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Optimization of liquid electrostatic coating

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Abstract

Soybean oil with emulsifiers was atomized by electrohydrodynamic spraying. The relationships between voltage (20–40 kV), flow rate (28–88 g/s), emulsifier content (10–15%), apparent viscosity (45–53 mPa-s), conductivity (0.1–0.2 μS/m) and surface tension (43.1–46.0 mN/m) and both coating reproducibility and efficiency were mapped utilizing Response Surface Methodology. Voltage had the most significant effect on reproducibility, followed closely by conductivity, and then flow rate. Viscosity had the least significant effect on coating reproducibility and was only significant through interaction with other factors. Surface tension was not a significant effect. Reproducibility was increased by increasing charge concentration, which decreased droplet size. This was achieved at intermediate voltage, low conductivity, high viscosity and low flow rate. Flow rate had the most significant effect on efficiency followed by voltage and emulsifier content. Efficiency increased at low flow rate and voltage. Optimum conditions produce an optimum charge concentration, resulting in the most reproducible and efficient coating.

Keywords: Liquid coating; Electrostatics; Efficiency; Conductivity; Viscosity

1. Introduction

The electrostatic atomization of liquids is used in many diverse fields, including pollution research, meteorological experiments, crop spraying, paint spraying, electrostatic printing and the propulsion of space vehicles [1]. Electrostatic spraying systems have been used successfully in many industries for applying liquid sprays with improved spray depositions [2].

One of the emerging technologies in food manufacturing is the utilization of liquid electrostatic coating systems for coating foods with oils, emulsifiers and flavors. Electrostatic spraying has been used for the application of smoke flavors during smoke curing of fish and pork products, for impregnation of bread with vegetable oil, and for application of polishing and other liquid coating agents to sugar, confectionary and chocolate products [3].

The reason for this interest is the high degree of controllability and efficiency associated with the electrostatic atomization of liquids. The use of electrostatics has enabled certain industries to significantly improve their processes. In the agricultural application of pesticides, the use of electrostatics increased the deposition by a 2.3:1 ratio over traditional non-charged systems [4], increased evenness of the pesticide on the leaves [2], and decreased the amount of pesticide needed to control insects and weeds [5].

The areas that are most important in coating operations, including those utilizing electrostatics, are control, quality and cost reduction. Current coating systems have problems in these areas. Theoretically, electrostatics offers great potential for improvement. However, a lack of understanding of the underlying relationships between operating variables and spray quality in food systems has delayed the integration of these systems into the food industry.

In general, reproducibility and efficiency in electrostatic oiling have not been studied but droplet size and charge to mass have been. The factors having a statistically significant effect on droplet size and charge-to-mass are voltage, conductivity, mass flow rate, viscosity and surface tension, with conductivity having the greatest effect and

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surface tension having the least significant effect [6]. Therefore, it is likely that these factors would have the greatest effect on reproducibility and efficiency as well.

Smaller droplets should produce more reproducible coating. As the charge to mass increases, the drop size produced by electrohydrodynamic spraying decreases [6]. The charge to mass ratio on the droplet is increased by increasing conductivity [6] and increasing flow rate [7,8] but the highest charge to mass ratios occur at an intermediate voltage [4]. As voltage increases, charge to mass increases linearly, then decreases or is constant due to corona discharge [9]. Increasing charge to mass tends to decrease evenness [4]; however, many of the effects are in opposition. Therefore, it is difficult to predict how reproducibility and efficiency will be affected.

Very little work has been done on understanding the role of these factors on reproducibility and efficiency of spraying in food applications. This study maps the relationships between the machine and solution properties voltage, flow rate, emulsifier concentration, viscosity, surface tension and conductivity, and the final quality attributes reproducibility and efficiency. This was done to understand the underlying relationships important to the electrostatic atomization of liquids in food systems, optimize the process using RSM, and facilitate utilization of this technology in the food industry.

2. Materials and methods

Samples were coated in a TDC liquid electrostatic coater (Terronics Development Corporation, Elwood, IN). The pump used was a model 7144-05 magnetic drive pump with a variable speed of 180–3600 RPM (Micropump Inc., Vancouver, WA.). The voltage was controlled using a Hipotronics voltage source (Terronics Development Corporation, Elwood, IN) with an output capability of 0–60 kV and a maximum current rating of 2MA- 50/60 Hz.

The nozzle used was made of non-conductive material and contained a metal sheet with a serrated edge that charges the oil by conduction. The element was imbedded between the two-halves of the nozzle. Atomization occurs due to electrohydrodynamic disruption of the oil surface. Food-grade Alcolic-S lecithin (American lecithin company, Oxford, CT), soybean oil (Gordon Food Systems, Grand Rapids, MI) and methanol (Fisher Scientific, Fair Lawn, NJ) were used.

The effects of different concentrations of lecithin and methanol in soybean oil on conductivity and viscosity were plotted. Lecithin and methanol were selected due to their near-linear relationship with viscosity and conductivity and because the effect of combinations of methanol and lecithin on conductivity and viscosity was shown to be different from that of lecithin and methanol separately. Adding methanol enhanced the effect of lecithin on conductivity and viscosity resulting in combinations of conductivity and viscosity that can't be achieved by either lecithin or methanol alone. Methanol has no effect on conductivity by itself and only a small impact on viscosity. A full factorial design was used to map the effect of methanol and lecithin on conductivity and viscosity.

Conductivity was measured using a model 3200 conductivity meter using a model 3256 conductivity cell (Yellow Spring Instruments Corp, Yellow Springs, Ohio). Although the meter had an automatic calibration element, it was externally calibrated monthly to ensure proper measurement.

Apparent viscosity was measured using a Brookfield model DV-II + (RV) digital viscometer (Brookfield Engineering Labs Inc, Stoughton, MA) with spindle S00 (UL adapter), at 4.0 RPM. The solution and spindle were placed in the water-jacketed holder. 10 ml of sample were placed into the UL adapter container and then the spindle was inserted and a measurement taken after 30 s as the reading stabilized. The spindle and the container were cleaned after every sample. Tests were conducted at 25 °C.

Surface tension was measured using a SensaDyne Bubble Tensiometer Model PC500-LV (Chem-Dyne Research Corporation, Mesa, AZ). The surface tension was measured by pouring 50 ml of solution into a 50 ml beaker and then slowly lowering the probes into the solution. When the flow of bubbles reached a steady pace and bubbles started emerging from the second probe, a reading was taken. The probes were removed after each measurement and cleaned by rinsing them with water then acetone and finally wiping them down.

Charge to mass was measured by spraying the oil into a Faraday cup. The charge was measured with a Keithley electrometer, while the mass was determined by weighing. To determine the average droplet size, sheets of oil-sensitive paper CF1 (Ciba-Geigy Ltd. Basle, Switzerland) were weighed before and after coating. The number of droplets was counted. Dividing the net weight of liquid by the total number of droplets yielded the average droplet weight.

Glass cover slides (18×18 mm) were pre-weighed and positioned in 4 rows of 5 with the 5 slides positioned in 9 slots spanning the entire spray field. An empty space was left between each slide and the ones around it. The slides were arranged on top of a piece of paper to create uniform attraction to ground and to prevent leakage from one slide to another. The machine was allowed to run for 30 s before coating to reach steady state. The conveyor belt was then turned on and the slides were coated. The slides were coated at room temperature, 25 °C. The solution run-order was randomized by the computer. After the slides were coated, they were removed using tweezers and weighed again.

To coat the food items, 12.5% lecithin was coated at 20 KV voltage and 47.5 g/min flow rate, or 35 KV voltage and 27.5 g/min flow rate. The food targets were 1 cm cubes of colby jack cheese (Sargento Foods Inc. Plymouth, Wisconsin), 5×1 cm rectangles of milk chocolate (Hershey Food Corporation Hershey, PA) and 2.5×2.5 cm square club crackers (Keebler Co., Elmhurst, IL).