Vibrational Excitation and Analysis of Fluids to Predict Atomization Characteristics

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Abstract

In industrial spraying and coating, fluids to be atomized are often complex solutions, mixtures, emulsions and suspensions of multiple constituents. While prediction of and insight into the resulting droplet size and spray dynamics is challenging enough for Newtonian, simple fluids, such as fuels, it is even more poorly developed for these complex fluids. A particular case is agricultural spraying where "tank mixes" of many (apprx. 6 – 8) formulations of crop production agents are often prepared and sprayed. These mixes are commonly observed to behave very differently from simple test fluids used to develop atomization and spray transport models. As a precursor to developing a field-deployable system for testing fluids prior to or during atomization, the feasibility of vibration measurements as an indictor of fluid atomization properties was investigated. A number of fluid mixtures, including agrochemicals and spray adjuvants such as surfactants, polymers and herbicides were sprayed using typical agricultural flat fan and hollow cone hydraulic nozzles. During spraying, the characteristic vibration of the liquid sheet exiting the nozzle orifice was measured and the droplet size spectra were determined. The composition of the fluid was found to affect both the vibration and the droplet size. Decreased droplet size was correlated with higher vibration, particularly in the 7 to 9 kHz range. Alteration of the fluid mixture through additions of surfactants or polymers was easily detected through vibrational analysis.

Introduction and Theoretical Background

The physical results of atomization, i.e., droplet size spectra, spray kinetics and spray distribution, are strongly influenced by the atomizer design and the fluid physical properties. Unlike combustion and other atomization processes where the fluid properties are well defined, relatively invariant or even standardized, industrial processes may atomize slurries, mixtures and other complex fluids. A particular case is the spray application of agricultural pesticides, fertilizers and growth regulators. Commercially, an application can include a number, up to ten or more, of individual constituents of a "tank mix". Because these individual products may be supplied by a number of manufacturers and each tank mix preparation may be unique, there are seldom any data upon which nozzle selection or droplet size prediction can be made for the particular tank mix. The consequences of this lack of control over atomization properties and poor guidance for nozzle selection can range from inadequate target coverage when droplet size is excessively large or unacceptable spray drift and environmental contamination when droplet size is excessively small.

The goal of the project which this paper addresses is the development and evaluation of a means by which atomization properties of a fluid and the atomization process can be predicted and monitored. The end product will be a field deployable device that can be used to test fluid mixtures prior to atomization and/or monitor the atomization process in real time to provide the equipment operator or process controller with guidance about the atomization process or proper selection of atomizers and operating conditions. The engineering premise of the technique is to use the natural vibration characteristics of atomization as an indicator of the atomization process.

The fundamental understanding of the mechanical vibration associated with atomization and the influence of fluid physical properties on the vibration was discussed by Lefebvre [1] and detailed by the work of York et al. [2] which addressed sheet breakup similar to that of a flat fan, hydraulic atomizer often used in agricultural spraying (Figure 1).

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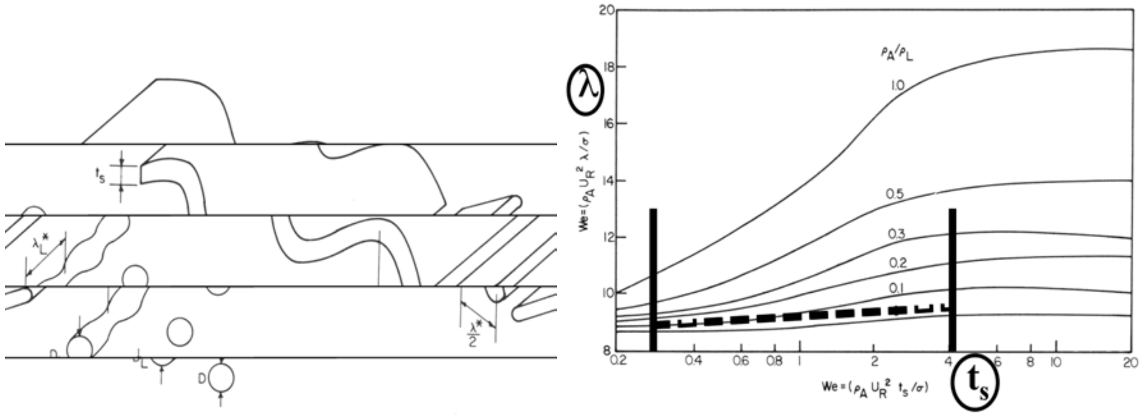


Figure 1. Generalized sheet break-up model of atomization showing (left) the characteristic wave length, λ, and the sheet thickness t_s; given the sheet exit velocity of U, the characteristic frequency would be U/λ; the nondimensional plot on the right indicates the relationship between atomization variables in ideal sheet break up (adapted from York et al. [2]).

The fundamental mechanism, described by the sheet thickness and instability wavelength Weber numbers was used to estimate the expected frequencies of typical atomization from typical agricultural flat fan nozzles. The parameters used were air density, $\rho_A = 1.29$ kg/m^3 , fluid density, $\rho_L = 1000$ kg/m^3 , the ratio, $\rho_A / \rho_L = 0.001$, surface tension values of $\sigma = 0.055$ to 0.073 kg/s^2 , exit sheet velocity, $U_r = 12$ to 15 m/s, sheet thickness, $t_s = 0.0001$ to 0.0003 m. This resulted in a We (t_s) = 0.3 to 2.0 and We (λ) = 9.0. Given that the expression of York et al. teaches We (λ) = $\rho_A U_r^2 \lambda / \sigma$□$f = U_r / \lambda$ (right plot of Figure 1), characteristic frequencies of the nozzle would be $f = \rho_A U_r^3 / 9 \sigma$, resulting in expected frequencies of f = 3.5 to 9.5 kHz with higher frequencies associated with lower surface tension. Note that surface tension is the primary fluid property directly expressed in the theory (density, ρ_L plays a minor role). While not expressed explicitly, fluid viscosity would implicitly affect the sheet thickness and the velocity distribution within the sheet itself. Therefore, the basic premise that fluid properties would affect the frequency distribution, viz., the power spectrum, of the atomization process was theoretically confirmed and the expected range of frequencies (centered at 6 kHz) was estimated.

Materials and Methods

With the primary application of the work expected to be agricultural pesticide spraying, the experimental approach was focused on agricultural materials and atomizers. Actual industrial tank mixes of commercial products were used to create a range of mixtures. Nozzles were selected from typical nozzles used on the industry and two types of droplet size measurements were made, viz., "static" measurements, where the nozzles discharged spray into quiescent air and "dynamic" measurements in a wind tunnel where the nozzles discharged into high speed air flow, simulating spraying from an aircraft. A series of droplet size tests were conducted with a range of nozzle, operating conditions (pressure, air speed, orientation between nozzle and air stream) and fluids. The test matrix included flat fan, disc-core, hollow cone, deflector plate, straight stream and air inclusion nozzles. All nozzles were manufactured by Spraying Systems, Inc. except for the deflector plate nozzle which was manufacturer by CP Products, Inc. Operating pressures were 280 and 560 kPa. Air speeds for the dynamic tests were 160 and 240 km/h. The test fluids included 9 commonly used spray mixture adjuvants, ranging from organosilicone surfactant (SI-100, RNA Corporation) to paraffinic petroleum oils (Oil Spreader, Custom Agricultural Formulators, Inc.) to polymer anti-drift agents (Mist Control, Miller Chemical, Inc.) The herbicide glyphosate was also tested as an active ingredient using two formulations (Round Up Ultra Max, Monsanto, Inc.; Rodeo, Dow Chemical, Inc.) Solid powders were modeled using a kaolin clay material, (Surround, Englehard Chemical, Inc.). While a wide range of tank mixes were tested, only a small sample of the experimental results can be presented in this paper.

The wind tunnel test facility for dynamic atomization measurements had a 0.6 x 0.6 m wide working section, a length of 3 m and could achieve air speeds of 250 km/hr. Droplet size spectra were measured using a Sympatec Helios droplet size analyzer with the R-7 lens option. All runs were replicated a minimum of three times. Vibration was measured using an ICP Triaxial accelerometer (PCB Piezoelectronics, Inc.) coupled to a range of spray nozzles operating at 280 kPa. Vibration (acceleration) was recorded on an oscilloscope (Tektronix 4044B) and analyzed through a Fast Fourier Transform to produce the vibration spectra over the range of 100 Hz to 10 kHz. The technique was described further by Giles [3]. All runs were replicated three times.

Results and Discussion

The following results, selected from the large number of tests, highlights the effect of fluid properties on droplet size using two important classes of adjuvants, viz., a surfactant used to reduce surface tension and a polymer used to decrease the generation of small droplets and moreover, the simultaneous addition of these two adjuvants to a spray mix and it also addresses two important atomization situations: a) a straight stream nozzle oriented normal to a high speed airstream, indicative of aerial application and b) a disk core, hollow cone nozzle operating at a 0 degree orientation (co-linear) with the airflow at a velocity typically found in orchard air blast sprayers.

For the first comparison, data were used for four representative test fluids: a) municipal tap water, b) water + 0.25% v/v of an organosilicone surfactant (SI-100) expected to reduce the surface tension below 30 dyne/cm, c) water + 1.0% v/v of a polyvinyl polymer (Mist-Control) expected to reduce the generation of small droplets, and d) water + 0.25% SI-100 and 1.0% Mist Control, representing the seemingly contradictory tank mix recipes often observed in field applications. The droplet size spectra (expressed as cumulative distributions) are shown in Figure 2. As expected, the fluid properties did affect the resulting droplet size spectra, primarily the reduction of the vmd with the addition of surfactant and the increase of the vmd with the addition of polymer and the predominant effect of surfactant when both polymer and surfactant were added.

Vibration data from the same fluid mixtures were drawn from the library of results. A typical power spectrum for vibration from a standard agricultural nozzle (Turbo TeeJet 11004) for the example fluids is shown in Figure 3. The predominant frequency of atomization is centered at approximately 5.5 kHz, as predicted by the fundamental theory. However, fluid differences are more apparent in the higher frequencies and when the scale is changed from a logarithmic to a linear scale. In most cases of data analysis, the most significant differences in vibration results were found in the 7 to 9 kHz frequency band, consistent with the theoretical development. For these fluids, data were drawn from the vibrations observed for the standard 11005 flat fan nozzle and the Turbo TeeJet 11004 chambered-type flat fan nozzle. The vibration results are shown in Figure 4.

The raw power spectra are shown as the thin lines and a moving average is shown in the thick lines. The results show, as hypothesized, that the more easily atomized fluid, i.e., the surfactant solution, produced noticeably more vibration in the 7 – 9 kHz frequency band while the polymer solution produced almost no vibration in the frequency band. The vibration and droplet size results from these tests were combined by summing the relative vibration from the two test nozzles and comparing to the volume median diameter of the droplet size tests. The results are shown in Figure 5, along with a power-law fitted curve. These results indicate the feasibility of detecting atomization differences in fluids using vibration and even suggest that useful, empirical numerical relationships may exist.

Another example is presented to address a common aspect of ground-based spraying. Considering that glyphosate is a very commonly applied herbicide and also a concern for spray drift, this example will use the product Rodeo, an aquatic environment formulation of glyphosate with few surfactants added. Rodeo alone was tested and Rodeo + the surfactant SI-100 was tested. Using a common ground application nozzle used for drift reduction, the Turbo TeeJet 11004, a chamber-type flat fan nozzle operating at 280 kPa, the droplet size spectra for the two tank mixtures were measured as shown in Figure 6 and the vibration profile was also measured using the same nozzle operating at 280 kPa (Figure 7). The droplet size was observed to significantly decrease with the addition of the surfactant and vibration was noted to significantly increase with the addition of the surfactant. An applicator making a simple test would immediately be alerted to the increased drift potential due to the addition of the adjuvant. The adjuvant increased the fraction of droplets under 200 μm from 28 to 40% and reduced the volume median diameter from 275 to 225 μm.

A final example illustrates the benefit of adding a drift control agent and how the vibration system could indicate to an applicator that the tank mix addition would enlarge the droplet size spectra, and potentially reduce drift. In the example, the common product Round Up Original Max (with included surfactants blended into the formulation as labeled and sold by the agrochemical company) was sprayed through a small hollow cone nozzle (TX-6) at 280 kPa. Then, a drift control agent, namely a polymer (Mist Control) was added to the tank. The droplet size spectra for the spray, with and without the polymer is shown in Figure 8. Correspondingly, the vibration profile, again through the Turbo TeeJet 11004 nozzle at 280 kPa is also shown (Figure 9). Again, as in previous examples, the effect of the drift reducing agent was readily obvious in both the vibration and droplet size results.

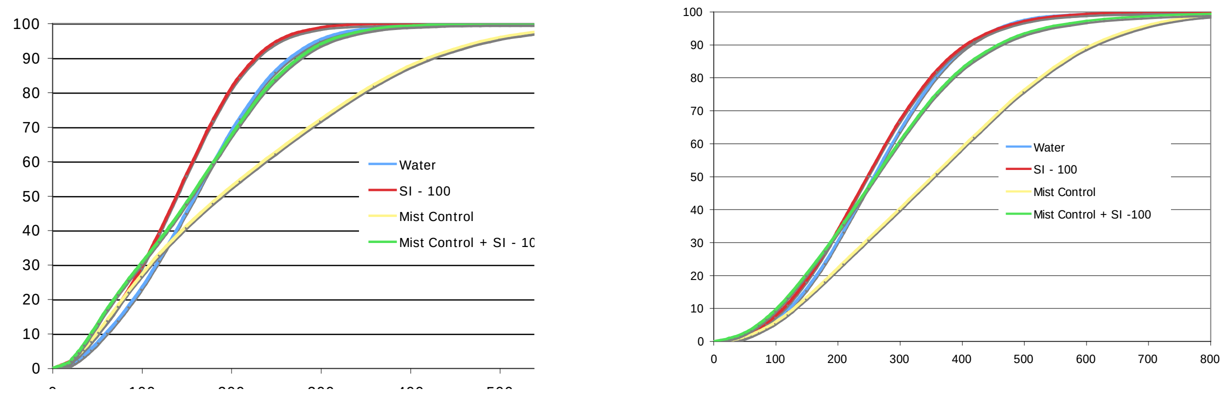


Figure 2. Droplet size spectra for (left) an aerial application (D5 straight stream, 90 deg, 240 km/hr) and (right) an orchard air blast application (D5-45 hollow cone, 0 deg, 160 km/hr) for four test fluid mixtures.

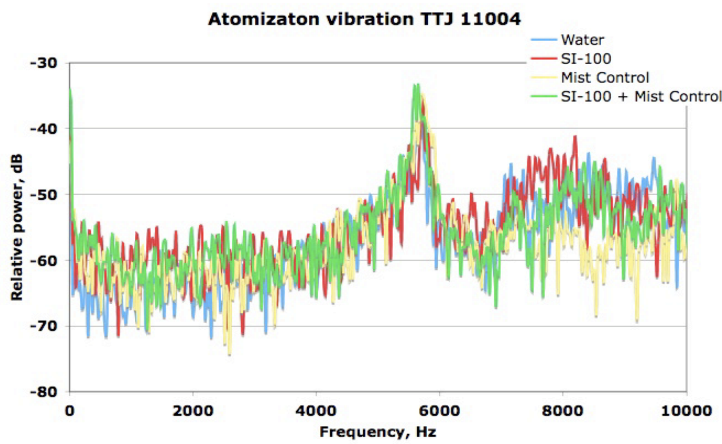


Figure 3. Observed vibration data for test fluids of water, water+surfactant, water+ polymer and water+surfactant+polymer discharged from a Turbo TeeJet 11004 nozzle at 280 kPa operating pressure.

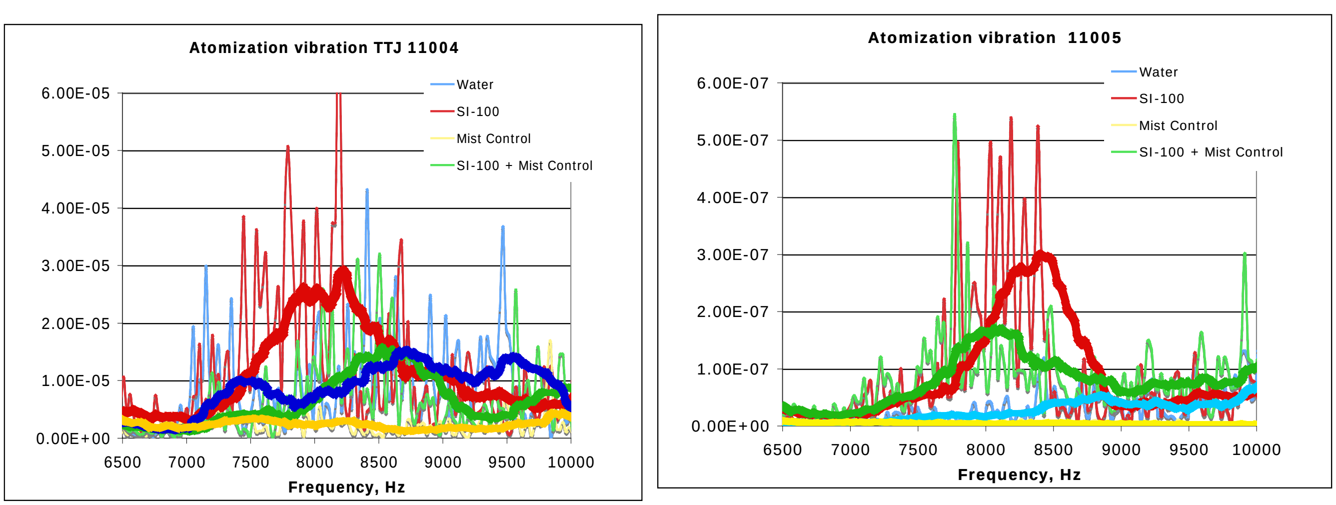


Figure 4. Vibration results for test fluids of water, water+surfactant, water+ polymer and water+surfactant+polymer atomized with a TTJ 11004 and a 11005 flat fan nozzle at 280 kPa liquid pressure.

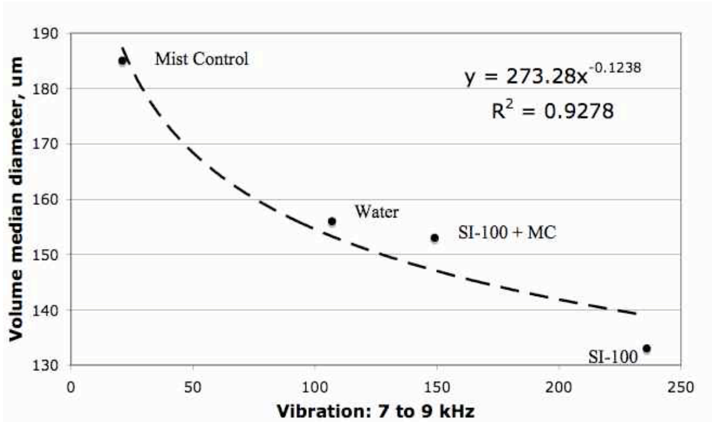


Figure 5. Relationship between vibration results of four test fluids and the corresponding vmd of the droplet size spectra for the fluid when atomized in conditions simulating aerial application.

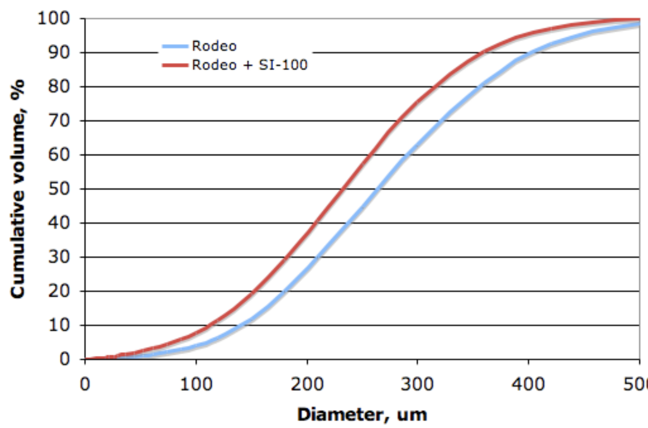
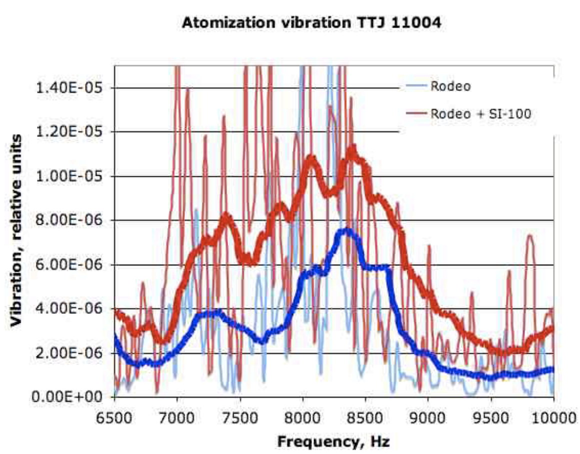


Figure 6. Droplet size spectra for glyphosate (Rodeo) with and without a surfactant when atomized through a TurboTeeJet 11004 nozzle at 280 kPa .



- Figure 7. Vibration spectra for glyphosate (Rodeo) with and without a surfactant when atomized through a TurboTeeJet 11004 nozzle at 280 kPa.

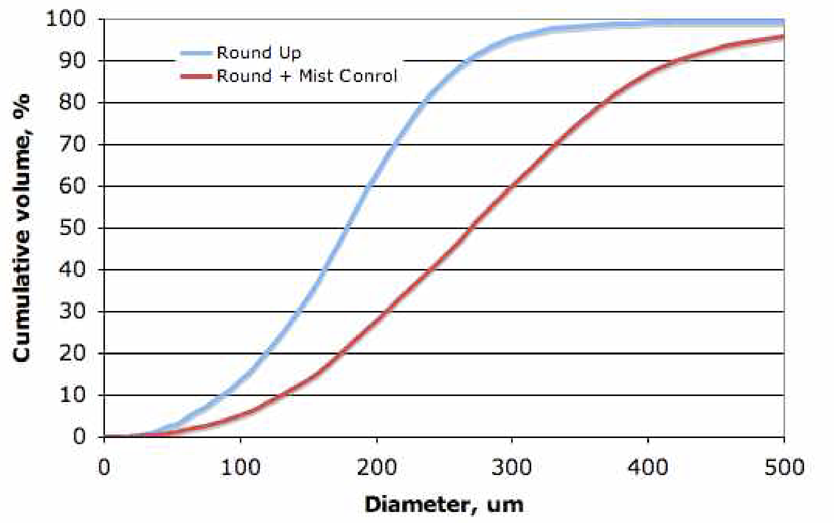


Figure 8. Droplet size spectra for glyphosate (Round Up Original Max) with and without a polymer when atomized through a TX -6 hollow cone nozzle at 280 kPa.

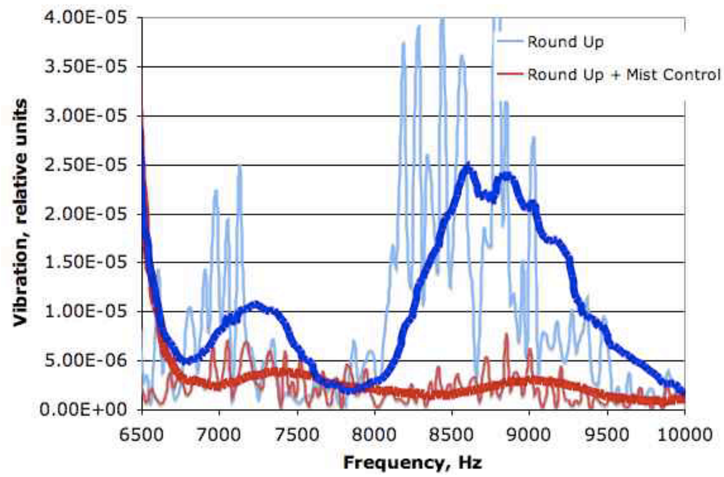


Figure 9. Vibration spectra for glyphosate (Round Up Original Max) with and without a polymer when atomized through a TurboTeeJet 11004 nozzle at 280 kPa.

Conclusion

A relationship between vibration of a range of fluids during atomization and the effect of fluid properties on resulting droplet size spectra was observed. As expected, fluids with characteristics of being easier to atomize produced smaller droplet size spectra and, concurrently, higher magnitudes of vibration in the 6 to 9 kHz frequency band. The results suggest that measurement of vibration of fluids during atomization may be useful in predicting droplet size spectra or fluid physical properties.

References

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