.e. a vertical wind tunnel (Hofstee and Huisman, 1990). Alternatively, calibration methods can be used based on movement of particles in fall tests (Grift et al., 1997; Walker et al., 1997; Grift and Hofstee, 2002; Villette et al., 2008). The projected surface area is often calculated by using the diameter of the equivalent sphere, i.e. the sphere with the same volume and density as the fertiliser grain.

No modelling or hybrid approach has yet succeeded in perfectly predicting the spread pattern of a centrifugal spreader (Olieslagers et al., 1996; Reumers et al., 2003; Dintwa et al., 2004; Villette et al., 2008; Vangeyte, 2013). Discrete Element Method (DEM) models (Van Liedekerke et al., 2006; Van Liedekerke et al., 2009) show promising results for short vanes and a reduced disc speed (300 rpm). However, increasing deviations were found when the disc rotational speed was increased to 400 rpm. It should be noted that values up to 1000 rpm are used in practice to obtain large working widths (> 30 m). It is clear that uncertainties in models calculating motion on the disc and ballistic models as well as errors in methods to measure initial conditions of particles in hybrid methods can introduce deviations between the real and predicted spread pattern, and therefore do not allow proper calibration of centrifugal spreaders. Due to heterogeneity of the fertiliser and various parameters that influence the spread pattern, as well as flexibility in the physiology of crops, small deviations are tolerated. For transverse spread patterns, i.e. the distribution of fertiliser perpendicular to the driving direction, a coefficient of variation of 15% and 25% is tolerated for nitrogenous and non-nitrogenous fertilisers respectively (Lawrence and Yule, 2005). For the two-dimensional static spread pattern, there is no general agreement yet on a universal parameter to quantify the difference and acceptable tolerance limits.

Considering the working principle of centrifugal spreaders, it is possible that the fertiliser grains obtain spin by friction with the disc and/or the vanes. From research (predominantly on sports ball aerodynamics) it is known that concurrent spinning and translational movement of a projectile causes alteration in the trajectory in the air, known as the Magnus effect (Mehta and Pallis, 2001; Craig et al., 2006). The projectile creates a whirlpool of rotating air about itself, increasing the velocity of the air at one side and decreasing it at the other. According to Bernoulli's principle, this creates a pressure difference resulting in a force, the Magnus force. Zou et al. (2007) investigated the effect of this force on the trajectory of saltating sand grains. An increase in travelled distance up to 24.9% was found, dependent on the shear velocity (0.67–0.87 m s^{-1}), the lift-off angle (15–60°) and the rotational speed (1260–5030 rad/s) of the grains (0.2–0.3 mm in size).

As a result, it is possible that ballistic models for fertiliser particles that do not take this effect into account are responsible for the inaccuracy of the "predict rather than collect" methods mentioned above (Liedekerke, 2007). In literature, a few models have been developed that account for particle spin on a spreading disc (Patterson and Reece, 1962; Aphale et al., 2003). Only the case of a non-concave disc with radial straight vanes was investigated. The effect of the Magnus force and spin in general on the trajectory of fertiliser particles in the air has not been investigated in literature yet.