Comparison of Agricultural Spray Measurement Techniques

Steven A. Fredericks\textsuperscript{a}, Daniel C Bissell\textsuperscript{a}, Christopher J. Hogan\textsuperscript{b}, Bernard Olson\textsuperscript{b}, Lillian C Magidow\textsuperscript{a}, Gregory K Dahl\textsuperscript{a}, Joe V Gednalske\textsuperscript{a}

\textsuperscript{a}Winfield United, River Falls, WI
\textsuperscript{b}University of Minnesota, Department of Mechanical Engineering, Minneapolis, MN
Outline

• What are we measuring?
  • Droplet size distributions
  • Distribution Statistics

• What story does that tell us?
  • Interpreting distributions

• How do we measure it?
  • Measurement techniques

• When should we choose which method?
Droplet Size Distributions

• **Histogram**
  • \( dV \) plotted against \( D \)
  • Sensitive to binning
    • Choice of \( dD \) important
  • Usually default output

• **Cumulative**
  • \( \sum dV \) plotted against \( D \)
  • Hard to identify peak locations or multimodal distributions
Droplet Size Distributions

• Distribution Function
  • $dV/dD$ plotted against $D$
  • Less sensitive to binning
  • Easy to manipulate mathematically
  • Best choice for performing fits
    • Poisson Distribution
    • Log Normal Distribution
    • Gamma Distribution
Weighted Distributions

- **Volume** – spray volume in a size bin: $dV = \frac{\pi}{6} D^3 dN$
- **Number** – number of droplets in a size bin: $dN$
- **Area** – surface area in a size bin: $dA = 4\pi D^2 dN$
Weighted Distributions – Physical Meaning

Number  VS  Volume
Weighted Distributions – What they tell us

• Volume (or mass)
  • Gives dosing information
  • Standard for air quality measurements (μg/m³)
  • Weighted towards larger drops

• Number (or frequency)
  • Governs transport process
  • Gives insight into atomization process
  • Weighed towards smaller drops

• Area
  • Governs optical properties (haze)
  • Used in respiratory health and inhaled pharmaceuticals
Distribution Statistics

• Reduce full distribution to representative value(s)
• Potentially remove important information
• Common Examples:
  • Weighted Means: \( D_{i,0} = \frac{\sum (dN \ast D^i)}{N} \)
    • Diameter of average drop in the spray
  • Weighted Medians: \( D_{\phi_{0.5}} \) 50% in Cumulative Distribution
    • 50% of spray will be in drops larger diameter
  • Relative Spans: \( \left( D_{\phi_{0.9}} - D_{\phi_{0.1}} \right) / D_{\phi_{0.5}} \)
    • Distribution width approximation
  • Fraction below threshold
Statistics Example – XR 11003 with water

\[ D_{1.0} = 107, \quad D_{2.0} = 266, \quad D_{3.0} = 354 \]

\[ 88.2\% \]
\[ 44.1\% \]
\[ 22.4\% \]

\[ D_{N0.5} = 75 \]
\[ D_{V0.5} = 320 \]
\[ D_{A0.5} = 219 \]

150 µm
Distribution Statistics

• More descriptive, but less common
  • Fit parameters
    • Gaussian
    • Poisson
    • Log Normal
    • Gamma
  • Moments: \( \mu_i = \int d^i \ast \phi(d) dd \)
  • Standard Central Moments: \( \frac{\mu_i}{\mu_2^{i/2}} = \frac{\int (d-\mu_1)^i \ast \phi(d) dd}{(\int (d-\mu_1)^2 \ast \phi(d) dd)^{i/2}} \)
    • mean, standard deviation, skew, kurtosis, etc.
Distribution vs Statistics

• Statistics
  • Easy to communicate
  • (Try to) collapse distribution to representative values
  • Increase number of statistics reported to better classify the distribution

• Distributions
  • Tell the whole story
  • Same VMD and % fines can have very different dynamics
Measurement Methods

• Optical Sizing – Usually lab methods
  • Imaging (Flow Visualization/Shadowgraphy)
  • Laser Diffraction (LD)
  • Phase Doppler Particle Analysis (PDPA)

• Aerodynamic Sampling – Usually field methods
  • Filter Samplers
  • Impactors
  • Elutriators
Imaging (Flow Visualization/Shadowgraphy)

- Camera
- Plane of Best Focus
- Focal Depth / Depth of Field
- Back Light Illumination (Diffuse or Collimated)
Imaging Takeaways

• Good for qualitative observations
• Difficult to produce quantitative measurements
• Require several frames for converged statistics
• Resolution and framerate limited
• Depth of field influences size measurement
• Out of focus rejection required
Laser Diffraction
Laser Diffraction Takeaways

• Integrated, volumetric measurement
• Measures spatial intensity distribution
• Distribution measurement
• Low sensitivity to drop shape and refractive index
Phase Doppler Particle Analysis
Phase Doppler Particle Analysis
Phase Doppler Particle Analysis Takeaways

• Point measurement
• Sensitive to drop shape and complex refractive index
• Information about individual drops
• Size and velocity information
Measurement Comparisons – Field of View

Laser Diffraction

Phase Doppler Particle Analysis

Imaging (variable)

Not To Scale
Measurement Comparisons - Experiment

- Standalone spray stand
- TSI 2-component PDPA, FSA3500
- Internal Reflection, $D_{\text{max}} \sim 1700\text{um}$
- 120 mm downstream of outlet, 33 sweeps 3mm increments

- Wind tunnel environment, 15mph
- Sympatec HELOS, R7 lens,
- $D_{\text{max}} \sim 2200\text{um}$, 9ms Sampling Rate
- 400 mm downstream
Laser Diffraction Selected Data – TTI 11004

Roundup + Xtendimax
Truncated Leading Edge in LD

- Only observed in number distributions
- Moves as peak shifts
- Data inversion/fitting artifact?
- Large droplets obscuring small ones?
Droplet Obscuration

Droplet overlap very common in volumetric measurements.
Droplet overlap very common in volumetric measurements.

Frame B

156.4 um
74.8 um
380.8 um
PDPA Selected Data – TTI 11004

Roundup + Xtendimax

Number Distribution

Volume Distribution
Non-Spherical Droplets in PDPA
Data Intercomparison – TTI 11004

Roundup + Xtendimax

Number Distribution

Volume Distribution

LD
PDPA
Data Intercomparison – TTI 11004

Roundup + Xtendimax + OnTarget

Number Distribution

Volume Distribution

LD
PDPA
Data Intercomparison – TTI 11004

Roundup + Xtendimax + OnTarget + InterLock

Number Distribution

Volume Distribution
Data Intercomparison – UR 11004

Roundup + Xtendimax

**Number Distribution**

**Volume Distribution**

LD

PDPA
Data Intercomparison – XR 11004

Roundup + Xtendimax

Number Distribution

Volume Distribution

\( \frac{dN_{\text{frac}}}{d\log(D)} \)

\( \frac{dV_{\text{frac}}}{d\log(D)} \)

LD
PDPA
## Measurements Summary

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Imaging</th>
<th>Laser Diffraction</th>
<th>Phase Doppler Particle Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Volume</td>
<td>Largest, integrated in optical path, variable with optics</td>
<td>Large, integrated in optical path</td>
<td>Single point, flux measurement</td>
</tr>
<tr>
<td>Measurement Output</td>
<td>Qualitative, Individual droplet size possible</td>
<td>Binned size distribution</td>
<td>Individual droplet size and velocity</td>
</tr>
<tr>
<td>Challenges</td>
<td>Focusing, Image processing, Resolution</td>
<td>Black box data processing, Binned measurement</td>
<td>Non-spherical droplets, Inhomogeneous droplets</td>
</tr>
<tr>
<td>Advantages</td>
<td>Minimal equipment required</td>
<td>Turn-key operation, quick distribution measurements</td>
<td>Detailed per-drop data collection</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>Minimal alignment, Extensive processing, Medium duration</td>
<td>Minimal alignment, Short sampling duration</td>
<td>Involved alignment/focusing, Long sampling duration</td>
</tr>
<tr>
<td>Best Choice For</td>
<td>Droplet interactions and spray morphology, Number distributions</td>
<td>Sharp distributions, high throughput testing, Volume distributions</td>
<td>Detailed droplet statistics, Broad distributions (&gt;~1mm), Number distributions</td>
</tr>
</tbody>
</table>
## Measurements Selection

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Imaging</th>
<th>Laser Diffraction</th>
<th>PDPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Sheet</td>
<td>☺</td>
<td></td>
<td>☺</td>
</tr>
<tr>
<td>Sheet Breakup</td>
<td>☺</td>
<td></td>
<td>☺</td>
</tr>
<tr>
<td>Droplet Size Distribution</td>
<td>☹</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Number Distribution</td>
<td>☹</td>
<td>☹</td>
<td>☺</td>
</tr>
<tr>
<td>Volume Distribution</td>
<td>☹</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Individual Droplet Data</td>
<td>☹</td>
<td></td>
<td>☺</td>
</tr>
<tr>
<td>Non-Spherical Droplets &amp; Ligaments</td>
<td>☹</td>
<td>☺</td>
<td>☹</td>
</tr>
<tr>
<td>Droplet Velocity</td>
<td>☹</td>
<td></td>
<td>☺</td>
</tr>
<tr>
<td>Droplets with Emulsions (Complex Tank Mixes)</td>
<td>☹</td>
<td>☺</td>
<td>☹</td>
</tr>
<tr>
<td>Droplets with Solid Suspensions (SC Formulations)</td>
<td>☹</td>
<td>☺</td>
<td>☹</td>
</tr>
<tr>
<td>Droplets with Air Bubbles (Air Inclusion Nozzles)</td>
<td>☹</td>
<td>☺</td>
<td>☹</td>
</tr>
</tbody>
</table>

No Symbol: Not Possible       ☺: Good Choice       ☹: Possible but Difficult       ☹: Likely to Produce Errors
Wrap Up

• There is no best measurement technique
  • Each technique has tradeoffs
  • Target the measurement to the question

• Winfield United is leveraging them all!
  • We have the capability to perform all 3 methods
  • Intercompare results for a more complete understanding

• Collaboration with UMN researchers
  • Developing improved calibration methods across all 3 techniques
Thank You

Q & A

Steven Fredericks
Sr. Research Engineer
Winfield United
Sfredericks@landolakes.com