A Computational Study of the Fluid Particles Distribution in an Helicopter Wake

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Abstract. This paper presents a Computational Fluid Dynamics (CFD) study of droplet spray dispersal in the wake of a Mi-2 helicopter up to 600 m downstream. The Reynolds-averaged Navier-Stokes (RANS) equation use a Lagrangian (droplet phase) and Eulerian (fluid phase) procedure to predict the droplet trajectories through the turbulent aircraft wake. The methods described have the potential to improve current models for aerial spraying and help in the development of new spraying procedure. In this study, models are developed for the sprays released from atomizers mounted on a helicopter. A parametric study of the aircraft model examines the effects of crosswinds on the helicopter’s vortex structures and the resulting droplet trajectories. The study shows that such influence is underestimated in the current models. A comparison of our results with those obtained with AGricultural DISPersal (AGDISP) is also presented.

1. Introduction

The spread of various substances by aircraft takes place in many areas of human life, from military applications and protection of forests to agricultural aviation. It should be mentioned that a very large and very substantial amount of aircraft are employed in crop protection treatments, as well as in the management of forests. Chemical agents are most commonly used, due to their high degree of effectiveness in killing pests, diseases and weeds, at relatively low costs. However, one of the fundamental limitations in the application of this technique is the chance of chemical agent drift [12]. By drift we mean, the unintentional movement and settlement of agents, outside the area that is being treated.

For the past fifty years from the first study by Reed [11], many theoretical models and a large data-collection effort has been undertaken [16]. From the 1980s until now, the development of Lagrangian droplet trajectory models has been suggested. Experimental research and the revolution in computer technology have enabled better modeling of aircraft vortex wakes and the tracking of droplets within them. This has ultimately led to the development of the Lagrangian AGricultural DISPersal (AGDISP) model, which has become the industry standard. AGDISP was developed by the USDA Forest Service and is based on equations of motion governing the behavior of droplets in a fluid. However, the most important limitations of AGDISP are connected to a very simple representation of the wakes produced by an aircraft. Even so, the Lagrangian models are more capable of capturing the near-wake flow field effects of aircraft than the Gaussian approach.

Subsequent authors, such as Деревя́нко [5] developed this theory, considering a bi-plane system. They assumed two pairs of horseshoe vortices, which took into account the influence of the propeller slipstream and cross winds. Moreover, Деревя́нко included the evaporation of droplets. These issues were also addressed in further scientific research and a Lagrangian trajectory model was adopted [2]. An extensive field study and model validation effort [3] confirmed the predictive capability of the Lagrangian model [17] to approximately 500 m downwind. In Poland, an elaborate model of spraying from airplane was suggested by Pietruszka [10], who developed the most appropriate, vortex-swirling...
theory. During the same period, other researchers independently developed their own spray-drift models or contributed essential parts of the modeling process. These models are shown in [13,14,18].

2. Aim and theoretical background

The aim of this study is to present mathematical models that describe the physics of the spread and distribution of atomized liquid droplets, in the air, by a helicopter. Based on analysis of the models, the quality and usefulness of these theories, in fieldwork and any possible indications of future directions of research will be considered.

The flight of any aircraft results in a disturbance of the velocity field, in a large area of its flight path. This is due to the turbulence field flowing from the wings, tail-planes or rotors and propellers. In further distances behind the aircraft, vorticity is concentrated into two vortices, at a distance of about 0.8 of a wingspan or rotor to one another [8,9]. The energy of these disturbances makes it necessary to take into account their effect on spray droplet trajectory. This trajectory depends mainly on droplet size and the position of the nozzle along the wing or the rotor [13].

The AGDISP model is based on the following assumptions for a helicopter: when an aircraft flies at constant altitude and speed, the aerodynamic lift generated by the aircraft equals the aircraft’s weight. The majority of lift is carried by the wings or rotors and generates one pair of swirling masses of air (vortices) downstream of the aircraft. The rollup of this trailing vorticity is approximated as occurring immediately downstream of a helicopter and the local swirl velocity, around each of the two vortices, is given by:

\[
v = \frac{\Gamma}{2\pi \max(r, r_c)^2},
\]

where, \(\Gamma\) is vortex circulation strength, given by:

\[
\Gamma = \frac{(1-\rho)w}{2\rho \mu U^2},
\]

\(r\) is the distance from the vortex center to the droplet position, \(r_c\) is vortex core radius, \(w\) is aircraft weight, \(R\) is the main rotor radius and \(U_c\) is a helicopter speed. Vortex strength decays with time, because of atmospheric turbulence, following a simple decay model:

\[
F = \exp\left(-\frac{x}{R}\right).
\]

More explanations one can find in the original work by Bilanin et al. [2] and later papers [16,17]. The influence of area coverage on the flow velocity profile is explained more precisely in [7].

3. Motion of droplets

Sprayed droplets, with a high, initial velocity, have a significant distribution of diameters, within the range of few to several hundred \(\mu m\) (depending on the type of sprayers). This corresponds to Reynolds’s numbers, with respect to their sedimentation velocity, of \(0.1 \leq Re \leq 100\). According to the work [4], drag force acting on the droplet versus the Reynolds number \(Re = \frac{2d}{v}\) can be presented in the form:

\[
C_D = \begin{cases} 
0.424 & Re \geq 1000 \\
\frac{24}{Re}(1 + 0.16Re^{0.667}) & 0.5 < Re < 1000 \\
\frac{24}{Re} + 4.5 & Re \leq 0.5
\end{cases}
\]

(4)

For this range of Reynold’s numbers, an error in the drag coefficient does not exceed 6%. The equation of droplet motion, in its general form, can be written as:

\[
\frac{d}{dt}\left(m\cdot \vec{v}\right) = m\vec{g} + \vec{F_D} + \vec{F_A} + \vec{F_M} + \vec{F_B},
\]

(5)

where, \(m = \frac{\pi d^3}{6}\) is the mass of a droplet, while \(\vec{F_D}, \vec{F_A}, \vec{F_M}, \vec{F_B}\) are aerodynamic drag force, buoyancy force and Magnus and Basset forces, respectively. In the present form of motion, the last two forces are omitted. This is due to the fact, that such assumptions were adopted in previous works (so in this work to compare result), without significantly affecting the results of the calculations. This equation is solved
having given the velocity field of the air around droplets. The trajectory equation $\frac{dR_d}{dt} = v_d$ can be solved as well using the implicit and the trapezoidal schemes, where the new location of a droplet is given in the form $R_d^{n+1} = R_d^n + \frac{1}{2} \Delta t(v_d^n + v_d^{n+1})$. More details can be found in [4]. The evaporation of droplets is given in the formula:

$$m_d(t + \Delta t) = m_d(t) - N_i A_d M_{w,i} \Delta t,$$

where $A_d$ is the surface and $M_{w,i}$ is the molecular weight of the droplet and $N_i$ - molar flux of vapour given in the form:

$$N_i = k_c(c_{i,s} - c_{i,\infty}).$$

Here $c_{i,s}$ and $c_{i,\infty}$ is the vapour concentration at the droplet surface and the vapour concentration in the bulk gas, respectively. $k_c$ can be received from the equation:

$$\frac{k_c d_d}{D_{i,m}} = 2 + 0.6 Re^{1/2} Sc^{1/3},$$

where the Schmidt number has the form $Sc = \mu/(\rho D_{i,m})$ for the diffusion coefficient of vapour in the bulk $D_{i,m}$. More detailed discussion of these issues are presented in the paper [4].

4. Object of research

The object of the study is the PZL Świdnik Mi-2 helicopter, equipped with apparatus for ULV spraying in the form of rotating sprayers (atomizers) AR-86.00.00 produced by the WSK PZL Świdnik, used in chemicalization treatment. For the study it has been assumed an altitude of the aircraft equal to $h = 5$ m and a speed corresponding to the most commonly used in treatments by means of helicopters $v_r = 22$ m/s. The helicopter had the equipment that allows registration of: flight speed, pump rotations, atomizers rotation and the pressure of the pump.

Field experiments were carried out in the years 1987-1992 on the Academy of Agriculture and Technology in Olsztyn research training ground, constituted at the former airfield in Gryźliny near Olsztyn at the area of 150 hectares covered with grass. In this area, parallel to the direction of the wind, a 800 m long measurement line was delineated with the samplers enabling to determine not only the size and density of the spray, but also, which is very important, changes in the diameter of the droplets for the given drift distance. The computational model of the plane is a three-dimensional full-scale model of the Mi-2 helicopter designed in by means of ANSYS 16.2 Design Modeller. The model includes the fuselage and two rotors treated as pressure drop. In order to simplify the geometry, certain components of lesser significance were not included [4]. The fluid domain is given in the Figure 3. Dimensions of the domain: 600 m long, 160 m wide and 33 m height. Its total volume is 3168000m$^3$. 

Figure 1. Mi-2 helicopter geometry.

Figure 2. The schematic drawing of the research experiment site and the measurement line: 1 - measure line, 2 – flight path, 3 – mass samplers, 4 – droplet samplers, 5 – masts, 6 – measurements of meteorological parameters, 7 – cameras, 8 – markers.
flow direction. Four sides act as a far field with specified velocity conditions that impose the wind, one acts as an outlet and one as a ground. The flow simulations have been computed using Reynolds-averaged Navier-Stokes (RANS) equations solver based on the finite volume method. A commercial code, ANSYS Fluent, has been chosen for this purpose [4]. The basic set of gas phase governing equations is given in (9). This is a general equation with symbols given in the Table 1. The equations have been closed with the Menter K-ω SST 4-equations turbulence model, more adequate in terms of the flow turbulization behind the aircraft [4]. Since the pressure farfield condition was used on fluid boundary of the domain, the ideal gas model of density, as demanded by this condition, was also assumed.

\[
\frac{\partial (\rho \phi)}{\partial t} + \frac{\partial (\rho u \phi)}{\partial x} + \frac{\partial (\rho v \phi)}{\partial y} + \frac{\partial (\rho w \phi)}{\partial z} = \frac{\partial}{\partial x} \left( \Gamma \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma \frac{\partial \phi}{\partial z} \right) + S_\phi. \quad (9)
\]

Discrete phase was chosen as interacting with continuous phase and droplets diameter distribution was represented by Rosin-Ramler distribution with total flow rate 1.378 kg/s.

5. Results.

The theoretical models should be useful for predicting the behavior of spray released from aircraft and be able to calculate the distribution of a mass aimed at the target field. The AGDISP model was shown to overpredict deposition rates, relative to experimental field data [6], although recent improvements have allowed the latest version of AGDISP to match field data. However, the study shows that the mass distribution generated by AGDISP software does not exactly match the distribution received during the field experiments.

Figures below present a comparison of the theoretical calculations and data collected, during field experiments carried out at the research training ground of the Academy of Agriculture and Technology, which the experimental data was presented in the study by Seredyn et al. [15]. Analysis was done using a 30% water solution of urea, with an additional 2% of nigrosine, with settings for a 20.23 dm³/ha dose. Atmospheric conditions were measured as: wing velocity – 5.1 m/s, temperature – 290.2 K and humidity.
– 65%. For the helicopter, the following conditions occurred:
flight velocity – 22.8 m/s, height – 5 m and two sprayers on the boom.

First of all, after calculating the solution, it is quite different from that one received by means of the AGDISP model. In the Figure 5 it is clearly visible that the turbulence around the helicopter is very high and disappears very quickly according to CFD predictions. In AGDISP model the turbulence is constant.

Figure 5. Turbulent kinetic energy.

Now, in the Figure 6 the vorticity generated by the helicopter in flight is presented. One can conclude very simply, that the assumption about two counter rotating masses of the air is not justified. The conclusions form the CFD calculations are close to the Joulin or Misaka predictions [8,9]. It is stated, that the vorticity roll-up is a quite long lasting process and quite complicated, especially after the helicopter such as Mi-2. From the figure we can see that 10 m after the helicopter the vorticity is more complicated, than those after 100 and more meters. On the other hand, according to the AGDISP model predictions the paths of the droplets exhibit the symmetry with respect to the plane passing through the axis of the helicopter. Whereas the paths of droplets, which were calculated in the CFD analysis, are quite complicated what is obvious from the observations. These paths are presented in the Figure 7.

Now the main problem will be considered. Of course, the main aim of the study is to receive the mass distribution on the ground, which can be received, using the Mi-2 aircraft with the agricultural equipment set mounted on it. First of all, it is very convenient to present the contours of the droplets in their spatial distribution. The droplets diameter distribution was set according to studies presented in the paper [15] and ranges from 10.77 to 320.6 micrometres.

Figures 8 and 9 give the overview of such contours. From the first picture one is able to read the droplets distribution for spraying in the air with respect to their mass distribution in planes perpendicular to the direction of the flight. At the beginning, droplets are gathered in very small volumes, but the situation is changing very soon, what is obvious, having given information about the velocity field behind the aircraft with the wind. The symmetrical structures vanish and the droplets are moving in the wind direction as well as maintaining the rotational movement caused by the swirling air.
The Figure 9 gives the other information, mainly about the distribution of the droplets with respect to their diameters. At the beginning, the released droplets are very quickly intercepted by the air stream. The droplets with greater diameters are more cumulated at the beginning. After a very short time small droplets are caught by the vortices generated by the helicopter, whereas the bigger ones are falling down due to gravity. Of course, from the pictures it is readable the general behaviour of the droplets. Almost all droplets are moving outwardly from the vertical plane oriented with the flight velocity and including aircrafts center of gravity. It means, that more mass is moving in this direction comparing to models with the simple modelling of vortex lines, assuming its fixed position and not including the influence of the ground.

**Figure 7.** The flight paths of the droplets according to CFD (two droplets of 113 μm diameter – top, many droplets – bottom).

**Figure 8.** The contours of the droplets concentration (kg/m³) according to CFD in 3 planes - 10 m, 100 m and 400 m behind the helicopter (x axis).
Finally, the experimental volume fraction of the droplets in the direction of the wind comparing to the theoretical models predictions is presented. From the Figure 10 it is seen, that the mass distribution on the ground is more complicated in the experimental case, compared to the AGDISP model predictions. The results given by the AGDISP model is very similar to the ‘free’ Bache and Sayer model predictions [1]. The ‘free’ model, although is closer to the experiment in the stripe from 0 to 10 m. The AGDISP model fits better in the stripe from 25 to 150 m.

Figure 9. The contours of the droplets diameters according to CFD in 3 planes – 10 m, 100 m and 200 m behind the helicopter (x axis).

Figure 10. Mass distribution for the Mi-2 helicopter: the blue line – field test, the orange line – AGDISP, the yellow line – CFD, the black dotted line – Bache and Sayer (‘free’- without the wake) model.

6. Major conclusions
In this paper the behavior of droplets released from aircraft is approached by a CFD model based on Reynolds-averaged Navier-Stokes (RANS) models, a Lagrangian model for the droplet phase and Eulerian model for fluid phase. The authors analyzed the spray of droplets from the Mi-2 agricultural helicopter, by means of CFD simulations, using the Discrete Phase Model (DPM) method. The three-
dimensional full-scale CFD model of the helicopter and surrounding flow field has been created. The CFD models demonstrated very important influence of vortices on droplets. The CFD results were compared to field data as well as to AGDISP and other theoretical models predictions.

In summary, however, the need for further study is highly noticeable. Firstly, the modeled results, which were obtained from the CFD calculations, are more consistent with experimental data showing two maxima of mass concentration. However, there is still a compulsion to implement the physics of flow around an aircraft to a more advanced degree through the refinement of the geometry of the helicopter. Secondly, such theoretical analysis and their improvements provide a low-cost alternative to field experiments aiming to optimize the lateral distribution of sprayed droplets. Finally, further research, both theoretical and experimental, is needed to produce a higher degree of conformity between results received by means of mathematical models and field tests. In the authors’ opinion the final step in the development of such research is the use of Computational Flow Dynamics calculations.

7. References

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