# MITIGATION OF AIR POLLUTION: MACRO TO MICRO-SCALE STUDY OF PARTICLE CAPTURE BY UNCHARGED AND CHARGED DROPLETS

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# MITIGATION OF AIR POLLUTION: MACRO TO MICRO-SCALE STUDY OF PARTICLE CAPTURE BY UNCHARGED AND CHARGED DROPLETS

by

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submitted

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# Certificate

This is to certify that the thesis entitled **"Mitigation of air pollution: Macro to micro-scale study of particle capture by uncharged and charged droplets"** is being submitted by **Mr. Debabrat Biswal** to the Indian Institute of Technology, Delhi for the award of the degree of **Doctor of Philosophy (Ph.D.)**. This thesis is a bonafide record of original research work carried out by him under my supervision in conformity with the rules and regulations of the institute. The contents of this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any Degree or Diploma.

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Place: New Delhi

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# Abstract

The emission of fine particles from the combustion of fossil fuels for energy production, found in the exhaust gases of industries and vehicles, creates a significant environmental threat. Fine and ultra-fine particulate matter is more hazardous than larger particles. These inhalable particles can be suspended in the atmosphere for a longer time. As a result, these particles can easily penetrate deep into the lungs and heart of human beings, leading to serious and incurable pulmonary and cardiovascular diseases. The cyclone, bag filter, electrostatic precipitator, wet scrubber, and wet electrostatic scrubber are employed to mitigate such particles. Out of the above technologies, the wet electrostatic scrubber is the most effective in mitigating these particles. But still, there is a lack of physics to understand the capturing mechanism between charged droplets and particles.

In this study, we investigate the charging mechanism of the particles and droplets, charge quantification, the phenomena of non-incorporation/non-attachment, and return/rebound of airborne particles/clusters upon impacting charged droplets. The study also delineates the innovative mechanism for removing non-conducting particles using a bouncing charged droplet. In the last objective of this study, we demonstrate the effectiveness of uncharged and charged droplets generated from the spray phenomenon on the removal of fine liquid

aerosol.

This research utilizes a charged pendant droplet incorporating fine particles to understand the interaction between particles and the droplet. A pin-plate electrode configuration is employed to study the movement of the particles dispersed on the ground electrode toward the charged droplet. A high-speed imaging technique is used to visualize and record the interaction phenomenon between the particles and the charged pendant droplet. The hollow glass beads, carbon black, silane-coated glass beads, and ash of incense sticks are used as testing particles. The finding of this study explains that the particles captured by the charged droplet depend on the particle wettability (hydrophilic and hydrophobic), conductivity, and dielectric constants. The charge acquired by the particles and the non-uniform electric field distribution are determined through mathematical modeling using MATLAB. DC and AC electric field experiments unequivocally demonstrate that the Faradaic induction mechanism at both the ground and droplet surfaces causes the acquisition or reversal of particle charges. The migration of particles and clusters is predominantly governed by Coulombic force, not dielectrophoretic force (DEP). Hydrophobic carbon particle clusters with high conductivity exhibit increased rebound/non-incorporation from the droplet, whereas hydrophilic glass beads with low conductivity do not show significant rebound and readily integrate into the droplet.

In the next objective of the study, we focus on the removal phenomenon of very low-conducting particles (silane-coated glass beads), high-conducting (carbon black), and moderate-conducting particles (glass beads) by an impacting and bouncing charged droplet. The silane-coated particles are removed from the droplet surface due to the deformation of the

drop and the electric repulsive force. In the case of carbon black and glass beads, the moving charged pendant droplet captures the particles due to the electrostatic force of attraction. Higher electric potentials lead to an increased spreading diameter of the droplet. The higher electric field enhances the contact area between the droplet and the particles, thereby removing more particles.

In the last objective of this thesis, we demonstrate the removal efficiency of the liquid aerosol by uncharged and charged droplets from a self-made experimental chamber. The paraffin oil and Di-Ethyl-Hexyl-Sebacat (DEHS) solution are used as a working aerosol. The liquid, namely tap water, employed for spraying, is dispersed using a hollow cone nozzle having a 1 mm orifice diameter. The findings from the distinct test setup show that uncharged droplets dispersed through a hollow cone nozzle exhibit a scavenging efficiency of approximately 58%. On the other hand, charged droplets demonstrate significantly higher scavenging efficiency, surpassing 90%. The investigation also reveals that the scavenging efficiency of both uncharged and charged droplets, when dispersed through a hollow cone nozzle at lower potentials (1 and 2 kV), is nearly identical.

# सार

जीवाश्म ईंधनों के दहन से ऊर्जा उत्पादन के लिए उत्सर्जित सूक्ष्म कण, जो उद्योगों और वाहनों की निकास गैसों में पाए जाते हैं, एक महत्वपूर्ण पर्यावरणीय खतरा पैदा करते हैं। सूक्ष्म और अति–सूक्ष्म कण बड़े कणों की तुलना में अधिक खतरनाक होते हैं। ये सांस में लेने योग्य कण वायुमंडल में लंबे समय तक निलंबित रह सकते हैं। परिणामस्वरूप, ये कण आसानी से मानव शरीर के फेफड़ों और हृदय में गहराई तक प्रवेश कर सकते हैं, जिससे गंभीर और लाइलाज फेफड़े और हृदय संबंधी रोग हो सकते हैं। इन कणों को कम करने के लिए साइक्लोन, बैग फ़िल्टर, इलेक्ट्रोस्टैटिक प्रीसिपिटेटर, वेट स्क्रबर और वेट इलेक्ट्रोस्टैटिक स्क्रबर का उपयोग किया जाता है। उपरोक्त तकनीकों में से, वेट इलेक्ट्रोस्टैटिक स्क्रबर इन कणों को कम करने में सबसे प्रभावी है। लेकिन फिर भी चार्ज की गई बूंदों और कणों के बीच कैप्चरिंग तंत्र को समझने के लिए भौतिकी की कमी है।

इस अध्ययन में, हम कणों और बूंदों के चार्जिंग तंत्र, चार्ज की मात्रा का निर्धारण, और चार्ज की गई बूंदों के साथ टकराने पर वायुमंडलीय कणों/क्लस्टरों के पुनः लौटने/रिबाउंड होने के घटनाक्रम का अध्ययन करते हैं। अध्ययन में नॉन–कंडक्टिंग कणों को बाउंसिंग चार्ज की गई बूंद से हटाने के लिए एक नवाचारात्मक तंत्र का वर्णन भी किया गया है। इस अध्ययन के अंतिम उद्देश्य में, हम यह प्रदर्शित करते हैं कि बिना चार्ज और चार्ज की गई बूंदों, जो स्प्रे से उत्पन्न होती हैं, के द्वारा सूक्ष्म तरल एयरोसोल को हटाने की प्रभावशीलता कैसी होती है।

यह शोध चार्ज की गई लटकती बूंद का उपयोग करता है जिसमें सूक्ष्म कण समाहित होते हैं, ताकि कणों और बूंद के बीच की अंतःक्रिया को समझा जा सके। पिन–प्लेट इलेक्ट्रोड विन्यास का उपयोग किया जाता है ताकि ग्राउंड इलेक्ट्रोड पर फैले कणों की चार्ज की गई बूंद की ओर गति का अध्ययन किया जा सके। कणों और चार्ज की गई लटकती बूंद के बीच की अंतःक्रिया को दृश्य बनाने और रिकॉर्ड करने के लिए हाई–स्पीड इमेजिंग तकनीक का उपयोग किया जाता है। खोखले कांच के मोती, कार्बन ब्लैक, साइलन–लेपित कांच के मोती, और अगरबत्ती की राख को परीक्षण कणों के रूप में उपयोग किया गया है। इस अध्ययन के निष्कर्ष बताते हैं कि चार्ज की गई बूंद द्वारा कणों का कैप्चर कणों की वेटेबिलिटी (हाइड्रोफिलिक और हाइड्रोफोबिक), कंडक्टिविटी, और डाइलेक्ट्रिक कॉन्स्टेंट पर निर्भर करता है। कणों द्वारा प्राप्त चार्ज और असमान विद्युत क्षेत्र वितरण को मैथमेटिकल मॉडलिंग के माध्यम से MATLAB का उपयोग करके निर्धारित किया गया है। DC और AC विद्युत क्षेत्र के प्रयोग स्पष्ट रूप से प्रदर्शित करते हैं कि ग्राउंड और बूंद की सतहों पर फैराडिक प्रेरण तंत्र के कारण कणों द्वारा चार्ज प्राप्त करना या उलट जाना होता है। कणों और क्लस्टरों का प्रवास मुख्य रूप से कूलॉम्ब बल द्वारा शासित होता है, न कि डाइलेक्ट्रोफोरेटिक बल (DEP) द्वारा। उच्च कंडक्टिविटी वाले हाइड्रोफोबिक कार्बन कण क्लस्टर बूंद से बढ़ते हुए रिबाउंड/नॉन–इन्कॉरपोरेशन का प्रदर्शन करते हैं, जबकि कम कंडक्टिविटी वाले हाइड्रोफिलिक कांच के मोती महत्वपूर्ण रिबाउंड नहीं दिखाते हैं और आसानी से बूंद में समाहित हो जाते हैं।

अध्ययन के अगले उद्देश्य में, हम बहुत कम कंडक्टिविटी वाले कणों (साइलन–लेपित कांच के मोती), उच्च कंडक्टिविटी (कार्बन ब्लैक), और मध्यम कंडक्टिविटी वाले कणों (कांच के मोती) को चार्ज की गई बूंद द्वारा हटाने की घटना पर ध्यान केंद्रित करते हैं। साइलन–लेपित कण बूंद की सतह से बूंद के विकृति और विद्युत प्रतिकर्षण बल के कारण हट जाते हैं। कार्बन ब्लैक और कांच के मोतियों के मामले में, चलती हुई चार्ज की गई लटकती बूंद विद्युत आकर्षण बल के कारण कणों को कैप्चर करती है। उच्च विद्युत संभावनाएँ बूंद के फैलने के व्यास को बढ़ाती हैं। उच्च विद्युत क्षेत्र बूंद और कणों के बीच संपर्क क्षेत्र को बढ़ाता है, जिससे अधिक कण हटते हैं।

इस शोध के अंतिम उद्देश्य में, हम स्वयं के निर्मित प्रयोगात्मक कक्ष से बिना चार्ज और चार्ज की गई बूंदों द्वारा तरल एयरोसोल को हटाने की दक्षता का प्रदर्शन करते हैं। पैराफिन ऑयल और डाय–एथिल–हेक्सिल–सेबैकेट (DEHS) सॉल्यूशन को काम करने वाले एयरोसोल के रूप में उपयोग किया जाता है। छिड़काव के लिए उपयोग किया गया तरल, जिसे नल का पानी कहा जाता है, १ मिमी ऑरिफिस व्यास वाली खोखली शंकु नोजल का उपयोग करके फैलाया जाता है। अलग–अलग परीक्षण सेटअप से प्राप्त निष्कर्ष बताते हैं कि बिना चार्ज की गई बूंदें, जो खोखली शंकु नोजल के माध्यम से फैलाई जाती हैं, लगभग ५८% तक स्कैवेंजिंग दक्षता दिखाती हैं। दूसरी ओर, चार्ज की गई बूंदें, स्कैवेंजिंग दक्षता में काफी अधिक वृद्धि प्रदर्शित करती हैं, जो ९०% से अधिक होती है। जांच से यह भी पता चलता है कि जब बिना चार्ज और चार्ज की गई बूंदों को निचली संभावनाओं (१ और २ kV) पर खोखली शंकु नोजल के माध्यम से फैलाया जाता है, तो उनकी स्कैवेंजिंग दक्षता लगभग समान होती है।

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# Nomenclature

| | |
|---|---|
| $Stk$ | Stokes number [-] |
| $\alpha$ | Packing density [-] |
| $Pe$ | Peclet number [-] |
| $D_{diff}$ | Diffusion coefficient [$m^2/s$] |
| $k_B$ | Boltzman constant [$kgm^2/s^2/K$] |
| $C_c$ | Cunningham slip correction factor [-] |
| $T$ | Absolute temperature [K] |
| $C_i$ | Initial concentration Mass/number of aerosols without spray |
| $C_0$ | Mass/number concentration of particles with uncharged spray |
| $C_1$ | Mass/number concentration of particles with charged spray at 1 kV |
| $C_2$ | Mass/number concentration of particles with charged spray at 2 kV |
| $C_3$ | Mass/number concentration of particles with charged spray at 3 kV |
| $C_4$ | Mass/number concentration of particles with charged spray at 4 kV |

$C_5$ Mass/number concentration of particles with charged spray at 5 kV

$C_6$ Mass/number concentration of particles with charged spray at 6 kV

$C_7$ Mass/number concentration of particles with charged spray at 7 kV

$C_8$ Mass/number concentration of particles with charged spray at 8 kV

$C_9$ Mass/number concentration of particles with charged spray at 9 kV

$P$ Vapour pressure of aerosol generator [hPa]

$q$ Charge on droplet [C]

$V$ Applied DC potential [kV]

$\rho_p$ Density of particle [$kg/m^3$]

$E$ Non-uniform electric field distribution [$V/m$]

$E_r$ Non-uniform radial electric field distribution [V/m]

$E_z$ Non-uniform axial electric field distribution [V/m]

$a$ Radius of droplet [m]

$\epsilon_0$ Permittivity of free space [$F/m$]

$\eta_m$ Mass efficiency of the aerosol [%]

$\eta_n$ Number efficiency of the aerosol [%]

$\rho_p$ Particle density [$g/cc$]

$U$ Relative velocity between particle and droplet $[m/s]$

$\sigma_p$ Conductivity of the particle $[S/m]$

$\epsilon_{rp}$ Relative permittivity of the particle

$z_i$ Axial position of $i^{th}$ charge [m]

$\zeta_i$ Normalized charge at $i^{th}$ position [C]

$\epsilon$ Permittivity of the droplet $[F/m]$

$\sigma$ conductivity of the droplet $[S/m]$

$D_{eq}$ Equivalent diameter of the droplet [m]

$D_v$ Longitudinal diameter of the droplet [m]

$D_h$ Latitudinal diameter of the droplet [m]

$Re$ Reynolds number [-]

$d_p$ Diameter of particle [m]

$Oh$ Ohnesorge number [-]

$We$ Weber number [-]

$Ca_E$ Electric capillary number [-]

$Bo_E$ Electric Bond number [-]

$Bo$ Gravitational Bond number [-]

| | |
|---|---|
| $\rho$ | Density of the droplet [$kg/m^3$] |
| $\gamma$ | Interfacial tension of the droplet [$F/m$] |
| $v$ | Velocity of the droplet [$m/s$] |
| $\epsilon_d$ | Permittivity of the droplet [$F/m$] |
| $P_E$ | Electric stress [$N/m^2$] |
| $\mu$ | Dynamic viscosity of air [$Pas/m^2$] |
| $P_\gamma$ | Capillary stress [$N/m^2$] |
| $P_d$ | Pressure dynamics [$N/m^2$] |
| $\alpha$ & $\beta$ | Spreading factors [-] |
| $\eta_{imp}$ | Impaction efficiency [-] |
| $\eta_{int}$ | Interception efficiency [-] |
| $\eta_{diff}$ | Diffusion efficiency [-] |
| $S_\rho$ | Density ratio of liquid to air [-] |

# Motivations

Air pollution in both indoor and ambient environments is a matter of serious concern from the point of view of human health [1, 2], weather, and climate change[3]. The major components that are responsible for air pollution are particulate matter (both PM2.5 and PM10), ozone ($O_3$), nitrogen dioxide ($NO_2$), carbon dioxide ($CO_2$), carbon monoxide (CO), and sulfur dioxide ($SO_2$), etc [4]. The air pollutants have severe catalytic effects on human health by creating incurable diseases (cardiovascular, pulmonary) [5]. It is due to the presence of particulate matter (including both PM2.5 and PM10) in the atmosphere [5]. From the existing literature, it was observed that the concentration of PM2.5 has more adverse effects on human health compared to PM10 [6]. The concentration of PM2.5 substantially varies between and within the regions of the world. In 2019, it was found that 90% of the global population lived where the PM2.5 concentration exceeded 10 $\mu g/m^3$ according to the WHO air quality guideline report [5]. According to the 2018 WHO report, the lowest concentration of PM2.5 was found in the American and European WHO regions. The average concentration was 7 $\mu g/m^3$. This average concentration of PM2.5 varies from 30 - 50 $\mu g/m^3$ in small island nations and 120 – 140 $\mu g/m^3$ in Asia and Middle Eastern countries, respectively [5]. Based on the air quality reports, particulate matter concentration is substantially increasing in Asian countries like China and India compared to other nations.

This is due to the rapid growth of the population and the developing economy. Several studies have shown that increased overall mortality is associated with short- and long-term exposure to PM2.5. Due to this finer particulate matter, around 8.8 million people die annually [5]. This catalytic effect of particulate matter forces researchers and scientists to take immediate action by inventing air pollution-controlling devices and mechanisms.

The motivation behind our research into charged droplet-based particulate mitigation arises from several critical limitations associated with conventional particle capture technologies, when targeting fine ($PM_{2.5}$) and ultrafine (PM$< 0.1\mu m$) particles. These particles, due to their small size and high mobility, are difficult to capture using existing methods, posing severe environmental and health concerns [7].

## Low capture efficiency for submicron and nano particles

Conventional technologies such as gravitational settling chambers, cyclonic separators, and standard wet scrubbers exhibit poor capture efficiencies for particles smaller than 2.5 μm. This inefficacy arises because, at these scales, inertial and gravitational forces become negligible compared to Brownian motion and viscous drag. Consequently, a substantial fraction of fine and ultrafine particles remains airborne, exacerbating ambient PM levels and associated respiratory risks [8].

## High energy requirement

While systems like electrostatic precipitators (ESPs) and high-efficiency particulate air (HEPA) filters demonstrate superior removal efficiencies for fine particles, they often suffer from considerable drawbacks. These include the requirement for high-voltage systems with as-

sociated safety concerns, elevated pressure drops necessitating greater energy input, and frequent maintenance due to electrode fouling or filter clogging [8]. Such factors increase the overall operational cost and hinder applicability in decentralized or mobile applications.

Traditional capture techniques predominantly rely on passive physical mechanisms such as inertial impaction, sedimentation, or filtration without leveraging electrostatic or physicochemical interactions to actively enhance capture [9]. Moreover, they typically lack the ability to modulate key parameters of the capture medium, such as droplet charge, size, or surface chemistry, limiting their tunability and responsiveness during operation.

These limitations collectively highlight the need for novel, adaptable, and energy-efficient mitigation strategies. Charged droplet-based systems, by integrating electrohydrodynamic principles and droplet properties, offer a promising alternative for enhanced removal of submicron particles in both static and mobile scenarios [10].

# Organization of the thesis

The thesis has been compiled with the following chapters.

1. **Chapter 1:** Introduction.
2. **Chapter 2:** Literature review.
3. **Chapter 3:** Study of electro-migration and capture of particles by a charged pendant droplet.
4. **Chapter 4:** Charged drop impinging on particles dispersed over a metallic plate: An experimental method of self-cleaning.
5. **Chapter 5:** Mitigation of fine hydrophobic liquid aerosols by uncharged and charged spray.
6. **Chapter 6:** Conclusion and future scope.