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Energy efficient primary atomization of viscous food oils using an electrostatic method

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ABSTRACT

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 10 m/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.

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 μm 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 Turnbull, 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

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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, $\rho_g u_j^2 d/\sigma$

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 µm 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.

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

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 and −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, $0.06 \le L \le 0.30$ 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 2.6–385.6 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