
Manoj Kumar Patel1,2,*, Hemant K Sahoo3, Manoj K Nayak1,2, Ashwani Kumar2, C Ghanshyam1,2, Amod Kumar1,2

1 Academy of Scientific and Innovative Research, AcSIR-CSIO, Chandigarh-160 030, INDIA
2 CSIR-Central Scientific Instruments Organisation, Chandigarh-160 030, INDIA

Abstract—There is an urgent need for new chemical application sprayer in Indian agricultural pesticides spraying. The present paper aims to design and develop of an air-assisted electrostatic nozzle based on induction-charging with a specific focus on Indian agricultural and geographical scenario. A new air-assisted electrostatic nozzle has been designed and developed for small scale farms with enhanced performance. This nozzle is light weight, highly efficient, reduces pesticide use and human health risks, and eco-friendly. An air-assisted electrostatic nozzle system is a combination of an air-assisted nozzle and induction based electrostatic charging mechanism. The portable high voltage power supply is generated from a rechargeable dc battery, raised to few kilovolts, in-house with nozzle itself.

Keywords—Air-assisted Nozzle, Induction-Charging, Spray Patternator, Spray Swath Width, Volume Median Diameter (VMD).

I. INTRODUCTION

Electrostatic force field application to agricultural spraying, one of the most promising methods to apply the protective liquid based sprays onto the biological surfaces of living crops and orchards, has revolutionized the agricultural pesticide spraying techniques by making advances and developments via off-target pest control to increase the deposition efficiency and surface bio-efficacy [1]-[5]. Electrostatic spraying process has been used in many other applications such as thin film deposition, painting, printing etc. [6]-[9]. Electrostatic spraying achieves more complete coverage of difficult targets than uncharged spraying in addition to minimizing wastage and environmental impact from over-dose and off-target spray drift [10]-[12]. Earlier electrostatic spray systems developed and commercialized in countries such as USA, China etc. were motorized and mounted on tractors, helicopters, and other vehicles, which is not suitable and economical to Indian farming community because of geographical conditions and economic constraints [13]. According to Agricultural Census Division, in India, the farming is carried out in small scales and the farms land are divided in small pieces of land; it may because of government policy of allocation of farms or geographical and agro-climatic conditions. It will not only true in case of Indian farming but also for any small scale farming of any other economies. Most of the Indian farmers are way behind with available electrostatic sprayers because of financial reasons and availability. They need robust pesticides application equipment so that it can be used with minimum labor or without any exceptional expertise[14].

Despite the available literature, significant research work has not been carried out on optimization of design and performance parameters of air-assisted electrostatic nozzle such as electrode position, electrode material for spray charging, liquid flow rate, trade-off between air pressure and liquid flow rate, conductivity of liquid etc. In this paper, theoretical and engineering aspects of the design and development of a portable air-assisted electrostatic nozzle with enhanced performance have been presented along with the high voltage power supply generated from a rechargeable dc battery raised to few kilovolts in-house with nozzle itself. The experimental results show that the performance of the air-assisted electrostatic nozzle has been enhanced significantly and in good agreement with the theoretical calculations in terms of significant increase in charge to mass ratio and hence deposition efficiency and bio-efficacy. In agro chemical, bio-efficacy is a measure of the biological efficacy of an active ingredient of

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II. MATERIAL AND METHODS

The design and development of air-assisted electrostatic nozzle primarily includes design of the air-assisted nozzle, high voltage generation and appropriate method of droplet charging, optimization of different parameters, deposition study onto actual targets etc. Nozzle design parameters include hydrodynamics of liquid flow and atomization of liquid. High voltage generation consists of a rechargeable dc battery and a dc to dc converter, the dc voltage of rechargeable battery raised to few kilovolts, connected to charging electrode. The charging of conductive liquid is based on induction principle. In electrostatic nozzle design, the parameters to be optimized are: charge to mass ratio variation with applied voltage, liquid conductivity, applied air pressure, liquid flow rate and target distance. The deposition study includes a set of experimental observations which shows the deposition rate and uniformity of coverage [15]-[18].

A. Design of Air-Assisted Nozzle

The A twin fluid, internal mixing, air-induced, concentric, air-assisted electrostatic nozzle with annular ring electrode made of nickel has been designed and developed as shown in Fig. 1. The cone angle of spraying of the designed nozzle is approximately 25°. This design is in such a way that to ensure proper co-axial alignment between ring electrode and the nozzle.

![Fig. 1 Schematic diagram of air-assisted electrostatic nozzle](image)

The charge induced on the jet is proportional to the surface area exposed to electric field and the magnitude of the normal component \( E_n \) of the field. The amount of induced charge may be expressed as \( q_t = \varepsilon_0 \varepsilon_f \int E_n dA \). For the given construction of nozzle body which dictates the jet break-up process, this effect must be achieved by proper selection of the geometry of the charging electrode arrangement. For developed nozzle, assume that the average value of height (h) of liquid tank is approximately 0.5 m, therefore the velocity of the liquid flow approximately is 3.13 m/s. The pressure head of the liquid having the height of 0.5 m is 0.05 bars. It means that, even if you apply some pressure to the liquid to overcome the liquid head problem, it should not exceed 0.05 bars otherwise the flow rate might be changed. It is found that for the better/finer spray, the liquid to air ratio supposed to be 1:100, and most commonly used liquid flow for agriculture spray nozzle is 60-250 ml/min.

B. High Voltage Generation and Droplet Charging

A major portion of the electrostatic crop spraying has been in the development of reliable means for droplet charging. Electrostatic induction based charging has proved to be a very satisfactory method of charging spray droplets for agricultural pesticide applications. In electrostatic induction charging, direct charge-transfer to droplet formation zone of a liquid jet results from electrostatic induction of electrons onto the continuous jet and in order to maintain it at ground potential, the presence of a closely positioned electrode of positive polarity is required. The method used here for the droplet charging is induction electrification process, reducing the shock and hazardous to operate the nozzle system [19], [20].

C. Performance Measurement of the Electrostatic Nozzle

Experimentally, the performance of the air-assisted electrostatic nozzle can be evaluated in terms of charge to mass ratio, which signifies the chargeability of the finely divided spray droplets by the charging electrode. Charge to mass ratio
depends on electrical and mechanical properties of the liquid as well as material of the charging electrode. The former definition of existing electrostatic methods for measuring charge to mass ratio has been used in the experiments i.e. a specially designed Faraday Cage (Fabricated at CSIR-Central Scientific Instruments Organisation) was connected to the earth potential via a digital multi-meter (Model No.6514, Keithley). The dimensions of Faraday cage were 600x300x300 mm and to support the meshes the Perspex material was used to build the structure.

The contact of the charge droplets onto the wire meshes of Faraday cage and transfer of the charge to the earth caused an electrical current which was detected by microampere meter. The charged liquid spray was collected at a specific time and weighted. Then the spray current was divided by the mass flow rate to determine the charge to mass ratio. To measure the charge to mass ratio equation (1) has been used.

\[
\text{Charge to mass ratio} = \frac{i_s}{Q_m} \text{mC/kg} \tag{1}
\]

Where \(i_s\) is the measured spray current (A) and \(Q_m\) is the mass flow rate of liquid (kg/s).

D. Optimization of Performance Parameters

In the design and development of air-assisted electrostatic nozzle the major parameters to be optimized for the nozzle to work efficiently are: air feed-rate and liquid-flow, air and liquid flow pressure, variation of the liquid flow with the applied air pressure, charge to mass variation with liquid conductivity and electrode placing from the nozzle tip, power consumption etc. The developed electrostatic nozzle must cover all the liquid based pesticides; therefore, there is trade-off between liquid conductivity and power consumption.

III. EXPERIMENTAL

Spray application treatments include air-assisted electrostatic nozzle and non-electrostatic air-assisted nozzle (named AAESN, designed and developed by CSIR-Central Scientific Instruments Organisation). The high voltage electrostatic power supply has been provided to charging electrode with a high voltage module (ULTAVOLT +20 kV, 1.5 mA, 30W, for laboratory experiments only). The laboratory experiments were conducted in open air and at ambient conditions (T= 288±2 K, RH= 50±3%). The compressed air has been provided from the air compressor (Model No: SAN10101, ELGI Equipment Ltd., CFM 3.89), air regulator for regulated air supply (Model No: LOE-D-MINI C643, FESTO) along with air flow meter (Model No: PFM711S-C8-C-A-WS-X731).

A. Study Layout and Laboratory Conditions

In laboratory, all treatments were made using manual and physical handling of the nozzle along with specified direction of spraying (0.25m/sec, 1.2m distance from the ground). The experimental conditions are shown in Table I. Cotton plants have been used for the experiments. Water sensitive papers were affixed at the height of 1.0 m within the canopies of cotton plants at front and back side of the leaves and normal tap water was applied. The plants were sprayed electrostatically as well as non-electrostatically and the results were compared. After the water treatments were made, the cards were allowed to dry before being collected. Target samples were collected 20 minutes after spraying.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric temperature (K)</td>
<td>288±2</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>50±3%</td>
</tr>
<tr>
<td>Conductivity of tap water (mS/cm)</td>
<td>0.206</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>ρ≈999</td>
</tr>
<tr>
<td>Viscosity (kg/m-s)</td>
<td>μ=1.002x10⁻³</td>
</tr>
<tr>
<td>Surface tension (N/m)</td>
<td>γ=0.072</td>
</tr>
<tr>
<td>Permittivity (C²/N-m²)</td>
<td>ε=708.88 x 10⁻¹²</td>
</tr>
<tr>
<td>Dielectric constant of water</td>
<td>K=80</td>
</tr>
<tr>
<td>Dielectric constant of air</td>
<td>1</td>
</tr>
</tbody>
</table>

After each treatment, sufficient time was allowed for the spray material to move downward and the material deposited on the WSPs and the papers to dry. The lab test papers are scanned and the average amount of droplets was recorded. WSPs were analyzed using ImageJ (DropletScan...
scanner-based system, a java based image processing scanning program that can quickly evaluate spray deposit distribution on water sensitive paper. Deposition $DV_{0.1}$, $DV_{0.5}$, $DV_{0.9}$, percent area coverage, and number of droplets per card were determined. The use of water sensitive papers (WSPs) in determining application density and distribution was also explored [21], [22]. All the analysis was performed using open excess Microsoft Excel.

B. Spray Distribution, Swath Width of the Spray

A stationary bench (Spray Patternator) of the dimensions 1000x1200 mm has been prepared with the equidistant 40 grooves ($C_1, C_2, C_3, ..., C_{40}$) of width 27.5 mm and each row is divided by a 2.5 mm width, a diving wall as shown in Fig. 2. The spray is vertically directed and landing onto the equidistant grooves and the liquid is collected into the test tubes connected to the outlet of each grooves.

![Fig. 2 Experimental set-up for spray swath width, target coverage and uniformity of distribution measurement](image_url)

The number of grooves in which the liquid is collected multiplied by the equidistant width (27.5+2.5 mm) will give the swath width of the spray. Double of the tangent of the measured angle is the measure of spray cone angle.

IV. RESULTS AND DISCUSSION

A. Charge to Mass Variation with Applied Voltage

As shown in Fig. 3, there is an initial rapid increase of the charge to mass ratio upto a critical (peak) applied voltage and then starts decreasing or almost constant at a higher applied voltage to a corresponding liquid flow rate, electrical and mechanical properties of liquid and the geometry of the charging electrode. This voltage is called saturation voltage corresponding to that particular electrode material. This peak appears corresponding to dimension and shape of the electrode and properties of liquid to be sprayed, because the charging time constant changes with the conductivity of liquid. After saturation point, the inductive charging tends towards conductive charging, encountered by positive current and therefore, charge to mass ratio decreases.

![Fig. 3 Charge to mass (with negative sign) variation with the applied voltage to charging electrode at liquid flow rate of 65 ml/min and applied air pressure of 4 bars](image_url)

Here, there are two conflicting requirements; for high charging efficiency, the electrode should be close enough 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 Coulomb force. Wetting of the charging electrode should be avoided since this phenomenon leads to deterioration of the atomizer performance and the nozzle system.
B. Spray Coverage and Uniformity of Distribution

In the experiments, a Relative Span Factor (RSF) is calculated by using equation (3) which indicates the uniformity of drop size distribution. The closer this number to 1, the more uniform the spray will be. Relative Span Factor is calculated for both the cases, non-electrostatic (NES-2, RSF=1.21, front and RSF=0.84, back) and electrostatic spraying (ES-1, RSF=1.16, front and 0.91 back), and it is found that for electrostatic spraying, a more uniform distribution is obtained, as shown in Fig. 4.

\[ RSF = \frac{D_{90.9} - D_{90.1}}{D_{90.5}} \]  

(3)

Number of deposits per unit area and percent coverage in electrostatic spraying (ES-1) has been increased compared to non-electrostatic spraying (NES-2). The total number of count of deposits onto front and back of the WSPs has increased significantly when sprayed electrostatically, keeping all the experimental conditions identical i.e. applied air pressure and liquid flow rate.

WSP analysis shows the same general trend revealed by the conventional liquid collecting method, which makes it a reliable means to measure the characteristics of spray applications.

C. Spray Swath Width

The experiments have been performed with and without the applied voltage to measure the target coverage, uniformity and swath width of the spray. The distance (z = 700 mm) between nozzle tip and the stationary platform kept constant as shown in Fig. 5, for all experimental observations.

![Fig. 5 Spray swath width with and without applied voltage](image)

The liquid is collected in test tubes and measured volumetrically. The collected amount in test tubes plotted statistically in both the cases i.e. non-electrostatic as well as electrostatic spraying.

In case of non-electrostatic spraying, the sprayed liquid has covered test tubes from \( C_{16} \) to \( C_{24} \) (number of grooves = 9). Therefore the width of spray coverage \( y = 272.5 \) mm (27.5x9+2.5x10=272.5) and hence the spray angle was found approximately 22º (\( \alpha = 2(\tan^{-1}(0.195)) \)). In case of electrostatic spraying, the liquid was collected in 13 test tubes (\( C_{14} \) to \( C_{26} \)) and therefore, the width of spray coverage \( x = 392.5 \) mm (27.5x13+2.5x14=392.5). In this case, the calculated spray angle was found approximately 31º (\( \beta = 2(\tan^{-1}(0.28)) \)). Experimental results showed that, there was a significant increase in spray angle (\( \beta > \alpha \)). Spray swath width and hence target canopy coverage has been increased with the applied charging voltage. The reason of increased spray angle is electrostatic repulsive force among the negatively charged droplets. Assuming the groove \( C_{20} \) is the centermost test tube for liquid
collection, it is found that grooves equidistant from the centermost groove approximately have equal amount of liquid.

V. CONCLUSION

The deposition of liquid was enhanced 2-3 fold with electrostatic application under the same conditions while using non-electrostatic nozzle. A remarkable phenomena “wraparound effect” was utilized and provided backside deposition 4-5 fold efficiently with increased uniformity. The average size of the spray droplets was found of the diameter 40 µm (VMD). The maximum charge to mass ratio was achieved at an applied voltage of 2.5 kV with an applied air pressure of 4 bars. The designed and developed air-assisted electrostatic spray system utilizes the power generated with the dc-dc convertor through the rechargeable dc battery. The nozzle is easy to carry and economical for small scale farmers especially for developing economies. In addition, electrostatic nozzle saves the overdose as well as chemicals consumption and thus preventing from the environmental pollution. Designed spray nozzle system addresses all the safety measures and concerns regarding easy-to-use and smooth operation.

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