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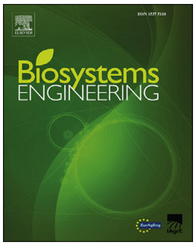

Research Paper

Determining the effect of wind on the ballistic flight of fertiliser particles

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With the increase in working widths for applicators, granular fertiliser particles spread by centrifugal spreaders have more extensive airborne trajectories. In the field, particles can be subjected to wind which can cause their trajectories to change. In this paper, a 3D ballistic model was developed describing the motion of fertiliser particles taking wind effects into account. The physical properties of eight commonly used fertiliser types were determined: particle density, size distribution and angle of repose. X-ray micro computed tomography was used to determine the shape of the particles and estimate the corresponding drag coefficient. Using these parameters in the newly derived ballistic model, the effect of wind on individual fertiliser trajectories was quantified for each fertiliser type. Three wind directions (head- tail- and crosswind) were analysed for two windspeeds: 3 and 6 m s^{-1}. The magnitude of the effect was strongly dependent on the physical properties of the fertiliser type, the windspeed and wind direction. Simulations showed that a windspeed of 3 m s^{-1} already can affect the landing position of individual fertiliser particles by several metres. Generally, particles with lower density, smaller size and a more irregular shape were more sensitive to wind.

1. Introduction

Precision agriculture requires application of the right amount of fertiliser at the right place at the right time. The centrifugal fertiliser spreader is most commonly used machine for the application of granular fertiliser, because of its robustness, simplicity and low cost (Villette, Cointault, Piron, Chopinet, & Paindavoine, 2008a). Over recent years it has evolved towards

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Nomenclature

a	Acceleration of particle, m s^{-2}
A_{eq}	Surface area of equivalent sphere, pixels
$A_{particle}$	Surface area of particle, pixels
A_{proj}	Projected surface area of particle, m^2
CT	Computed tomography, –
d	Particle diameter, m
D_e	Equivalent diameter, pixels
F_d	Drag force, N
F_g	Gravitational force, N
m	Particle mass, kg
Re	Reynolds number, –
t	Time, s
v	Particle velocity, m s^{-1}
V	Scanned particle volume, voxels
v_{rel}	Relative particle velocity, m s^{-1}
V_w	Wind velocity, m s^{-1}
μ_{air}	Dynamic viscosity of air, kg m^{-1} s^{-1}
ρ	Particle density, kg m^{-3}
ρ_{air}	Density of air, kg m^{-3}
ϕ	Sphericity, –

using larger working widths to increase productivity and decrease costs (Grafton, Izquierdo, Yule, Willis, & Manning, 2015a). Due to the pattern shape of the fertiliser distribution perpendicular to the machine's driving direction (i.e. the transverse spreading pattern), overlap is required between subsequent swaths. The spreading width, or width over which particles are deposited, is larger than the distance between these swaths and widths can reach to over 45 m. This increased airborne distance for particles results in more error-sensitive spreading patterns. Poor performance of spreaders can be caused by fertiliser quality, erroneous spreader settings and lack of calibration (Yule, 1996; Grafton et al., 2015a; Hijazi et al., 2014; Tissot, Miserque, Mostade, Huyghebaert, & Destain, 2002). However, when the equipment is properly calibrated, external factors play a far more important role. Wind has a direct effect on the trajectory of fertiliser particles from the spreaders. Particularly in the case of centrifugal spreaders, due to their large spreading width; wind can cause deviation in the anticipated particle trajectories, resulting in local over- and under-application of nutrients thereby leading to undesired economic and ecological effects (Søgaard & Kierkegaard, 1994). A field experiment by Grafton, Yule, Robertson, Chok, and Manning (2015b) illustrated that there was a large overall effect from crosswind on the transverse spreading pattern of centrifugal spreaders. The effect on the individual trajectories and the interaction with particle physical properties however remains unclear. The hypothesis behind this work is that this could be addressed by modelling the ballistic flight of the particles.

A 3D ballistic model incorporating the effects of wind was developed. The physical particle properties of eight different fertiliser types were determined, including shape which was computed by means of X-ray micro-computed tomography (CT). Simulations with the ballistic model were carried out to quantify the effect of wind on individual fertiliser trajectories.

2. Materials and methods

2.1. Ballistic model

The motion of a fertiliser particle moving in non-moving air can be described using Newton's second law:

$$m\frac{d\vec{v}}{dt} = \vec{F}_d + \vec{F}_g \tag{1}$$

with: m and v resp. the mass [kg] and the velocity [m s^{-1}] of the particle, F_g the gravitational force and F_d the drag force [N]

The drag force can be calculated as follows:

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

with: C_d the drag coefficient [–], A_{proj} the projected surface area of the equivalent sphere [m^2], ρ_{air} the density of air [kg m^{-3}]

The drag coefficient depends on fluid and particle properties which are expressed in the dimensionless Reynolds number.

$$Re = \frac{d\,|\vec{v}|\,\rho_{air}}{\mu_{air}} \tag{3}$$

with: d the diameter [m] μ_{air} the dynamic viscosity [kg m^{-1} s^{-1}]

In literature, some authors regard fertiliser particles as ideal spheres (Antille, Gallar, Miller, & Godwin, 2015; Aphale et al., 2003; Cool, Pieters, Mertens, Hijazi, & Vangeyte, 2014) and therefore used well-established equations for the drag coefficient in relation to the Reynolds number. Others determined the drag coefficient experimentally using a horizontal (Parkin, Basford, & Miller, 2005) or vertical wind tunnel or fall tests (Grift, Walker, & Hofstee, 1997; Hofstee, 1992; Kweon & Grift, 2006) The main drawback of these techniques is that the terminal velocity is used to determine the drag coefficient which, for most particles, is much smaller than the velocity of fertilizer particles reached during the spreading process. While some fertiliser types can have a spherical shape, most particles deviate from this ideal shape. In this paper, the following equation was used to determine the drag coefficient as a function of the Reynolds number and the sphericity factor (Chien, 1994):

$$C_d = \frac{30}{Re} + 67.289e^{-5.03\phi} \tag{4}$$

with: ϕ the sphericity factor [–]

To model the effect of a horizontal wind flow, the drag force should be calculated based on the relative motion of the particle to the air.

$$\vec{v}_{rel} = \vec{v} - \vec{v}_w \tag{5}$$

With: v_{rel} the velocity of the particle relative to the air, v_w the wind velocity [m s^{-1}]

Based on Eqs. (1) (3) (4) and (5), the following set of differential equations can be derived, describing motion in a three-dimensional Cartesian coordinate system (x,y,z) with z perpendicular to the ground surface.