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Modelling the spray drift by a modified Gaussian tilting plume model

By C STAINIER[1], V ROBAYE[1], B SCHIFFERS[2] and F LEBEAU[1]

[1]*Unité de Mécanique et construction,*
[2]*Laboratoire de phytopharmacie, Gembloux Agricultural University, Passage des Déportés 2, B-5030 Gembloux, Belgium*

Summary

The increased concern about environmental effect of pesticides use has resulted in abundant research on spray drift. Spray drift modelling has been developed to get a better understanding of the parameters involved and better estimation of the off-target spray deposit. Two groups of models have received extensive attention:

- Random-walk and computational fluid dynamics (CFD) models have been used to predict the effect of: nozzle height, spray pressure, wind speed,... and were validated with wind tunnels trials.
- Statistical models based on field trials results have been developed to estimate off-target spray deposit for different sprayers in various environmental conditions.

A third group, Gaussian dispersion models, have received early attention in spray drift modelling but are not so popular, despite their international success in environmental pollution modelling. The adaptation of such a model to ground spraying is proposed. The nozzle droplet size distribution measured with a Malvern laser particle analyser is used to divide the nozzle output into several size classes. The spray deposit (or footprint) of each diameter class is computed. The summation of these footprints results in the global drift of the nozzle. The methodology is applied to derive the drift of a flat fan nozzle located in a wind tunnel and the potential of this approach is discussed.

Key words: Drift, Gaussian tilting plume model, spray nozzle, droplet spectra

Introduction

Spray drift modelling has received intensive attention during last decades as pesticide application has remained necessary to produce agricultural products of quality at an affordable price while increased concern has been raised about their environmental impact.

The choice of model depends on the specific objectives. Models based on fluid dynamics equations are mainly used to give information about effect of parameters hardly highlighted in experiments because of deposits variability and allow a better physical understanding of the drift phenomenon. If CFD models are more complex than Random-walk ones, both allow good quantitative prediction in wind tunnel condition. However they fail to furnish good field drift prediction as complex input such as wind direction and nozzle movement representative of real field conditions are difficult to specify. Statistical models furnish field observation based quantitative drift predictions but their results are doubtful outside the limits of the application conditions prevailing during the field trials. Dispersion models are based on sound statistical theoretical basis than make them successful in many outdoor applications and furnish a simple analytical solution that needs much less computational power than CFD or Random walk models. However, simplistic hypothesis used when estimating agricultural nozzle drift give inaccurate results. As a matter of fact, these models give similar result to CFD or random walk models when uniform diameters and speed of droplets are considered, but the results are quite different in the case of a complex spray generated with agricultural nozzles due to the large droplet size spectra and speed. The objective of this paper is to evaluate some adaptation to the Gaussian tilting plume model to better take into account the characteristics of the spray application, as those model have proved their efficiency in aerial pollution dispersion

Literature Review

Four different model types are used to predict spray drift:

"Random-walk" (or Markov type) models

Some research groups have been developed their own drift modelling software based on the Random-walk approach. These models describe each single droplet pathway to compute drift. Each droplet outputs from the nozzle with an initial speed function of the spraying pressure and a direction depending on the spray distribution close to the nozzle (Smith & Miller, 1993). The droplet pathway is computed based on Newton's second law using gravitational forces that are constant and air friction forces that depend on air and droplet speed. In addition to wind speed, often taking into account the logarithmic profile, models may include the air flow created by the droplets. Picot *et al.* (1986) add turbulence as a random wind speed and direction stochastically dependent on atmospheric stability to mean wind speed. Cox *et al* (2000) take into account the crop shape dependent turbulence when droplets reach the leaves. Droplet evaporation was computed to continuously reduce its diameter along the trajectory (Holterman *et al.* 1998). The global drift is computed as the result of the addition of many droplets pathway. A few thousands of droplets was found representative (Holterman *et al.*, 1997), (Miller & Hadfield, 1989), (Hobson *et al.*, 1993). These models are mainly unidimentionnal and sometimes bidimentionnal close to the nozzle.

Computational fluid dynamics

Some commercial fluid dynamics software, mainly Fluent and CFX, were used to model spray drift in controlled conditions. Many variables (Zhu *et al.*, 1994) are used by these models as they include the latest fluid mechanic theories to compute the droplet pathway, what is their main difference with random-walk ones. Even if these models are able to compute local geometry and interaction between close droplets (Loth, 2000), global drift results are quite similar to Markov type models due to gravity and friction forces that are much significant on droplet behaviour than the other parameters. Reichard *et al.* (1992 *a,b*) verified the validity of CFD model as well as the influence of parameters such as wind, relative humidity, spray height, in wind tunnel using a single size droplet generator.

Statistical models

Different sophistication levels of statistical models exist but all are based on database of multiple field drift measurements (Smith *et al.*, 2000). The quick and high predictive level for many outdoor applications conditions is the main advantage of this experimental approach. But the main difficulty is to obtain the huge amount of good quality measurements needed as well as the high variability of the drift than can be scaled up from four to 16 times. In general, statistical models are based on multiple regressions to study independent parameters effect on deposits. That kind of model is used by the BBA in Germany (Herbst & Ganzelmeier, 2000) and EPA in the United-States (Teske *et al.*, 1997)

Gaussian models (dispersion model)

Gaussian models are usually used in the case of gas dispersion and atmospheric pollution. With few adaptations, this kind of modelling can be used for particle diffusion where the wind direction is considered as the centre line of the smoke cloud. On the perpendicular direction of the wind, the distribution has a Gaussian shape with a linear increase of the amplitude while moving downwind from the emission source. That leads to a high concentration of particles close to the source witch decreases continuously while going further. This model being a conservative model means that the integer of equal length sections of the cloud in wind direction contains the same amount of particles. The increasing rate of the cloud is linked to dispersions coefficients that depend on air stability and surface roughness. Gaussian models are well known to be robust for dispersion applications, even if they are considered as statistical and of low theoretical interest by the scientific community (Bache & Sayer, 1975). Even though, some Gaussian model were developed for aircraft spray drift (Craig, 2004). The parameters of such models are the particles flow rate, mean wind speed, dispersion parameters, emission height and sedimentation speed of the particles (Craig *et al.*, 1998).

Theoretical Considerations

Fundamental equation

The fundamental theoretical equation used for aerial dispersion pollution in our model is the Gaussian tilting plume model (equation 1) witch describes the diffusion of a particle cloud emitted upward from a point source (Reible, 1998):

$$C(x,y,z;Hs)=\frac{Q_m}{2\pi\sigma_y\sigma_z U}\exp\left(\left[-\frac{y^2}{2\sigma_y^2}\right]-\left[\frac{\left\{z-\left(Hs-\frac{v_p x}{U}\right)\right\}^2}{2\sigma_z^2}\right]\right) \quad (1)$$

with $C(x,y,z;Hs)$: deposits in function of the position in the win direction (mL m^{-1});
x: horizontal distance along the wind direction (m);
y: horizontal distance along the perpendicular direction of the wind (m);
z: height from the ground (m);
H_s: modified height of the particles emission point (discharge height) (m);
Q_m: particle flow rate (mL s^{-1});
σ_y: dispersion coefficient along y axis (m);
σ_z: dispersion coefficient along z axis (m);
U: mean wind speed along x axis (m s^{-1});
v_p: sedimentation speed of particles (m s^{-1}).

This equation is called "tilting plume model" regarding to the sloop of the higher concentration line around witch particles follow a Gaussian distribution (Fig. 1). It is a sedimentation approximation of the particles in atmosphere. The model validity decrease when moving away from the point where the maximum concentration line reaches the zero height level. Equation 1 is used to estimate ground deposits in the wind direction.

The particle flow rate at ground level is given by the product of sedimentation speed and the particle concentration reaching the ground as expressed by Equation (2):

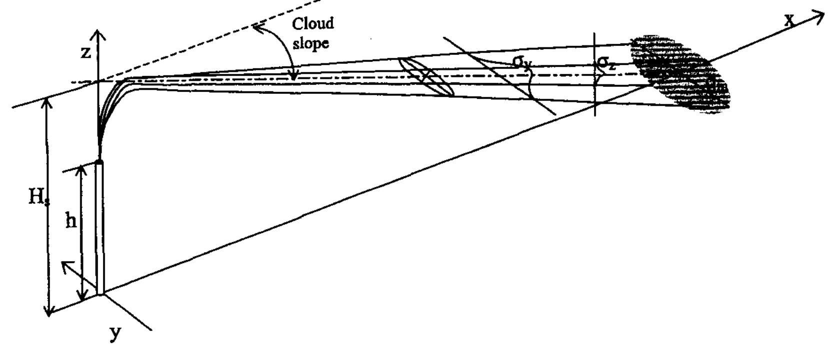

Fig. 1. Tilting plume model schematic representation.

$$q_m = v_p C(x,y,z;Hs) = \frac{Q_m v_p}{2\pi\sigma_y\sigma_z U}\exp\left(\left[-\frac{y^2}{2\sigma_y^2}\right]-\left[\frac{\left\{z-\left(Hs-\frac{v_p x}{U}\right)\right\}^2}{2\sigma_z^2}\right]\right) \quad (2)$$

With q_m : particle deposit rate mL (m² s⁻¹)

This equation is further called the "footprint". It is the analytical solution of a simple transport model similar to a simple random walk model with specific initial conditions.

Adaptability of the tilting plume model to the spray drift

To be applied successfully to the spray drift, the model has to give accurate predictions of the deposit regarding the spray and material characteristics (nozzle type, boom speed, spray height, pressure, distances between nozzles, nozzle orientation, liquid properties, crop kind and growth) as well as the weather parameters (mean wind speed and direction, wind turbulences or atmospheric stability, relative humidity, temperature.). To reach this objective, the model parameters must be correctly set based on these real field conditions.

Each parameter of the model tilting plume model is discussed to evaluate its adaptability to the field conditions within a global spray drift model.

Coordinate system (x,y,z) : the centre of the positioning system is set on the vertical line passing through the emission point assumed as the centre of the nozzle orifice in this case and the x-axis is the mean wind direction during the time needed for the droplet to reach the target. For a particular nozzle position in the field, this local coordinate system can be related to a global coordinate system on the basis of the position and orientation of the nozzle. As that flying time depends on the droplet size and its initial speed, x-axis direction of the footprint can change for each droplet size.

Furthermore, the two-dimensional character of the spray pattern and can be taken into account in the model using a simple two-dimensional mathematical convolution of the nozzle spray distribution with the footprint using in a procedure similar to the one used to compute the spray deposits under a moving boom (Lebeau, 2004). The movement of the nozzle can also be taken into account the way presented in the former article.

height chimney. The particles are emitted with an initial speed function of the gas heat, particle size and weight. The vertical speed of the particles decreases with the height due to the friction forces in the air. *Hs* is the height of the intersection between the vertical axis (z-axis) and the theorical maximum of concentration line located at the centre of the smoke cloud. In the spray nozzle case, *Hs* correspond to the height of the nozzle decreased by the length needed by the droplets to reach the sedimentation speed (Lagrangian time scale). That distance is function of the initial speed and diameter of the droplets and both depend on spraying pressure, nozzle type and orientation. Relationships between speed, VMD and height can be found in Miller *et al.* (1996) and Ghosh & Hunt (1994).

Particle flow rate (Q_m): in the case of a spray nozzle, the flow rate depends on pressure. For the proposed model, the flow rate is divided proportionally to the relative volume of each chosen droplet class given by granulometer measurements. Eventually, the droplet diameter can be decreased to take into account the evaporation linked to the relative humidity and the temperature. The flow may also be distributed in space following the nozzle spray distribution and nozzle height. That way the model gives both drift and the application rate.

Dispersion coefficient along y-axis (σ_y): this coefficient expresses the expansion rate of the particle cloud in the horizontal plane perpendicularly to the wind direction, what results in a two-dimensional footprint. It depends on the horizontal wind turbulence itself function of ground roughness (Hobson, 1993) and atmospheric stability (evaluated using Obukov length). Another mean to estimate the dispersion coefficient in the field is the 3D high frequency wind speed measurement with ultrasonic anemometer. The dispersion coefficient is different for large or small droplets and is directly linked to the "lagrangian time scale" that corresponds to the time constant of a first order system. Some scale order of this parameter is available in Anon. (2002).

Dispersion coefficient along z-axis (σ_z) : this coefficient express the height expansion rate of the particle cloud. Its value may be different of the y-axis dispersion coefficient but may be estimated the same way. For a given mean wind speed, a high σ_z value will drive concentration maximum close to the emission point, will decrease its value and increase the amount of long distance deposits.

Mean wind velocity along x-axis (U): the wind speed will determine distance where the maximum of concentration will reach the ground and thus determine the mean distance of deposit. The wind has different effects on the droplets function of their size because the sedimentation time increases with decreasing diameters so the wind may convey small droplets further.

Sedimentation speed (v_p): the particles sedimentation speed determine the slope of the maximum concentration line. It depends mainly on the Stokes law for the 10–1000 µm droplet diameter generated by agricultural spray nozzles.

A first evaluation of the model in wind tunnel condition offers some first insights of this approach capability (Stainier *et al.*, 2006). It is shown that even if the model was capable to predict drift with a relatively good agreement with the experimental results; the remaining discrepancies could be explained to be related with poor fitting of the different model parameters, suggesting further amelioration on the basis of further parametrical optimisation.

Conclusion

The presented spray model uses a robust and simple theoretical basis, Gaussian tilting plume model, to predict drift of an agricultural nozzle. Although the simple theoretical basis, it was shown that the effect of the most important characteristics of spray droplets of an agricultural nozzle can be taken into account by a individualisation of the drift effect on the different droplet classes.

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