ENERGY EFFICIENT PRIMARY ATOMIZATION OF VISCOUS FOOD OILS USING AN ELECTROSTATIC METHOD

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Food oil coating applications typically require spraying with relatively viscous liquids. Traditional spray methods can by inefficient, requiring a large amount of energy to produce a uniform coating and/or producing a significant degree of overspray. The electrostatic charge injection atomization technique is shown to be appropriate for these viscous and dielectric food oils, where an additional electrical power of $\approx 0.1W$ *is required. Electrical performance data and also spray imaging and quantitative drop size measurement using phase Doppler interferometry are presented for atomizer orifice diameters of 150 and 250* μm *and liquid injection velocities of 10m/s . The typical average drop diameter is typically 70% of the orifice diameter. The results show the atomization performance is independent of liquid viscosity over a viscosity range of factor 50.*

KEY WORDS: *electrohydrodynamics, electrostatic atomization, soybean oil*

NOMENCLATURE

D_{10}	arithmetic mean diameter, μm
d	orifice diameter, μm
I_T	total current, μA
I_L	leakage current, μA
I_S	total current, μA
L	inter-electrode gap, μm
n	refractive index
Q_L	flow rate, ml/min
q	charge, C
q_v	spray specific charge, C/m^3
r	radial position, mm
u	velocity, m/s
u_j	jet velocity, m/s
V	voltage, V
λ	wavelength, nm
μ	dynamic viscosity, cP
ρ	density, g/ml
ρ_e	electrical resistivity, Ωm
σ	surface tension, dyn/cm
Re_j	Reynolds Number, $u_j \rho_l d/\mu_l$
We	Weber Number, $\rho_g {u_j}^2 d/\sigma$

1. INTRODUCTION

Oil coating applications can be found in many industries, here we focus on the food processing industry. Edible oil coatings are typically used to apply ingredients and as release agents. The goal is to apply an even coating of oil of known weight per unit area with minimal overspray. Overspray can result in the undesired collection of oil on surrounding surfaces and the need to filter oil from the surrounding air to maintain air quality standards.

Traditionally, oil is sprayed using hydraulic nozzles; high pressure is used to generate the kinetic energy necessary to overcome the viscosity and surface energy density to generate atomization. Larger droplets mostly hit the intended target to be coated but may ricochet off, resulting in overspray. Smaller droplets with low velocities may get carried off by the air currents generated by the nozzle spray. These smaller droplets result in the majority of the overspray. Droplet sizes of 10 microns and under can penetrate deep into a person’s lungs and pose significant health risks resulting in the need for filtration, Cooper and Alley (2011).

In many cases, oil is heated before it is sprayed to reduce its viscosity to obtain a more uniform spray pattern. Heating also increases the number of small droplets that do not collect on the intended target Kalata et al (2014). Spraying hot oil may lead to uncomfortable and dangerous work conditions by increasing the air temperature in the environment around the process and by being a burn hazard if anyone was to come in contact with it. Also, heating oil can add significant cost to an oil coating process.

Spraying oil by electrostatic atomization using a charge injection nozzle atomizes the liquid without the need to heat or apply high pressures while reducing overspray. The focus of this study was to analyze the spray characteristics of an electrostatic atomization nozzle spraying pure soybean oil. This study experimentally investigated drop size, velocity and spray pattern concentration for various flow rates, orifice diameters.

Charge injection electrostatic atomizers are unique in being able to electrically charge and then electrostatically atomize dielectric oils at industrially useful flow rates. Early research was conducted by Kim and Robinson (1976) and Robinson et al (1980). Charge injection atomizers contain both the high voltage and ground electrodes together in the nozzle. The dielectric fluid flows between the two electrodes before exiting the nozzle through an orifice. The fluid exits as a solid jet which then breaks up into individual droplets when the electrons move to the surface of the jet and overcome the surface tension forces. This process is called electrostatic atomization and has been studied extensively for mineral oils by Yule et al (1995), Shrimpton and Yule (1999), Rigit and Shrimpton (2006) among others. This type of charge injection can work with high pressures Ergene et al (2011), and can work with higher flow rates while providing higher charge injection than electrostatic spraying nozzles. This study is focused on high viscosity food oils in order to demonstrate the excellent atomization performance response of the technique with respect to a severe increase in viscosity. In addition to demonstrate the technique can be use to spray edible oils on coating applications, where the electrically charge plume should reduce overspray, due to the electrically charged drops being attracted to the target surface.

2. MATERIALS AND METHODS

The oil used in this study is 100% food-grade soybean oil, the properties of which can be found in Table 1. The density of the oil was measured using a pycnometer and was found to be slightly less than that of water. The surface tension was measured using a Kruss K20 tensiometer, and it was found to be about half that of water. The refractive index of the oil was measured using a Reichert AR200 Digital Refractometer. This property was utilized in the setup of the phase Doppler interferometry system used to measure droplet size and velocity. Dynamic viscosity was measured using a Brookfield DV-II viscometer. A constant viscosity value was measured for various shear rates demonstrating that the soybean oil is a Newtonian fluid. Resistivity was derived from a conductivity measurement taken with a D-2, Inc. jet fuel handheld conductivity meter.

A schematic of the nozzle setup used in this study is shown in Fig. 1. A pressure vessel was used to deliver oil to the nozzle. The oil was filtered with two 10 micron oil filters connected in parallel to reduce the overall pressure drop across the filters. A rotameter style flow meter was used to measure the volumetric flow rate of the oil. A high precision needle valve was used to control the oil flow rate, and a 100 psi digital pressure gauge was used to measure the pressure at the nozzle.

The nozzle used in this study is a 3rd generation electrostatic atomizer designed by Rigit and Shrimpton (2006), which is a plane-to-plane charge injection nozzle. This design features a guide for the electrode to keep it centered over the orifice and allows for the inter-electrode gap, L, to be easily adjusted. This adjustment was made using a micrometer head with a non-rotating spindle that has a resolution of 0.0254 mm (0.001 in). Removable orifice plates attach to the bottom of the nozzle allowing the flexibility to test various orifice diameters, d. These features are shown in the nozzle section view shown in Fig. 2. A blunt tungsten round bar with its sharp edges removed made up the high voltage electrode in this nozzle producing a plane-to-plane charge injection atomizer. The charge that builds up on the electrode surface is pulled off by the moving oil and is also believed to be injected into the oil through an electrochemical process Alj et al (1985) resulting in strong levels of charge injection.

An Acopian N030HP1 high-voltage power supply (HVPS) was used in this experiment to charge the nozzle. This HVPS outputs a negative polarity voltage between 0 to

-30 kV with the current limited to a maximum of 1 mA. Since this power supply contains analog meters for display of the output voltage and current, two Falcon F35 digital panel voltage meters were wired to the HVPS to monitor these outputs providing a resolution of 100 V and 0.1 mA respectively.

The electrical performance of the nozzle was determined by measuring the leakage current, I_L; the current that leaks to the body of the nozzle, and the spray current, I_S; the current carried by the spray plume. The spray current was measured directly using a BK Precision 2831E digital multimeter (DMM) with a resolution of 0.1 μA. The spray current was generated by the collection of the charged spray on steel wool lining the spray can. With the small inter-electrode gaps used in this study, $0.06 \leq L \leq 0.30$ mm, there was a risk of a catastrophic breakdown or arc between the two electrodes in the nozzle if dirt or air got in between them or if the voltage was too high. Attempting to measure the leakage current directly and without protection could lead to permanent damage to a DMM when a catastrophic breakdown occurs. To protect the DMM, an MTL-Instruments CA90F surge protector was used to discharge the current from the electrical discharge to ground safely.

Drop size and velocity measurements were taken with an Artium PDI-200MD two-dimensional phase Doppler interferometry (PDI) system along with Artium Integrated Management Software (AIMS) version 4.4. This device measures droplet size, velocity in two directions for each particle that passes through the measurement volume generated by intersecting laser beam pairs. The PDI system was setup with a 500 mm and 1000 mm focal length lenses for the transmitter and receiver respectively and with the receiver positioned for the 40 degrees off-axis forward scatter position providing a measurable drop size range of 2.6 to 385.6 μm. The primary measurement channel utilized a pair of green, $\lambda = 532\ nm$, laser beams that measured droplet size and axial velocity, which was established to be the positive z-direction, denoted by u_z. The second channel used a pair of red, $\lambda = 660\ nm$, laser beams and only measured droplet velocity in the radial direction, u_r. The phase Doppler measurement technique has been well studied and can be further reviewed in publications by Bachalo and Houser (1984). The instrument setup and acquisition were performed like that described by Bade and Schick (2011).

The spray plume shape and distribution was analyzed using an Olympus i-SPEED TR high-speed imaging (HSI) system and the LaVision, Inc. SprayMaster system. The HSI system can acquire videos with a frame rate up to 10,000 fps and with a maximum pixel resolution of 1280 x 1024 up to 2,000 fps. HSI was used to view the primary ligament breakup mechanism of the charge injection atomizer. The LaVision SprayMaster system was used to take laser sheet images (LSI) of planar cross sections of the spray. This system consisted of an Electro Scientific Industries, Inc. Solo PIV Nd:YAG dual laser and a LaVision high-speed Imager Intense camera. The LSI system uses a short-duration pulsed laser that is passed through a divergent lens to generate a laser sheet that illuminates a cross-section of the spray. This green $\lambda = 532\ nm$ laser sheet had a Gaussian intensity profile and is about 1 mm thick. A band-pass lens filter is attached to the camera lens only allowing the light of the wavelength of the laser to pass to the CCD sensor. The liquid droplets scatter the laser light according to the Mie theory where the light intensity is equivalent to the surface area of the droplet. This system was used to qualitatively evaluate the spray plume distribution and to quantitatively evaluate shape and size.

3. RESULTS AND DISCUSSION

The electrical performance of the electrostatic atomization nozzle was investigated for various orifice diameters (d), inter-electrode gap ratios (L/d), and flow rates (Q_L). The electrical performance was evaluated by calculating the total current (I_T) injected into the fluid as well as the volumetric spray specific charge (q_v) or just spray specific charge. These values are calculated by Eqs. 1 and 2 below. The total current is the sum of both the leakage and spray currents whereas the spray specific charge is the ratio of the spray current to the volumetric flow rate of the oil.

$$I_T = I_S + I_L \tag{1}$$

$$q_v = \frac{I_S}{Q_L} \tag{2}$$

The electrical performance of the nozzle was evaluated by plotting total current and spray specific charge versus voltage as can be found in Figs. 3 through 4 respectively. Note the stepwise graph for spray specific charge. This is due to the resolution of the DMM used being of the same order of magnitude as the spray current values measured. It appears that a linear relationship exists between both the total current and spray specific charge versus voltage. The spray specific charge reaches a maximum value before a sudden decrease to a value near, but above, zero. This is called the super-critical breakdown or partial breakdown condition where spray specific charge suddenly decreases but the total current continues to increase unaffected. For this condition, the charge injection is unaffected but the injected charge escapes to the nozzle body and by corona discharges in the air around the liquid jet before generating atomization Shrimpton and Masheyek (2009). It is also noted that the electrical power to generate atomization is minimal, less than 0.1W.

For both orifice diameters and jet velocities tested, the inter-electrode gap had the same impact on the total current and spray specific charge injected into the oil. Both of these values increased as the inter-electrode gap was increased. An increase in the jet velocity and its associated flow rate reduced the I_T and q_v for a given L/d and voltage. We tested a range of L/d values and $L/d = 0.8 - 1.0$ was found to be optimal in terms of operational stability. If L/d is too small then the atomizer electrically shorts, and if too large the electrical spray current is not sufficient. Hence only $L/d = 0.8 - 1.0$ data are presented in this paper. Table 2 shows the maximum spray specific charge for the various orifice diameters and flow rates tested. The maximum spray specific charge increased for higher flow rates but was reduced when the orifice diameter was increased from 150 μm to 200 μm. The observations discussed for the total current and spray specific charge versus voltage follows expected trends displayed in previous studies by Rigit and Shrimpton (2006), Malkawi (2009) and others. Note, for Table 2, the length scale used to calculate Re and We numbers was the orifice diameter. The Reynolds Number indicates whether a liquid jet is in a laminar or a turbulent state, and the boundary for this regime change is when $Re \approx 2000$. The classic example is the flow emerging from a tap, when in laminar flow the surface is smooth and glassy. Clearly, from table 2, the liquid jet in this atomizer is operating in the laminar regime, and this is due to the elevated viscosity of the liquid. The Weber number represents the ratio of the disruptive inertial forces at the jet surface and the stabilizing surface tension forces. Higher values represent changes in the atomization regime and better natural atomization (ignoring charge effects) due to relatively more aerodynamic forces. However this also requires higher Re_j, of the order 1000. Therefore the baseline (zero charge) jet break up mechanism is very much like a dripping tap, which is known as ’Rayleigh Breakup’. We can therefore safely conclude that the atomization of the jet to drops is driven entirely by electrical forces, which makes the electrical power required to achieve this quite remarkable.

The characteristics of the spray plume were investigated using HSI and LSI. Fig. 5 shows the primary breakup mechanism for the charge injection electrostatic atomizer. Perturbations develop in the solid jet that exits the nozzle, which moves the charges on the surface of the jet closer to each other. The mutual repulsion of the like charges bend the solid jet forming the expanding helical pattern shown in Fig. 5. Eventually, the helical ligaments stretch too far and break apart into droplets Malkawi et al (2010). The secondary atomization is not visible in Fig. 5, but can be seen in Fig. 6. Small droplets with high charge to mass ratio escape from the larger droplets in the spray plume. These smaller droplets are fairly uniform in size and initially move normal to the direction of the larger drops they escape from. They move slowly with respect to the larger droplets in the spray plume, and are easily carried by the electrical field generated by the nozzle along with air currents. The majority of these drops collect on the nozzle body or on neighboring surfaces, which makes it important to ground all surfaces in the vicinity of the electrostatic atomizer to prevent the buildup of charge and the chance for static discharge. This observation was also noted by Shrimpton and Yule (1999) when spraying kerosene. From this testing with soybean oil, the small droplets could not be eliminated but could be greatly reduced by lowering the voltage. When the nozzle is operating near maximum spray specific charge, it is generating a significant amount of these small, highly charged droplets. For the metal coating application noted in the introduction, the preferred mode of operation is to inject at approximately 70% of the maximum spray charge. This provides excellent uniform coating and minimal overspray.

Fig. 7 shows laser sheet images taken at various distances from the nozzle. 1500 images were taken at each height from the nozzle, were averaged into a single image and then corrected for the camera angle. The electrostatic atomizer makes a full cone spray pattern. At a distance of 40 mm from the nozzle, the spray plume was very concentrated as is shown by the dark red in the center of the spray as is shown in Fig. 8. Note, the green trail above the spray plume in this figure (in the +y region around x=0) is due to the illumination of the spray plume above the laser sheet due to the scattering of the laser sheet light. At further distances from the nozzle, the spray plume expands and becomes less dense. The small droplets generated by secondary atomization are not easily captured by the LSI system, but the very faint outer-spray is primarily made up of these droplets. These small droplets have very small surface area, hence, did not scatter as intense of a light on the camera as the larger droplets did.

The drop size statistics and velocities were measured using a PDI system and the results are shown in Fig. 9. The arithmetic mean diameter, D_{10} is plotted versus radial position from the center of the spray for the conditions tested at four different spray distances. The drops size, D, was normalized by the orifice diameter, d, for the given test condition. Drop size measurements were taken for the operating conditions of 150 and 200 μm orifice diameters, 10 m/s jet velocities and an L/d ratio of 0.8 with the nozzle operating steadily under maximum spray specific charge. The larger droplets made up the main spray plume while outside the main spray plume resided much smaller and slowly moving droplets. Similar drop size trends have been previously published by Shrimpton and Yule (1999) for kerosene ($u_{inj} = 10\ m/s$, $d = 250\ \mu m$, $\rho_v = 1.2\ C/m^3$), which has a dynamic viscosity around 1.3 cP. This is roughly 2% that of soybean oil. Both soybean oil and kerosene have similar surface tension, which are 33 dyn/cm and 25 dyn/cm respectively. This seeming independence in viscosity would be an important advantage of spraying these types of highly viscous dielectric fluids via electrostatic atomization nozzle instead of a traditional hydraulic nozzle where spray performance is greatly affected by the viscosity of the fluid. The reason for this lies in the jet atomization mechanism, and this has been discussed fully in Malkawi et al (2010). The kerosene spray is generated by a jet that breaks up without a helical instability as shown in Figure 5. This is revealed further in Figure 9, noting that the largest drops for the kerosene spray are on the axial centreline. Whereas for the current results, it is observed in Figure 9 that the largest drops are not found on the axis, but away from it. Furthermore it is observed that the large drop peak moves away from the axis at larger axial distances. This is due to the helical instability shown in Figure 5, and discussed more fully in Malkawi et al (2010).

4. CONCLUSION

This study investigates the viability in spraying soybean oil for coating applications via an electrostatic atomizing nozzle in an energy efficient manner. Various orifice diameters and jet velocities were studied for their effect on drop size. It was shown that the nozzle produced a full cone spray plume with fairly uniform spray coverage at 100 mm. Secondary atomization does generate undesired small droplets that drift with air currents, these charged and easily captured on grounded conducting plates or mesh. The atomizer can be operated at lower voltages to still obtain good atomization, but avoid these small drops being generated, and thus reduce overspray. The atomizer is ideal for oil coating applications as the charged droplets have relatively low momentum and are easily collected onto surfaces to be coated. The electric space charge in the spray plume naturally spreads the plume enhancing a uniform coating. The potential of the electrostatic atomizer’s performance being independent of viscosity is be a great benefit for using this nozzle over conventional hydraulic nozzles for oil coating processes and warrants further investigation.

5. REFERENCES

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FIGURE CAPTIONS AND TABLES

TABLE 1: Properties of Soybean Oil

Property	Value
Density, ρ (g/ml)	0.914
Dynamic Viscosity, μ (cP)	61.0
Surface Tension, σ (dyn/cm)	33.0
Refractive Index, n	1.474
Electrical Resistivity, ρ_e $(10^{10}\ \Omega m)$	66.7

TABLE 2: Maximum spray specific charge achieved for Soybean Oil with $L/d = 0.8$.

d (μm)	Q_v $\left(\frac{ml}{min}\right)$	u_j $\left(\frac{m}{s}\right)$	$q_{v,max}$ $\left(\frac{C}{m^3}\right)$	Re_j	We_j
150	10.6	10	3.9	20.7	382
	15.9	15	4.1	31.0	859
200	18.8	10	2.2	27.5	509
	28.3	15	2.5	41.3	1145

Figure 1 : Schematic of experiment setup.

Figure 2 : Section view of the electrostatic atomizer.

Figure 3 : Total current versus voltage for $L/d = 0.8.$ Note D indicated in the Legend is the orifice diameter.

Figure 4 : Spray specific charge versus voltage for $L/d = 0.8.$ Note D indicated in the Legend is the orifice diameter.

Figure 5 : HSI for $d = 150\mu m$, $L/d = 0.8$, $u_j = 10m/s$ and $q_v = 2.2C/m^3$ recorded at 5,000 fps.

Figure 6 : Electrostatic atomizer operating with $d = 200\mu m$, $L/d = 1.0$, $u_j = 10m/s$ and $q_v = 2.2C/m^3$.

Figure 7 : LSI for $d = 200\mu m$, $L/d = 0.8$, $u_j = 10m/s$ and $q_v = 1.2C/m^3$ at various distances from the nozzle.

Figure 8 : LSI at 40 mm from the nozzle.

Figure 9 : Normalized arithmetic mean diameter, D_{10}/d, for $L/d = 0.8$ and $u_j = 10m/s$. Kerosene data from Shrimpton and Yule (1999).