A numerical analysis of flat fan aerial crop spray

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Abstract. Spray drift mitigation, in the agriculture aerial spraying literature, and spray quality in the application of plant protection products, still continues as two critical components in evaluating shareholder value. A study on off-target drift and ground deposit onto a 250 m strip were simulated through series of Computational Fluid Dynamic (CFD) simulations. The drift patterns for evaporating droplets were released from a constant aircraft velocity at 30 m/s (60 mph) carrying 20 m swath width spray boom with 12 fan-type nozzles at released height from the ground ranging from 3.7 m to 4.7 m. Droplet trajectories are calculated from the given airspeed with a Lagrangian model for particle dispersion excluding any wind effect perturbation. The proposed CFD’s model predictions agreed well with cited literatures for a wide range of atmospheric stability values. The results revealed that there is considerable increased in spray drift and droplets trajectories with the increased in spray released height. It suggested that a combination of low aircraft spray released height with low airspeed is essential to improve spray quality and maximizing uniform deposition on the target area are significant in minimizing spray drift risks.

1. Introduction

In the last three decades, the growing concern of aerial spray deposits and proxy of pesticides residue is continuing to pose major threat to human being and environmental [1], adaptation to its negative effects has moved to the forefront of the stakeholder. Aerial spraying works are poorly understood by public and persistently criticized globally [1]. Aerial spraying works involving pesticide released into atmosphere at certain height above the crop or forest to the ground. Thus it requires atomizers that are able to meet with stringent environmental law and also ensuring pesticide stays in the intended area [2, 3, 4]. Spray drift is undesirable, but still the important role of pesticides or plant protection products in modern agriculture is undeniable in terms of reducing pest attacks and increasing high yield [5, 6]. Uneven spray distribution and drifted to adjacent areas has been pronounced as serious problems regarding aerial spray delivery [7]. Uniformity spray coverage area are desired in aerial crop spraying, thus improving aerial pesticide application to reach a satisfactory level of spray deposition in most cropping system is essential. Typically, aerial spray drift can be classified into two categories namely as downwind deposition and airborne or vapor drift [8]. The potential aerial spray drift can passively be improved predetermined by notable controllable factor such as boom length, nozzle type, spray angle, pressure, air speed, remain constant based on real application scenario [9], however the uncontrolled factor limitation atmospheric conditions such as wind speed, relative humidity and temperature are yet still remained [4,10]. Notable spray characteristics of aerial crop spraying is dependent on spray equipment such as atomization methods, sprayer nozzle types, spray adjuvants, meteorological conditions, crop characteristics and buffer zones. Amongst these variables, larger
Pray pressures and low spray boom height apparently significant in reducing spray drift [11]. Nozzle size and design selection is the most critical parameter in aerial spraying as it influenced the spray droplets spectrums and droplet velocity characteristics [12, 13].

Studies on the aerial crop spray quality has been very limited especially the droplet dispersal process; an area of research within the spray characteristics of aerial pesticide delivery [4, 14]. On the other hand, there are plentiful reports on the outdoor analysis available on aerial drift affecting factor; for example, the works originates from spray drift task force (SDTF) known as agricultural dispersion models (AGDISP) in United States [5, 9].

For assessing the aerial pesticide application, various methods can be used at the outdoor and indoor environments such as (i) full-scale measurements, (ii) wind-tunnel measurements or spray chambers, and (iii) numerical simulation with Computational Fluid Dynamics (CFD) [10, 15]. Each of the sampling techniques has advantages and disadvantages especially in terms of numbers, time constraint and cost. Recently, computer modelling such as CFD provides whole-field flow data, fast and reproducible, repeatable and controllable conditions, reliable data, rapid, economical and accurate means however at the expense of incompatibility [16]. CFD is increasingly used to study a wide range of atmospheric and environmental processes [17].

The objective of this study is to investigate on the effect of low velocity, variation by lowering the boom spray released to the ground from flat fan 90-degree atomizers, the particle mass concentration released, nozzles orientation and the droplet trajectories. Regions of interest that depicts the most important unsteady flow would be a common series of divisions from horizontally projected from 0 to 250 m distance away from the spray sources [10]. Thus, a 3D CFD, which is a useful approach to predict the probable unsteady flow characteristics is recommended in understanding the spray deposition based on the effect of spray technology and spray liquid properties as reported by Baeten et.al [15]. According to Ryan et al. [4], the most suitable technique to represent the actual event is by using 3D volume of fluid multiphase model, which consists of mainly two phases: (i) air and (ii) water.

2. Methodology

In the present work, an unsteady 3D CFD using Fluent version 15.0 from ANSYS® modelling was designed to simulate two-sub model; an airflow model [3] and a particle tracking model which are mutually coupled [4]. A Lagrangian approach representatives of approximate of 40000 droplets trajectories was utilized for all simulations.

2.1. Aerial Aircraft Configurations and Schematic Diagram

The present simulation aims to highlight the configuration parameters that represent the actual event of spray depositions of nozzle in controlled conditions without environmental factors perturbation. The commercial GT500® agriculture aircraft specification as shown in Figure 1a) was chosen as reference due to its favorability in agriculture aircraft pesticides delivery in most countries. It mainly used to cover widespread infestations, or inaccessible areas in steep or remote terrain. Engineering boom spraying technology, the state of art need to be tailored well fit the target specific infestations and reduces the risk of pesticides drifted to non-target or over spray surrounding areas. In this simulation, the aircraft speed was purposely conducted for 30 m/s (60 mph), comparative lower from previous studies which employed at higher airspeed between 54 m/s (120 mph) to 72 m/s (140 mph) for agriculture aircraft spraying [8, 9]. The reason was to configure the effect of low airspeed in agriculture aerial works spraying.

In this study, twelve set nozzles coordinates were allocated, mounted on aircraft boom spray unit releasing injections at various height (altitude) ranging from 3.7 m to 4.7 m above ground of 30 m/s speed imitates as aircraft spraying pesticide over plantation area. The nozzles schematic diagram mounted on aircraft boom as shown in Figure 1b) complete with the physical configurations dimension of GT 500® agriculture aircraft for the simulation as listed in Table 1 below.
Figure 1. a) Schematic diagram of GT500 aircraft flight path b) Schematic diagram of 6 nozzles mounted on aircraft boom.

Table 1. GT 500® Aircraft general configurations

| General GT500® Aircraft Configurations (dimension in meter) |
|-----------------------------------------------------------|
| Length | 9.94 |
| Height | 6.23 |
| Wingspan | 9.14 |
| Boom Length | 8.50 |
2.2. Computational domain setup and grid

Based on Figure 2, a 3D rectangular computational domain was developed with the dimensions of 280 x 40 x 40 (m) representing a sample of a flight path, with an assumption the centerline of the aircraft body is located 30m from the x axis of the total flight path length. The working domain was set to ensure that the domain size was not disturbed by the length of wing span and the turbulent airflow within flight path. The set up computational domain adapting the existing agriculture aircraft GT 500 in market is shown in Figure 2. Geometry and grid generated was executed and discretized using an appropriate mesh sizes consist of 549331 elements and 1100932 nodes as seen in Figure 3. The quality report indicated that meshed result had a good condition according to the skewness parameter, with an average values located at 0.23 as shown in Table 2.

Table 2. Mesh quality criteria parameters: skewness and element quality.

| Mesh Metric       | Skewness   | Element quality |
|-------------------|------------|-----------------|
| Minimum           | 5.806×10E-4 | 1.1881×10E-2    |
| Maximum           | 0.9400     | 0.9996          |
| Average           | 0.2318     | 0.4600          |
| Standard Deviation| 0.1289     | 0.3653          |

2.3. Boundary Conditions

With reference to Figure 2, in all simulations, a uniform air velocity profile was set based on the constant ‘velocity inlet’ and the opposite faces at atmospheric pressure condition was located at the outlet. At the inlet velocity, the air was forced to move inside the domain at the given velocity which is 30 m/s and enabling freely motion of the air, as well as particles. The bottom surface, considered as ‘Floor Wall’ was set as ‘stationary, no slip’ condition as substitute of the top of the plantation areas, trapping all the particles that collide with them, while the remaining three outer faces, the top and surround faces modelled as ‘symmetry’ properties. In addition, the operation pressure was defined as standard atmospheric pressure which is 101325 Pascal. The operation density was 1.225 kg/m³, the air density in standard conditions. The boundary condition assigned for each faces of the computed domain and the spray injection point and the exit of the flat fan’s nozzle are appointed at the origin.
point (0, 0, 0). The total spray injection points of 1200 droplets of particle tracks of the replicates 12 nozzles at an air velocity of 30 m/s were created by inserted coordinate with assumption the axial position of the aircraft located at the central of the computational domain.

2.4. Numerical parameters in Fluent and Spray Atomizer

The reference spray parameters used in this simulation was in the same conditions with previous study done by Fritz et.al [9]. The flat fan configurations were obtained from Lechler Nozzles Catalogue [19], that were operated at 276 kPa (40 psi) and 0-degree orientation. The spray particles were set as water-liquid droplets, injected into the computational domain from a 12 nozzle of 0.009 m of width, respectively. When the particles injections exit the nozzle tip, it undergoes a flash evaporation. The main spray parameters used to configure the solver are summarized in Table 3, such as the spray angle, maximum velocity of the spray plume, shape of the plume, as well as, the dimension of the nozzle. The standard particle size data were utilized associates with the Flat Fan Atomizer parameters. Data were fitted to the cumulative function of standard particle size data distribution. The corresponding parameters CFD solver as shown in Table 3 and Figure 4.

Table 3. Solver spray of flat fan atomizer parameter

| Variable                                    | Value        |
|---------------------------------------------|--------------|
| X, Y, Z-Center (m)                          | 0, 0.5, 3.7  |
| X, Y, Z-Virtual Origin (m)                  | -0.00045, 0.5, 3.7 |
| X, Y, Z-Fan Normal Vector                   | 0, 0, -1     |
| Flow Rate (kg/s)                            | 0.00915      |
| Spray Half Angle (degree)                   | 45           |
| Orifice Width (m)                           | 0.0009       |
| Flat Fan Sheet Constant                     | 3            |
| Atomizer Dispersion Angle                   | 6            |

The solution of the differential equations for mass and momentum was done in a sequential manner, using the COUPLED algorithm [12]. The standard discretization scheme was used for the pressure and the second order upwind scheme for the momentum, turbulent kinetic energy and turbulent dissipation rate equations. The time step was 0.1 s, with a maximum limit of 200 iterations for total of 20 s simulation time including gravity effects with 9.81 m/s² in the vertical z axis negative direction. DPM model configuration the in the solver are listed in Table 4. The unsteady particle
tracking was used until convergence was reached in the simulation by using a default criterion value of $1.0 \times 10^{-3}$ for the continuity (pressure), x, y and z velocity, and for k and $\varepsilon$ turbulence parameters. The interaction with the continuous phase was also included to approximate the simulation to the real event, since the velocity difference between the two phases is high.

Table 4. Parameters for DPM setup

| Parameter                              | Value                  |
|----------------------------------------|------------------------|
| Interaction with Continuous Phase      | On                     |
| Unsteady Particle Tracking             | On                     |
| Inject Particles at                    | Particle Time Step     |
| Particle Time Step Size (s)            | 0.1                    |
| Drag Law                               | Spherical              |
| Two-way coupling turbulence            | On                     |

The drag law used (spherical) is the simplest and most used law, once it is the one that best fits the presented model amongst the four different options available in the solver. This drag law considers the particle as a sphere, which is an acceptable simplification for the water particles that exit the flat fan nozzle [4]. The total number of particle parcels streams injected for each simulation was approximately 40000.

3. Results and Discussion

3.1. Spray Deposition.

The relations of spray released height on spray quality and spray drift deposition was further analyzed from the plotted CFD contours in horizontal travel direction as function of particle mass concentration in various elevated height as shown in Figure 5. Results are consistent for unsteady phase contour at each spraying, corresponding to the standard flat fan 90 degree atomizers. It was observed that for each cases the height of emission or spray released height plays an important role whereby an increase of the boom height increased the level of deposits at different downwind distance or the swath width [16]. For released height of 4.7 meter the measured distance travelled from the sprayer was 50 m compared to 38 m for 3.7 m of released height. The results were in good agreement with previous study reported by Lebeau et.al [5]. These results agreed the same explanation reported by Dorr et.al [2], the droplets velocity was higher at close range near the nozzle released point and reduced as the particles travelled away from the spray sourced. The droplet particles were highly dense at the exit of the nozzle tip, decayed into turbulent atmosphere reaching a constant velocity of 30 m/s an equilibrium state in less than 20 seconds, decreased its velocity and diminished by air resistance which breaks up the droplets.
Figure 5. Spray deposition as function of particle mass concentration in height variation. Cross reference indicates nozzle location (spray source).

The sprayed deposition pattern is critical in aerial spraying works, illustrated the effects of aerial spraying works with optimum distance ranging not less than 2.4 m above the crop or ground compare to forestry application which is 6 m or higher. The turbulent dispersion, subjected to change and continue falling in effect of gravity magnitude which coincides at the end of the injection of the spray plume as proposed by Zhang et.al [3]. Generally, it was found that the maximum sprayed deposition area was achieved at the highest released height of 4.7 m compared for a released height of 3.7 m. Thus, a good combination of spray released height with low airspeed is significantly affected the aerial spraying deposition pattern. The results were further analyzed in Figure 7.

3.2. Spray Coverage.
The trajectory of scattered sprayed droplets of each cases was plotted along a horizontal travel direction to evaluate the evaporated droplets for different spray released height as seen in Figure 6. For each cases, there was a significant reduction trend in the particle mass concentration level as the spray released height elevated. Generally, the mass concentration in each time step reduces with the application rates. This is one attributed factor that relates between mass concentration with droplets diameter formation as the amount of droplets moisture was absorbed by the airflow present in the domain [2]. From Figure 6, the high mass concentration were located at 50 m to 100 m at the central of the plume and reduced as the droplets transported downstream positions at 250 m as the droplets...
dispersed outwards. Results showed that for a released height of 4.7 meter, the particle mass concentration had the lowest concentration which is 39% reduced from 0.1963 g/m$^3$ compare to 0.2743 g/m$^3$ for a released height of 3.7 m. These findings showed the same result explained by Ryan et.al [4] that at lowest spray released height, smaller droplets were formed and scattered outwards at quicker rates but less contribution in droplets volume compared to higher released height. Since uniformity spray distribution was the main aim of this simulation, it is suggested that aerial spraying at low released height ensuring that the particles trajectories is sufficient to reach the intended targets before drift occurs due to the initial airspeed as mentioned in the earlier studies by Dorr et.al [2].

![Figure 6](image-url)  

**Figure 6.** Downward deposition as function of constant velocity at various vertical height.
3.3. Spray Droplet Characterization.

Figure 7. Downward deposition as function of constant velocity at various vertical height.

Figure 7 represents the decreasing trend of particle mean diameter at the horizontal positioned of the plume which is 250 m from the spray source. For each cases, the curves shows a downward slope indicates that the particle mean diameter decreases with the increment of the downwind position. Higher spray released height at 4.7 m produce large droplets which is 216 microns compare to 130 microns for a released height of 3.7 m. The droplets produced range was consistent with classical theory reported by Fritz et.al [9], classifying the agricultural aerial pesticide spraying were targeting droplets spectrum for medium range from 100 to 300 microns (100 – 300 µm) with minimal smaller droplets categories which is 50 to 100 microns (< 50 -100 µm). The results indicated the overall droplet formation falls under medium range droplets which is given under ASAE S572 Standard Nozzles Classification by Droplet Spectra [8]. The influence of spray released height on the droplets spectrum is significant corresponding due to high transport time and evaporation. Smaller droplets tends to fall much slower compared to large droplets, thus gives good reliability towards the aim to minimize the drift potential. For all simulations, the speed for all falling droplets is governed by the effect of gravitational pull and the airflow interaction within the domain. These findings supports previous theories made by Dorr et.al [2]. These findings also elucidates the importance of reference nozzles especially the orifice size used in aerial spraying works. A good combination of operating pressure will increased in nozzle output as well as droplets spectrum production in terms of uniform distribution as well as minimizing spray drift.

4. Conclusion and Recommendations
The proposed CFD Lagrangian model was able to predict the aerial spray dispersion using flat fan atomizer at various sprays released height of constant 30 m/s aircraft speed was studied. This simulation is a necessary step towards the simulation of crop spray efficacy in aerial spraying delivery
in field-realistic conditions regarding operational variables, spray equipment and spray deposition. From the results obtained, several conclusions can be deduced:

a) The results revealed that there is considerable increased in spray drift and droplets trajectories with the increased in spray released height. These findings support the same result obtained by Viret et al [7]. The highest downwind deposition was found at 4.7 m at the distance of 50 m from the spray sourced, while the lowest was found at 3.7 m above the ground. The overall downwind deposition is in gradually decrease trend in each simulation. Thus, the aerial spray released height should be maintained not less than 2.4 m above crop or ground [9].

b) The result demonstrated that the increase in spray released height will increase the swath width. Two notable contributed factor which is the combining factor of operational variables with the spray equipment’s. Thus, emphasizing the reference nozzles is one of the critical factor in aircraft spray equipment’s. The nozzles feature such as orifice sizes influenced droplet spectrum, distribution and spray pattern.

c) Spray deposition can be improved by adjusting the spray boom settings by means of influencing spray equipment such as spray types, angle, pressure and volume to the target crop or ground effect. A care selection of nozzle types is essential to ensure that the agriculture aerial spray droplet is maintain in medium droplets ranging from 100 to 300 microns so that it reach uniformly towards the intended crop or coverage area [9].

4.1. Recommendations

These initial step could be viable alternative to use in future research in terms of improving the aerial spray distribution with minimize spray drift potential. Further suggestions can be done for future improvements:

a) The spray simulation is recommended to include with the meteorological conditions inclusive wind speed, temperature and relative humidity to study the real applications towards the spray deposition.

b) Introduce wing aircraft or boom spray in the computational domain to study the effect of vortex towards the spray deposition.

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