An investigation of airflow patterns created by high-clearance sprayers during field operations

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ABSTRACT
Field experiments and computational fluid dynamics (CFD) simulations were carried out to investigate the levels of turbulence that developed in the wake of high-clearance agricultural sprayers. Ultrasonic anemometers were mounted behind the booms of two sprayers to measure local airflow for various treatments of travel speed, lateral location along the booms, longitudinal location behind the booms, and ambient wind conditions. The primary metric used in this investigation was the turbulence kinetic energy (TKE). Significant differences were found in the TKE values for all the factors investigated. CFD modeling was performed to gain an understanding of the incremental contribution of various components of the sprayer to the TKE levels. Simulating the rotation of large agricultural tires indicated some level of turbulence in their wake suggesting they should not be ignored when assessing the wake of the sprayer. Simulation results also suggest that both the geometry of the sprayer and its travel speed influenced the airflow patterns. The investigation of the sprayer tractor with rotating tires revealed a large increase in TKE levels in the wake of the implement when increasing the travel speed from 2 to 8 m/s. The boom created an additional obstruction to the airflow and its own contribution to the levels of TKE, with localized impact where multiple members of the truss structure meet. This research established necessary baseline information and methodologies to support future efforts to better understand the impact of large sprayers operated at high speed.

KEYWORDS
Anemometers, CFD, Field measurements, High-clearance sprayers, Turbulence, Turbulence kinetic energy, Wake characterization.

RÉSUMÉ
Le sillage aérodynamique de pulvérisateurs enjambeurs auto tractés a été étudié via la réalisation d’essais au champ et de simulations en dynamique des fluides (CFD). Des anémomètres ultrasoniques ont été installés en aval de la rampe de deux pulvérisateurs afin de caractériser les courants d’air locaux en fonction de la vitesse du pulvérisateur, de la position latérale le long de la rampe, de la position longitudinale en aval de la rampe et des conditions de vent. L’indicateur principal utilisé est l’énergie cinétique turbulente (TKE). Tous les paramètres étudiés ont eu un effet significatif sur la TKE. Des modèles CFD ont été développés afin de mieux comprendre la contribution incrémentielle de diverses composantes du pulvérisateur sur la TKE. Simuler la rotation de pneus de grand diamètre indique un certain niveau de turbulence dans leur sillage suggérant qu’ils ne doivent pas être ignorés lors de l’évaluation du sillage du pulvérisateur. Les simulations suggèrent également que la vitesse d’avancement et la géométrie de l’équipement influencent toutes deux les écoulements d’air. Une augmentation significative des niveaux de TKE a été observée lorsque la vitesse d’avancement passe de 2 à 8 m/s. La rampe de pulvérisation crée une obstruction additionnelle et contribue à la TKE avec des impacts locaux plus marqués aux endroits où plusieurs membres de la structure se rencontrent. Cette recherche a permis d’établir des informations préliminaires et des méthodologies qui serviront à de futures investigations plus détaillées visant à comprendre les effets de pulvérisateurs de grandes dimensions opérés à vitesses élevées.

MOTS CLÉS
Anémomètres, CFD, Essais au champ, Énergie cinétique turbulente, Pulvérisateurs enjambeurs auto tractés, Sillage aérodynamique, Turbulence.

CITATION
https://doi.org/10.7451/CBE.2019.61.2.01
INTRODUCTION

A significant amount of resources is invested by agricultural producers for crop protection every year. The sprayer has become an important pillar of most farming businesses. With pesticides, herbicides, and desiccants application occurring throughout the growing season, high-clearance sprayers become important tools that can impact producers’ profitability. It is obvious that spraying operations are most efficient when the minimum amount of product is applied and the product reaches the intended target. Modern self-propelled sprayers are very large machines capable of travel speeds of up to 40 km/h (11 m/s). The underlying question that prompted the research work reported herein is related to the aerodynamic properties of these large sprayers in light of the increased travel speeds at which producers and custom applicators operate.

Optimal spray nozzle operation and spray drift have received some attention in the scientific and technical literature with passing references to the effect of travel speed. Aerodynamic properties of the spray pattern become increasingly important as the travel speed of the sprayer increases, with its potential for greater spray drift, lower canopy penetration, and reduced deposition uniformity. The negative environmental and societal impacts of increased pesticide drift should not be overlooked. The additional contribution of a large tractor chassis, boom components, and rotating wheels and tires complicate things further with detrimental impacts on pesticide performance observable in the field. Of particular note is the 2009 European directive (DIRECTIVE 2009/127/EC) that states that the machinery should be designed and constructed to ensure that pesticide is deposited on target areas to minimize losses to other areas and to prevent drift to the environment.

There exists a significant body of work on spray deposition and drift, with some of the studies putting emphasis on the equipment. The following literature review is not intended to be an exhaustive inventory of research efforts targeting spray technology; rather it highlights some of the research trends that support the need for the work reported in this article.

Lebeau et al. (2004) highlighted that the predictions of deposition models based on static laboratory testing are accurate for very low vertical or horizontal boom speed (< 0.3 m/s) and that the discrepancies that appear when predicting the actual deposition rate at higher application speeds may be caused by the head wind associated with the driving speed. They proposed a dynamic model that would account for the movement of a nozzle and could predict spray deposits with a precision of approximately 10%. A model for estimating spray drift from ground sprayers was proposed by Lebeau et al. (2011). The model is based on a Gaussian diffusion model where each sprayer nozzle is considered to be an instantaneous source having its own movements. A number of constants in the model are determined experimentally. Inputs of the model are the nozzle characteristics and embedded measurements, including a global positioning system, an ultrasonic anemometer, and several sensors to give information on the nozzle position and operation. When comparing the results of the model with experimental measurements of deposits, the model produces realistic maps of drift deposits for various wind conditions. The model was deemed a sound basis for the development of a real-time drift monitor compatible with realistic computational resources to be included in a spray controller.

Holterman et al. (1997) developed an analytical model to compute downwind spray drift from boom sprayers. Spray deposits were computed downwind from the sprayed crop field. The model incorporated driving speed and entrained air-currents below the nozzle. Input parameters were related to the geometry of the field, to the boom sprayer settings, and to environmental factors. The model was calibrated with a set of field trials using an experimental single-nozzle sprayer in a cross wind. Variations of boom height, spray nozzle size, driving speed, and liquid pressure were examined at varying wind speeds. Both experiments and simulations showed that boom height, wind speed, and nozzle size were the major factors affecting spray drift, whereas liquid pressure did not affect downwind spray deposits at all. A comparison between model results and those of a practical field trial showed a good agreement if field trials were averaged over several replications.

To analyse the influence of boom movements on spray distribution, Lardou et al. (2007) used a conveyor with a shaking platform. The test apparatus could generate uniform translations and rotational movements of a small boom under laboratory conditions. The overall ground spray distributions were studied using image analysis. The effects of boom height, boom speed, and nozzle type on dynamic spray distributions were analysed and compared with stationary distributions. The authors’ goal was to develop a test method for evaluating the impact of boom movement on spray distribution. Measurements of droplet size and velocity made with a phase Doppler analyser were added to complete the dynamic effect study. Tests were repeatable, but some fluctuations were obtained when boom height increased. The authors noted that static and dynamic distributions have the same overall unevenness, but this unevenness is more important in dynamic conditions due to turbulence effects. Roll and yaw increase unevenness. For roll movements, changes in nozzle heights explain the variations. For yaw movements, over-dosed areas are observed where the nozzles have a small horizontal velocity.

Murphy et al. (2000) provided some insights into the potential effect of the boom section on spray drift. Their study focused on the effect of plume porosity as affected by spray fineness and nozzle spacing, as well as of boom section on airborne drift. The wind tunnel airstream velocities investigated were 1 and 3 m/s. The dominant factor influencing airborne drift was found to be the spray quality determined by the nozzle characteristics. Murphy et al. (2000) noted that although the vertical profile of airborne drift was influenced by boom section, the magnitude of
difference between extremes of boom configuration were much less than changes due to nozzle characteristics.

Teske et al. (2015) used a wind tunnel to investigate the air motions around and in the wake of a ground sprayer. Their goal was to develop a wake model for inclusion in spray deposition models. The article summarizes the results of wind tunnel experiments and parametrizes the wind and turbulent energy field generated in the wake of a subscale (1:25) tractor-boom model. The authors stress that the wake of a tractor-boom combination is complex, with several factors influencing the wake including ambient wind, sprayer body, boom geometry, sprayer sheet blockage from nozzle effluent, tractor thermal exhaust and engine heating, tire motion, and surface effects from the ground and crop. They performed wind tunnel experiments with the wind direction along the centerline of the tractor. A boundary layer profile generation system was used. Results suggest that the tractor-boom combination impacts the velocity patterns within and near the tractor wake. As expected, the region behind the tractor is more chaotic. The wake begins to settle at a distance of 5 m downwind. The boom articulation linkages appear to have an impact on the velocity profile. The authors observed that the results support the unexpected conclusion that the velocity and turbulence fields behind the spray boom are essentially the same whether the nozzle boom spray is on or off. Teske et al. (2016a) later investigated airflow patterns around a spray rig to better understand the effect of wind direction on the wake of the spray rig. Their wind tunnel experiments involved measuring the velocity and turbulence levels with the wind blowing from five angles ranging from a headwind to a tailwind. Their overarching goal was to use the wake model to enhance atmospheric and surface effects to improve spray drift predictions.

The presence of the spray boom section is responsible for the measured velocity decrease downwind of the boom, regardless of the presence of a spray curtain, according to wind tunnel experiments carried out by Teske et al. (2016b). Also, they observed that the turbulence level decreases substantially below the boom section regardless of whether a spray is present or not. Their results confirmed that smaller droplets are more responsive to higher wind speeds in the tunnel and deposit farther downwind as a result, with the notable observation that a 19% increase in wind speed resulted in a much greater increase in deposition. One key result from their study is that the velocity and turbulence fields behind the spray boom are the same whether a spray curtain is present or not.

Sonic anemometers have been used to characterize turbulent flows induced by the motion of vehicles. Gordon et al. (2012) performed on-road measurements to investigate the effects of vehicle type and following distance on turbulence and pollutants mixing. Vehicle-mounted sonic anemometers were used. Rao et al. (2002) also used sonic anemometers to take measurements in vehicle wakes. The trailer-mounted instruments were used to collect data at a number of locations following a grid for vehicle speeds ranging from 16 to 80 km/h. Alonso-Estébanez et al. (2012) experimentally investigated traffic-induced turbulence. The study attempted to improve knowledge about the influence of traffic-related parameters on turbulence. Linear relationships between vehicle speed and TKE values were found with coefficients of determination of 0.75 and 0.55 for a larger truck and a delivery van, respectively. The vehicle-induced fluctuations in the wind components showed the highest values for the longitudinal component because of the wake-passing effect. In the analysis of wake produced by moving vehicles, it is indicated how the turbulence dissipates in relation to distance and height. The TKE values were found to be higher at the measuring points closer to the surface during the wake analysis. Values of wake-passing effect were obtained from three anemometers located at a height of 0.7 m. The larger vehicle produced TKE values of 4.6 m²/s² at 60 km/h, while the delivery van produced a TKE of 0.41 m²/s² at the same speed. The data suggested that most of the TKE was dissipated over a distance of 3 to 4 m for the larger vehicle.

The literature review clearly shows that Teske et al. (2009, 2011, 2015, 2016a, and 2016b) have made significant contributions to agricultural spray modeling, notably by developing several of the necessary building blocks required to characterize agricultural spray operations. Their more recent work on the wake of ground sprayers is of particular interest to the work reported herein. The approach taken in the present work is to develop the tools and establish a methodology to collect field data with full-scale sprayers. The proposed work aims to close the gap between wind tunnel investigations and field data, and provides baseline information to researchers collecting experimental data in field conditions.

The objectives of the research reported herein were (1) to study the airflow patterns that develop in the wake of high-clearance sprayers in field conditions, and (2) to develop computational fluid dynamics (CFD) models to generate data on airflow patterns that can guide experimental efforts, be correlated to field data, and provide a basis for the investigation of different machinery geometry or speed of operation scenarios. The overarching goal of this work is to develop a solid framework and identify trends that might help determine directions in research of wake effects when studying spray deposition and spray drift. The CFD modeling activities that were undertaken to guide the field experiments are presented first, followed by the materials and methods deployed for experimental data collection. A discussion of the results is presented next and a summary section concludes this article.

**Computational Fluid Dynamics Simulations**

Prior to conducting field trials, CFD simulations were performed. Given the relatively elaborate experimental setup, the acquisition of field data to develop a high-resolution map of the airflow patterns in the wake of sprayers had to be preceded by a limited-scope effort to establish a robust methodology. As part of that definition
phase reported herein, CFD models were developed to highlight regions of interest and identify trends (e.g., effect of travel speed or of various geometric features on the sprayer). Models of sprayer tires were initially developed to assess the potential contribution of the rotating tire and wheel on the turbulence generated by the sprayer. A model with a rotating reference frame was developed to capture the momentum of the tire and wheel. The outer surfaces of the tires have a tangential velocity boundary condition that assumes that only the component of velocity parallel to the surfaces is of interest. By using a moving reference frame for the wheel and tire body, a constant grid flux is added in the Navier-Stokes momentum equation and it also takes into account the pressure component of the forces at the surfaces (along with the shear component). This method applies extra momentum sources within the wheel-tire region to mimic motion. The tires were also subjected to the headwind that is used in wind tunnel (or open road) simulations to account for the velocity of the vehicle. The simulations were performed using the commercial software STAR-CCM+ and simulation parameters included a prism layer mesh, mesh refinement in the wake of the tire, k-ω turbulence, and segregated flow. The width of the fluid domain (tunnel) was approximately 10 times that of the tire, its length upwind of the tire approximately 4 times the tire diameter (D), its length downwind of the tire approximately 6.5D, and its height approximately 6D. The mesh size in the fluid domain was approximately 0.1 m, with 0.05 m elements in the wake refinement zone. The objective was to identify trends, and not necessarily to develop high-fidelity models. A 3D representation of the TKE values generated by one of the rotating tire investigated is presented in Fig. 1. On the figure, the elements in the domain that have a TKE value under the selected minimum value of 0.5 J/kg are not coloured. Conversely, any regions with a TKE value above the maximum of 2 J/kg is coloured red. While no hard conclusions can be drawn from the single wheel simulation, it provides an indication that the rotating wheel does generate relatively high TKE levels and that the energy dissipates over a distance of several meters; these observations were accounted for in the experimental design. Of note are the difference in the TKE levels and the extent of the region of influence when comparing the two modeling approaches (with and without the rotating reference frame). The results suggest that it is advisable to account for the rotation of the tires in future simulations. Various configurations of a full sprayer were also investigated as illustrated in Fig. 2. The sprayer models were prepared based on the same principles as the single wheel models. The size of the wind tunnel was 22.8 m high by 68.4 m long by 24 m wide. The model sprayer was a geometrical simplification of a large self-propelled sprayer (3.6 m wide by 9.7 m long by 11 m wide). The size of the elements in the prism layer mesh was 0.00625 m, and was progressively doubled in size seven times to reach an element size of 0.8 m in the regions further away from the sprayer. The mesh was refined over a distance of 10 m in the wake of the sprayer at a spread angle of 50°. The same rotating frame of reference was used for the wheels of the sprayer models.

Because of the initial observations made on the single wheel simulations, the region of the tires was further investigated from the sprayer simulations. Fig. 2 depicts the TKE values generated on a vertical plane passing through the wheels of the sprayer at mid-width. A comparison of Fig. 2a and Fig. 2b shows the impact of the rotating wheels that result in lower TKE values in the wake of the sprayer. Fig. 2c and Fig. 2d show the turbulence induced by the presence of the boom. In Fig. 2d removing the mudguards resulted in lower turbulence intensity around the wheels and in the wake of the sprayer.

Fig. 3 presents a 3D rendition of the TKE levels that develop around various configurations of the sprayer at travel speeds of 2 and 8 m/s. As expected, the airflow

![Fig. 1. TKE values resulting from the rotation and headwind for a flotation (650/65R38) tire at 8 m/s: (a) with, and (b) without a moving reference frame for the region inside the wheel (for reference, the figure is cut off at a longitudinal distance of approximately 5 m from the center of the wheel).](image-url)
patterns around a self-propelled sprayer are relatively complex. The increase in travel speed resulted in an increase in turbulence intensity and in the size of the region of influence of the sprayer. It can also be observed that the structural members of the boom have an influence in shielding the region immediately downwind or in generating turbulence. It is also noteworthy that small changes in the geometry of the sprayer can have some impact on the turbulence levels. For instance, removing the mudguards (Fig. 3d) has some impact on the turbulence in the wake of the sprayer. Again, the inclusion of rotating wheels does reduce the turbulence intensity in the wake of the sprayer, especially at the lower travel speed (Fig. 3b). The lateral impact of including the wheel rotation can be observed at the 8 m/s travel speed (Fig. 3b' compared to Fig. 3a'; the flow patterns also appear to be affected over a distance of several meters in the longitudinal direction).

MATERIALS AND METHODS
Field Trials
Based on the results of the CFD simulations, field trials were planned. Two series of field experiments were conducted to quantify the flow field behind the booms of two full-size sprayers (Spra Coupe 4640 and John Deere R4045) as influenced by the travel speed of the implements. The study involved the use of ultrasonic anemometers (Young model 81000) on full-size sprayers traveling on agricultural land to map the airflow field around the implements. During each test run, three anemometers were used, with two located in the wake of the sprayer and one located ahead of the sprayer. The front anemometer was 1.8 m above the ground for the Spra Coupe, and 2.8 m above the ground for the John Deere. An adjustable structure was designed to attach to the booms of the sprayers and support the anemometers for field trials (Fig. 4). The support structure allowed the instruments to be situated at the locations of interest in the wake of the sprayer. As can be seen in Fig. 4, the support apparatus was minimal in structure and placed a good distance from the instruments to minimize any effects of the support structure on the airflow measurements. The locations of the anemometers during the field trials are illustrated in Fig. 5. All data were acquired at a rate of 50 Hz, except for the weather station that was set to record data every 30 seconds.

Table 1. Instruments and data acquisition system used during the field experiments.

<table>
<thead>
<tr>
<th>Description</th>
<th>Make</th>
<th>Model</th>
<th>Resolution</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic anemometers (3)</td>
<td>Young</td>
<td>81000</td>
<td>0.01 m/s and 0.1°</td>
<td>0-40 m/s; 0-360° azimuth; ±60° elevation</td>
<td>±0.05 m/s and ±2°</td>
</tr>
<tr>
<td>Three-axis accelerometers (2)</td>
<td>Silicon Designs</td>
<td>2220-025</td>
<td>0.001 g</td>
<td>±10 g</td>
<td>0.05%</td>
</tr>
<tr>
<td>Weather station</td>
<td>Onset Hobo</td>
<td>H21-002</td>
<td>0.02°C at 25°C; 0.1% RH; 0.5 m/s; 1°</td>
<td>-40°C to 75°C; 0-100% RH; 0-76 m/s; 0-355°</td>
<td>±0.21°C; ±2.5% from 10% to 90% RH; ±1.1 m/s; ±7°</td>
</tr>
<tr>
<td>Data acquisition system</td>
<td>Somat</td>
<td>eDAQ (ECP, ECOM, EHLS)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>16 bit</td>
</tr>
<tr>
<td>GPS receiver</td>
<td>Garmin</td>
<td>GPS18x-5Hz</td>
<td>n.a.</td>
<td>0-515 m/s</td>
<td>0.05 m/s</td>
</tr>
</tbody>
</table>

Fig. 2. Turbulent kinetic energy levels on a vertical plane passing through the wheels of the sprayer at mid-width: (a) tractor as a bluff body, (b) tractor with rotating wheels, (c) tractor with rotating wheels and boom, and (d) tractor with rotating wheels and boom but without mudguards.
Fig. 3. Turbulence kinetic energy results for various computational fluid dynamics scenarios (the lettered results correspond to a headwind of 2 m/s, the primed lettered results correspond to a headwind of 8 m/s; scenario (a) is the tractor as a bluff body, (b) is the tractor with rotating wheels (the pink vectors are used as a visual indicator of tire rotation), (c) is the tractor with tire rotation and boom structure, and (d) is the same as (c) but with the mudguards removed).
Two test series were conducted: measurements with the Spra Coupe were taken on December 3, 2015, and the John Deere sprayer was used on May 18, 2016. The booms of both sprayers were kept at a height of approximately 0.75 m above the ground. The anemometers in the wake of the boom were located at the same height as the boom. The wind was relatively calm on both days with minimal changes in direction (Fig. 6); the average wind speed and direction was 3.2 m/s and 149.2° on December 3 (RMS of 3.2 m/s and 149.3°), and 4.3 m/s and 280.5° on May 18 (RMS of 4.5 m/s and 281.3°). The air temperature, relative humidity, and barometric pressure were all stable during testing. The air temperature was within a range of approximately 4°C on December 3, and approximately 6°C on May 18. The experimental treatments are summarized in Table 2. The sprayers were driven on the same in-field test track. The length of the test track allowed for relatively long trials (60 to 120 seconds), and two replications of each test were performed (the sprayers were driven twice in each direction). The 10-s long portion of the data that was collected at the most stable travel speed for each trial was used for analysis.

Table 2. Experimental treatments.

<table>
<thead>
<tr>
<th></th>
<th>Spra Coupe</th>
<th>John Deere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel speed (m/s)</td>
<td>2, 8</td>
<td>2, 6, 8</td>
</tr>
<tr>
<td>Longitudinal position of the anemometers downwind of the nozzles (mm)</td>
<td>500, 900, 1500</td>
<td>406, 2171</td>
</tr>
<tr>
<td>Sprayer Heading</td>
<td>North, South</td>
<td>Boom, Tire [a]</td>
</tr>
<tr>
<td>Lateral position of the anemometers in the wake of the sprayer</td>
<td>n.a.</td>
<td>On [b], Off</td>
</tr>
<tr>
<td>Nozzles</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[a] the Tire position refers to that closest to the tire centerline while the Boom position is laterally further down the boom
[b] water was sprayed for the “nozzles on” treatment

Fig. 4. Adjustable support structure used to position the anemometers at the locations of interest.

Fig. 5. Location of the anemometers for (a) Spra Coupe and (b) John Deere sprayers (the blue circles represent the anemometers; dimensions are in millimeters; generic sprayers are used for illustrative purposes).
The turbulence kinetic energy (TKE) was used to characterize the wake of the sprayers in operational conditions in the field. The TKE is the mean kinetic energy per unit mass associated with eddies in turbulent flow. Physically, the turbulence kinetic energy is characterized by measured root-mean-square velocity fluctuations. A fluctuating velocity \( u' \) can be defined as the difference between the instantaneous velocity \( u \) and the mean velocity \( \bar{u} \):

\[
    u' = u - \bar{u}
\]  

where the overbar denotes a time average. A measure of the intensity of the turbulence is the root-mean-square \( \sigma \) of the fluctuating components of velocity \( u, v, \) and \( w \); Fig. 7 illustrates the axes of the anemometers.

\[
    \sigma (u') = \left( \overline{u'^2} \right)^{0.5}
\]

(2)

\[
    \sigma (v') = \left( \overline{v'^2} \right)^{0.5}
\]

(3)

\[
    \sigma (w') = \left( \overline{w'^2} \right)^{0.5}
\]

(4)

with the velocity components:

\[
    u = -1 \cdot \sin(\phi) \cdot (\text{wind speed} \cdot \cos(\theta))
\]

(5)

\[
    v = -1 \cdot \cos(\phi) \cdot (\text{wind speed} \cdot \cos(\theta))
\]

(6)

\[
    w = (\text{wind speed} \cdot \sin(\theta))
\]

(7)

where \( \phi \) is the wind direction angle and \( \theta \) the wind elevation angle.

These are formed by taking the square root of the time average of the squares of the fluctuating velocities. The root-mean-square values are standard deviations of instantaneous velocities. They are always positive quantities, and their magnitudes are a measure of the strength or intensity of the turbulence, or the spread of instantaneous velocities around the mean. TKE is calculated as:

\[
    TKE = 0.5 \left( \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right)
\]

(8)

The calculations were performed over 10-second periods where the sprayer travel velocity was stable during a test run. The air velocity components measured by the anemometers were normalized against the relative velocity of the air by vectorially combining the ambient wind velocity \( (u_w, v_w) \) and the sprayer velocity \( (u_s, v_s) \). The wind created by the sprayer is assumed to be in a direction opposite to the direction of travel, and to have a speed equal to the speed of travel of the sprayer.

**Fig. 7.** Cartesian axes of the anemometers.
The resultant magnitude was used to normalize the three velocity components of the air velocity vector measured by the anemometers:

$$\text{TKE}_n = 0.5 \left( \frac{u'^2}{U_{\text{ref}}^2} + \frac{v'^2}{U_{\text{ref}}^2} + \frac{w'^2}{U_{\text{ref}}^2} \right)$$

where $U_{\text{ref}} = \sqrt{(u' + u_s)^2 + (v' + v_s)^2}$

There are limitations with the proposed analysis. The measurement volume of the anemometers is approximately 130 mm high (distance between the top and bottom transducers on the instrument). The center of the sampled air column was vertically aligned with the sprayer nozzles. The turbulent length scale is a fraction of the height of the nozzles with respect to the ground (750 mm). The smaller scale eddies may have been filtered out as a result. The short sampling times also means that the larger time scales of the turbulence could not be captured. The data from the accelerometer mounted to one of the anemometers was analyzed for selected runs. The instantaneous velocity variations were small in all three directions (typical results between -0.1 and 0.1 m/s for trials at 8 m/s travel velocity and between -0.04 and 0.04 m/s for trials at 2 m/s), and the average velocity variations during the 10-s periods of interest were 0 m/s. It is therefore believed that vibration effects can be neglected for the purpose of this investigation.

Fig. 8. Summary of TKE results for the Spra Coupe sprayer at three distances behind the boom of the sprayer, two travel velocities, and two lateral locations along the boom (the “Tire” location is aligned with the centerline of the rear tire of the sprayer and the “Boom” location is 3,650 mm from the tire centerline along the boom; the target velocities of 2 and 8 m/s are used in the chart; the actual travel velocity may have varied).

RESULTS AND DISCUSSION

As mentioned, the TKE in the wake of the sprayers was the focus of the study. A graphical summary of the TKE results is presented in Fig. 8 and Fig. 9.

The normalized TKE data (TKE$_n$) in the wake of the sprayer were statistically analyzed. An analysis of variance (ANOVA) was performed using the general linear model at a 95% confidence level on the data set obtained with the two sprayers. The TKE$_n$ values obtained from the December 3 trials with the Spra Coupe were not normally distributed so a Box-Cox transformation was applied. The results of the ANOVA indicate that for the Spra Coupe used on that day, the TKE$_n$ is affected by the experimental treatments of travel speed, heading, and lateral location. Pairwise comparisons using Tukey simultaneous 95% confidence intervals confirm that the TKE$_n$ at the two travel speeds are significantly different. The same conclusion was reached for the two lateral locations and the two headings. The interaction plots (not presented) confirmed some of the observations made during data analysis. There is an interaction between the heading and the travel speed. It points to the effect of the wind and the amount of shielding provided by the tractor depending on the position of the anemometers with respect to the wind direction. The results of the statistical analysis are summarized in Table 3.
The ANOVA results for the trials involving the John Deere sprayer suggest that all the treatments had a significant impact on $\text{TKE}_n$, except for the presence of a water spray (nozzles on or off treatment; this observation is in agreement with what was reported by Teske et al., 2015). Tukey simultaneous 95% confidence intervals indicate that two lateral locations, the two headings, and the two longitudinal locations are significantly different for $\text{TKE}_n$. Only the 8 m/s travel speed was significantly different, with 2 and 6 m/s resulting in $\text{TKE}_n$ values that are not significantly different. A summary of the Tukey pairwise comparisons is included in Table 4.

**Table 3.** Comparison of the mean normalized $\text{TKE}$ values for the experimental treatments applied to the Spra Coupe sprayer (means that do not share a letter under the each treatment are significantly different according to Tukey’s pairwise comparison tests at a 95% confidence level).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Value</th>
<th>Mean $\text{TKE}_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral location</td>
<td>Boom</td>
<td>0.009 a</td>
</tr>
<tr>
<td></td>
<td>Tire</td>
<td>0.022 b</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>500 mm downwind of</td>
<td>0.013 a</td>
</tr>
<tr>
<td>location</td>
<td>the nozzles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>900 mm downwind of</td>
<td>0.014 a</td>
</tr>
<tr>
<td></td>
<td>the nozzles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,500 mm downwind of</td>
<td>0.016 a</td>
</tr>
<tr>
<td></td>
<td>the nozzles</td>
<td></td>
</tr>
<tr>
<td>Travel speed</td>
<td>2 m/s</td>
<td>0.026 a</td>
</tr>
<tr>
<td></td>
<td>8 m/s</td>
<td>0.008 b</td>
</tr>
<tr>
<td>Sprayer heading</td>
<td>North</td>
<td>0.031 a</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>0.007 b</td>
</tr>
</tbody>
</table>

**Table 4.** Comparison of the mean normalized $\text{TKE}$ values for the experimental treatments applied to the John Deere sprayer (means that do not share a letter under the each treatment are significantly different according to Tukey’s pairwise comparison tests at a 95% confidence level).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Value</th>
<th>Mean $\text{TKE}_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral location</td>
<td>Boom</td>
<td>0.040 a</td>
</tr>
<tr>
<td></td>
<td>Tire</td>
<td>0.020 b</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>406 mm downwind of</td>
<td>0.025 b</td>
</tr>
<tr>
<td>location</td>
<td>the nozzles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2,171 mm downwind of</td>
<td>0.031 a</td>
</tr>
<tr>
<td></td>
<td>the nozzles</td>
<td></td>
</tr>
<tr>
<td>Travel speed</td>
<td>2 m/s</td>
<td>0.034 a</td>
</tr>
<tr>
<td></td>
<td>6 m/s</td>
<td>0.031 a</td>
</tr>
<tr>
<td></td>
<td>8 m/s</td>
<td>0.021 b</td>
</tr>
<tr>
<td>Sprayer heading</td>
<td>North</td>
<td>0.024 a</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>0.033 b</td>
</tr>
<tr>
<td>Nozzles</td>
<td>On</td>
<td>0.028 a</td>
</tr>
<tr>
<td></td>
<td>Off</td>
<td>0.028 a</td>
</tr>
</tbody>
</table>

**Fig. 9.** Summary of TKE results for the John Deere sprayer at two distances behind the boom of the sprayer, three travel velocities, two lateral locations along the boom, and with the nozzles on and off (the “Tire” location is aligned with the centerline of the rear tire of the sprayer and the “Boom” location is 3,690 mm from the tire centerline along the boom; the target velocities of 2, 6 and 8 m/s are used in the chart; the actual travel velocity may have varied).
For both sprayers, increasing the travel speed from 2 to 8 m/s significantly impacted the TKE values. It is also interesting to note that the lateral location where the TKE was calculated, either in line with the rear tire of the sprayer or further down the boom, provides significantly different results. It is hypothesized that the geometry of the sprayers can explain the observed differences. The path between the rear tires and the boom of the Spra Coupe is a lot less obstructed than that of the John Deere. The larger John Deere sprayer has mudguards on all tires and its boom has more structural elements capable of affecting the airflow. The most notable interaction for the John Deere sprayer is that between heading and lateral location of the anemometers, again suggesting that shielding effects may be important. The limited number of replicates in the experimental data sets imposes prudence in the statistical analysis and interpretation of the results.

Teske et al. (2015) reported plots relating the value of \( q^2/U_0 r^2 \) for various spatial locations in the wake of the scale sprayer used in wind tunnel experiments. When considering their results at a boom height of 650 mm, 900 mm behind the boom, and a measurement height of 1,000 mm, the values of \( q^2/U_0 r^2 \) vary between approximately 0.035 and 0.05 for lateral distances from the sprayer centerline of approximately 1,500 and 5,000 mm, corresponding to the lateral locations investigated in this study (at the tire centerline and approximately 3,600 mm from the tire centerline). The TKE calculated from the field data for a boom height of 750 mm, 900 mm behind the boom averages between 0.019 and 0.033; those values are comparable to the results of Teske et al. (2015) in the same range of lateral locations along the boom.

CONCLUSIONS

The goal of this project was to develop data to address the high-level questions whether turbulent airflow patterns exist near the nozzles of high-clearance sprayers and to determine whether such turbulence can affect the spray. The importance and complexity of those research questions have been highlighted in the literature. Although this initial effort did not provide definite answers, it is hoped that an important foundation for further research has been established here.

The combination of large machines and high speeds of operation creates unprecedented aerodynamic conditions. While it is clear that these conditions are unknown, one must also recognize that the methods required to quantify them were also undefined. The research reported herein established robust experimental methods and numerically investigated fundamental underlying phenomena, which are both necessary steps required to progress towards the ultimate objective. The high dependency of the TKE results on the location where the data was collected (or simulated) suggest that high-resolution mapping of airflow in the wake of high-clearance sprayers is of interest.

The so-what to the work reported herein very much emphasizes the path forward. Further research will need to include multiphase CFD investigations where the effect of the airflow patterns on the liquid spray are studied. The experimental results in this study suggest that the presence of a spray does not affect the airflow (in agreement with Teske et al., 2015). The more important question is whether the spray is affected by the airflow. Another important question is how the drift is affected by the airflow. Future work will need to consider the energy of the spray in relation to the direction of airflow in the wake of the sprayer as well as the turbulence intensity. Ambient wind conditions will need to be considered as they have a significant impact on turbulence levels. It may also be necessary to consider more detailed sprayer topologies to include more geometry effects. While the analysis presented in this preliminary work is focused on TKE, the magnitude and direction of airflow vectors at locations of interest should also be considered in future work.

Vibrations from the sprayer and the relative roughness of the field (vs. wind tunnel or concrete track) are hypothesized to have introduced a certain level of variability in the air velocity measurements. As a result, two recommendations are made for further experimental work. The first is to extend the size of the data set in terms of replications of the treatments, but also the addition of measurement location to increase the resolution of airflow mapping behind the sprayer. The second recommendation is to use multi-hole probes more suited to complex flow fields (with high amounts of swirl such as in the wake of vehicles). The important impact of the ambient wind can also be better understood (and filtered out) with a larger amount of data. These measurements and simulations, combined with drift trials, will allow understanding the impact of the wake of the sprayer on the spray and on the fate of small droplets. These aspects currently elude the research community and are important factors in recommending efficient and safe spraying practices.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support provided by the Western Grains Research Foundation. They are also grateful to Mr. Kevin Ulrich for providing access to a test field.

REFERENCES


