Engineering in Agriculture, Environment and Food xxx (2016) 1–7

Contents lists available at ScienceDirect

Engineering in Agriculture, Environment and Food

journal homepage: http://www.sciencedirect.com/eaef

Enhanced performance of an air-assisted electrostatic nozzle: Role of electrode material and its dimensional considerations in spray charging

Manoj Kumar Patel [a, b, *], Monika Kundu [c], Hemant Kumar Sahoo [b], Manoj Kumar Nayak [b]

[a] Academy of Scientific and Innovative Research, Rafi Marg, New Delhi 110 011, India
[b] CSIR–Central Scientific Instruments Organisation, Chandigarh 160 030, India
[c] Central Institute of Post–Harvest Engineering and Technology, Ludhiana 141 004, India

ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form
24 March 2016
Accepted 12 May 2016
Available online xxx

Keywords:
Air-assisted electrostatic nozzle
Aerodynamics
Breakdown voltage
Corona onset
Electrode material
Induction charging

ABSTRACT

The development of reliable means of charging for finely divided particulate matter is among the major portion of the research activities in electrostatic spraying. This paper presents the role of electrode material and engineering aspects in spray charging with emphasis on theoretical considerations of selection of electrode material and its dimensional shape and size. It reveals the charge-to-mass ratio dependency on variables such as electrode material, shape and geometrical specifications, which is in good agreement with the theoretical considerations. For the particular designed electrostatic nozzle, it is found that optimum electrode position is in the range of 2.0–3.0 mm from the nozzle tip. The copper electroplated with nickel as a charging electrode material can be plausible alternative for spray charging as excellent charge-to-mass ratio 2.8 mC/kg is attained for improved efficacy and efficiency of the electrostatic spraying processes. Possible limitations requiring further research includes the design for maximum charge injection rate, which is thought to be limited by corona breakdown, again a trade-off in air media between charging electrode and liquid sheet.

1. Introduction

In the present scenario, electrostatic force field applications are gaining new dimensions to different fields such as in electrostatic spraying, electrostatic painting, electrostatically thin film deposition, environment preservation, dust control, drug delivery studies on electrostatically charged dry powder inhaler aerosols etc., among these application, air-assisted electrostatic pesticide spraying is the main focus in this study (Pascuzzi and Cerruto, 2015; Ru et al., 2005; Lyons et al., 2011; Ali et al., 2000; Ghimbeu et al., 2008; Zhu et al., 2008; Krupa et al., 2013; Patel and Ghanshyam, 2015). In the majority of these applications, the unique properties of the electrostatic forces are used to collect, direct, deposit, separate, or select very small or lightweight particles (Yule et al., 1995; Zhao et al., 2012; Ghanshaym et al., 2013; Law, 2001; Abhilash and Singh, 2009; Patel et al., 2015a,b).

Electrostatic spraying involves charging of the finely divided particulate, transport of charged particles between nozzle and target and actual deposition of the charged particles onto the intended target (Zhao et al., 2007; Yu et al., 2010; Maynagh et al., 2009; Sasaki et al., 2013; Maski and Durairaj, 2010; Patel et al., 2015a,b). An electrode coaxially surrounds the spray near the nozzle, the electrode is chargeable to a high electrostatic potential relative to the nozzle, whereby the liquid particles of the spray are inductively charged by passing through ring. In electrostatic spraying, the electrode material as well as the geometry of the electrode plays a key role in induction spray charging. In the available literature, the materials used for electrode were copper, brass and stainless steel (Ru et al., 2007a,b, 2008; Mamidi et al., 2012; Ru et al., 2007a,b; Laryea and No, 2004; Patel et al., 2012). It is examined in detail in numerous works such as those by Lehr and Hiller (1993) and Atten et al. (1997). Copper is corrosive and easily oxidized when exposed to air and ambient conditions, the major bottleneck lying in these materials. Recent work has used

* Corresponding author. Academy of Scientific and Innovative Research, Rafi Marg, New Delhi 110 011, India; CSIR–Central Scientific Instruments Organisation, Chandigarh 160 030, India.
E-mail address: manoj_patel@csio.res.in (M.K. Patel).

http://dx.doi.org/10.1016/j.eaef.2016.05.002
1881-8366/

Please cite this article in press as: Patel, M.K., et al., Enhanced performance of an air-assisted electrostatic nozzle: Role of electrode material and its dimensional considerations in spray charging, Engineering in Agriculture, Environment and Food (2016), http://dx.doi.org/10.1016/j.eaef.2016.05.002

electrodes coated in diamonds in order to achieve vastly improved charging characteristics through introducing sharp edges (Kourmatzis et al., 2010). Subsequently, our group (Patel et al., 2013) has used nickel (200/201 forged bar) as an electrode material for spray charging, reflecting good results in comparison to other electrode materials. Although, the nickel is a useful material as an electrode for spray charging and also non-corrosive, however it is expensive compared to the above mentioned electrode materials and again nickel is not suitable if the engineering aspects are taken into consideration such as soldering and other electrical connections.

Despite of available literature, it is obvious that very little research work has been carried out towards selection of electrode material for spray charging especially, in case of an air-assisted electrostatic nozzle for agricultural applications. In previous work, we have worked on nickel (200/201 forged bar) as a charging electrode material. In this paper, an alternative electrode material i.e. copper (98% pure) electroplated with nickel along with the performance of different shape and size of electrode has been presented for spray charging in electrostatic spraying nozzle. The recompenses of the nickel layer include high corrosion resistance, as well as, outstanding mechanical properties. Since the internal geometry of the nozzle cannot be modified instantly without serious consequences on droplet formation process, only the shape, size and position of the charging electrode may be altered during optimization. The performance has been calculated in term of charge-to-mass ratio as a function of electrode material and dimensional shape and size. The results with copper electroplated with nickel electrode are in good agreement with theoretical considerations and it is a good alternative to existing electrode materials for spray charging as far as the performance of the nozzle is considered i.e. free from corrosion etc.

2. Theory

The electrostatic spraying technique is a complex combination of the three processes: electro-hydrodynamics, aerodynamics and electrostatics (Ye et al., 2002). Electro-hydrodynamics is a combination of atomization of the liquid to be sprayed and charging the finely divided droplets inductively (Charru, 2011; Moore, 1973; Dumouchel, 2008; Jaworek and Krupa, 1999; Kelly, 1997; Teng et al., 1995; Patel, 2016). Aerodynamics includes the transport of the charged droplets to the intended target and the different forces acting on the charged droplets, which mainly decide the trajectory of the charged droplets (Law et al., 2000). Electrostatics explains deposition of charged particulate matter onto the surface of actual target. In this study mainly, the electro-hydrodynamics phenomena is covered in details i.e. role of electrode material and the optimization of parameters of spray charging along with some insight in the aerodynamics of electrostatic spraying techniques.

The schematic diagram of an air-assisted electrostatic nozzle has been shown in Fig. 1 for the liquid flow rate of 110–130 ml/min. The nozzle is air induced internally air mixing type with air pressure variation in the range of 3×10^5–4×10^5 Pa. Considering the hydrodynamic processes, for the average velocity of the water at the nozzle exit; and assuming the conditions for the applicability of Bernoulli's equation to the flow of liquid alone inside a nozzle are met (i.e. flow is steady, incompressible and shear stress is negligible).

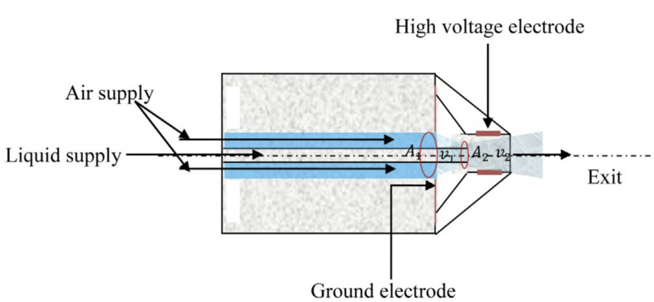

Fig. 1. Schematic diagram of an air-assisted electrostatic nozzle.

For the designed nozzle, $A_1 = 4.9*10^{-6}$ m^2 and $A_2 = 1.54*10^{-6}$ m^2. Volume flow rate of liquid in nozzle is 110 ml/min. Average velocities of water for respective area of cross sections at nozzle exit are $v_2 = 1.19$ m/s, and $v_1 = 0.37$ *m/s*, i.e. $v_2 \approx 3v_1$. Though the velocity of liquid flowing out of the nozzle has increased, but the air is at comparatively higher momentum than liquid. The liquid properties important for consideration to produce effective atomization are viscosity, surface tension and density, (Murthy, 1962).

Considering the electrodynamics part, for a liquid with non-zero conductivity, an applied electric field will cause a current to flow in it due to movement of charge carriers on opposite sides inside it. The process of charge induction on liquid surface involves a complex mechanism (Allah, 2002; Jackson, 1998). Inside the liquid, the net electric field is resultant of external applied and that due to induced charges. The negative charge will build up at the liquid surface until a net zero field results in the liquid. This condition is necessary for the current flow to be zero in the liquid. The time constant for this charge transfer to take place is $\tau = \varepsilon_r \varepsilon_0 \rho$. Droplets will be getting charged with time longer than τ, when droplets are formed in charging region. The relaxation time τ gives the decay rate of the free density in the given medium, the rate at which free charge is transferred from surface to interior, and the rate at which the field within the medium subsides to low levels. Now due to polarization of polar liquid, the surface of liquid has negative charge and the extra positive charge is grounded. As soon as air strikes and removes upper surface of liquid the droplets formed have a net negative charge.

In this particular case for $\rho = 22.2$ Ωm, $\varepsilon = 8.854*10^{-12}$ C^2/Nm^2, $\varepsilon_r = 80$, gives $\tau = 0.16*10^{-7}$ s. The droplet formation time for the liquid jet is given by $t_f = l/v$ (Albuquerque, 2010; Maheshwari and Chang, 2007). Where ε_r is the dielectric constant of the liquid, ε_0 is the permittivity of free space, ρ is the electrical resistivity of the liquid, l is the length of the jet and v is the liquid velocity. Droplet formation time $t_f \approx 2$ ms for $l = 2.5$ mm and the liquid velocity at the nozzle orifice exit $v_2 = 1.19$ m/s. Here, there are two conflicting requirements; for high charging efficiency, the electrode should be close to the liquid film, but if this distance is too small, the droplets are more likely to be attracted to the electrode surface due to Columbic force. Wetting of the charging electrode should be avoided since this phenomenon leads to deterioration of atomizer performance and increases the risk of electric discharge.

The minimum distance between the electrode and nozzle body is limited by the dielectric breakdown limit of $3*10^6$ V m^{-1} for dry air (Law, 1977; Peek, 2013). Poisson equation and the boundary conditions applicable to the particular geometry form a boundary value problem that can be solved numerically for any geometry to further derive/measure electrostatic potential, electric field, capacitance per unit length and charge densities. Since the liquid jet-electrode system happens to be a cylindrical configuration, it is analyzed by comparing with a similar cylindrical capacitor (Moon and Spencer, 1988).

Assume the capacitor is characterized by two perfectly conducting cylindrical shells of infinite length with radii r_j and r_e. The cylinders are separated by a homogeneous perfect insulator characterized by $\sigma = 0$ and $\varepsilon = \varepsilon_0 \varepsilon_r$. A dc voltage V is applied across the cylinders and charge separation occurs.

Please cite this article in press as: Patel, M.K., et al., Enhanced performance of an air-assisted electrostatic nozzle: Role of electrode material and its dimensional considerations in spray charging, Engineering in Agriculture, Environment and Food (2016), http://dx.doi.org/10.1016/j.eaef.2016.05.002