Laboratory study of the collection efficiency of submicron aerosol particles by cloud droplets.

Part II - Influence of electric charges.

Alexis Dépée¹,², Pascal Lemaître³**, Thomas Gelain¹, Marie Monier²,³, Andrea Flossmann²,³

[1] {Institut de Radioprotection et de Sûreté Nucléaire (IRSN), PSN-RES, SCA, Gif-sur-Yvette, France}
[2] {Université Clermont Auvergne, Laboratoire de Météorologie Physique, Clermont-Ferrand, France}
[3] {CNRS, INSU, UMR 6016, LaMP, Aubière, France}
*Correspondence to: Pascal Lemaître (pascal.lemaître@irsn.fr)

ABSTRACT

A new In-Cloud Aerosol Scavenging Experiment (In-CASE) has been developed to measure the collection efficiency (CE) of submicron aerosol particles by cloud droplets. Droplets fall at their terminal velocity through a one-meter-high chamber in a laminar flow containing aerosol particles. At the bottom of the In-CASE’s chamber, the droplet train is separated from the aerosol particles by clouds and precipitations (Jaenicke, 1993). The collection efficiency of submicron aerosol particles is measured by a High Efficiency Particulate Air (HEPA) filter. The collected droplets and the filter are then analysed by fluorescence spectrometry since the aerosol particles are atomised from a sodium fluorescein salt solution (CsH₃H₂Na₂O₄). In-CASE fully controls all the parameters which affect the CE - the droplets and aerosol particles size distributions are monodispersed, the electric charges of droplets and aerosol particles are known and set, while the relative humidity is indirectly controlled via the chamber’s temperature. This paper details the In-CASE setup and the dataset of 70 measurements obtained to study the impact of the electric charges on CE. For this purpose, droplets and particles charges are controlled through two charging systems developed in this work - both chargers are detailed below. The droplet charge varies from -3.0x10⁹ ± 1.4x10³ to +9.6x10⁹ ± 4.3x10⁹ elementary charges while the particle charge ranges from the neutralisation to -90 ± 9 elementary charges depending on the particle radius. A droplet radius of 48.5 ± 1.1 μm has been considered for four particle dry radii between 100 and 250 nm. These new CE measurements have been compared to the correlation of Kraemer and Johnstone (1955) and the extended model of Dépée et al. (2019) where thermophoresis and diffusiophoresis are also considered since the measurements have been performed at a relative humidity level of 95.1 ± 0.2 %. As a result, both models adequately describe the electric charge influence on the measured CEs. Furthermore, the effect of the image charge (Jackson, 1999) in the electrostatic forces is measured.

INTRODUCTION

Aerosol particles (APs) are a fundamental part of the atmosphere since they act on climate and more locally on meteorology (Twomey et al., 1974). They are also a key topic in human health where APs increase the likelihood of developing cardiovascular disorder (Crouse et al., 2012). For these reasons, the processes involved in the removing of the atmospheric AP have been investigated extensively over the last decades. Far away from the source, APs are mainly scavenged through their collection by clouds and precipitations (Jaenicke, 1993) - referred as the wet deposition. Since it has been reported that the AP collection by clouds prevails in the wet deposition (Flossmann, 1998; Laguionie et al., 2014), the modelling of the in-cloud AP collection remain an essential issue for the atmospheric sciences.

As previously stated in Part I of this work (Dépée et al., 2020) - In most of current AP wet removal models - like DESCAM (Detailed SCAvenging Model, Flossmann, 1985) - the AP collection is described through a microphysical parameter called “collection efficiency” (CE) which quantifies the ability of a droplet to capture the APs present in its surroundings during its fall. Many microphysical effects impact this CE and their contribution is mainly depending on the AP size. To be collected an AP has
to leave the streamline that surrounds the falling droplet to make contact with it. The nanometric
AP’s motion is affected by the collisions with air molecules - referred as the Brownian diffusion. It
results in random movement patterns (see Figure 1, A) which tend to increase the CE as the AP radius
decreases. For massive APs, there is an increase of CE as they retain an inertia strong enough to leave
the streamline when it curves and to go straight toward the droplet surface - phenomenon called
inertial impaction (see Figure 1, B). When considering intermediate AP size, the CE goes through a
minimum value called the “Greenfield gap” (Greenfield, 1957) where the AP diffusion and inertia are
weaker. In this gap, other microphysical effects can be involved to make the droplet encounter the
AP like the interception, for instance. It is the collection of APs following a streamline that
approaches the droplet within a distance equivalent to the particle radii (\(a\)) - see Figure 1, C. - Note
that there are also thermophoretic and diffusiophoretic forces which can have an influence on the
CE. These effects prevail in a subsaturated air - as it is the case sometimes in clouds - and are
discussed in Part I (Dépée et al., 2020).

Since droplets are naturally charged in clouds (Takahashi, 1973) as well as the atmospheric APs, there
are electrostatic forces which can influence the AP collection. Numerous numerical studies were
dedicated to the influence of the electric charges on CE - such as Grover et al. (1975), Jaworek et
al. (2002), Tinsley and his group (for instance - Tinsley et al., 2006 or Tinsley and Zhou, 2015). They
suggest an increase of the CE of orders of magnitude even when the AP is weakly charged. However, the AP charge increases when the APs are radioactive (Clement and Harrison, 1992) -
inducing an impact on CE even larger (Dépée et al., 2019). Thus, the AP “electroscaavenging” in clouds
has to be investigated, particularly for nuclear safety issues when the APs removal by clouds result
from the discharge of radioactive materials from a nuclear accident. Prior, the CE values considering
electrostatic forces need to be compared with experiments and, more specifically, the analytical
expression for electrostatic forces used in numerical studies (Jaworek et al., 2002 ; Tinsley et al.,
2006 ; Tinsley and Zhou, 2015 ; Dépée et al., 2019) has to be confronted.

When a droplet with a charge \(Q\) approaches an AP of charge \(q\), the partial influence of the AP
electrostatic field on the droplet leads to the re-orientation of the water dipoles. As a result, a
surface charge distribution on the droplet is created and supposed to be comparable to the one of a
conductive sphere. In an electrostatic equivalent problem, the droplet can be replaced by two-point
charges (Jackson, 1999). One modelling the charge distribution, inside the droplet and near its
surface, another for the residual droplet charge located at the droplet surface. Finally, the analytical
expression of the electrostatic forces is the addition of two Coulomb forces between the AP and the
two-point charges inside the droplet. The factored expression can be found in equation 7 of Dépée
et al. (2019) and further details can be found in Tinsley et al. (2000). It is holds two terms (Equation
(6)). The first one is the Coulomb inverse square term which prevails in the AP collection for large
enough AP electrical mobilities or electric charge products \(Q \times q\), attractive (Figure 1, D) or
repulsive (Figure 1, E) depending on whether the AP charge \(q\) and the droplet charge \(Q\) have unlike
or like signs. The second term is referred to the short-range attractive term and dominates for weak
electric charge products or for small AP electrical mobilities (Figure 1, F) and is always attractive
(due to the charge distribution at the droplet surface with opposite sign to the AP charge \(q\)). A
detailed study of their contribution can be found in Dépée et al. (2019).

Several laboratory studies were also performed regarding the influence of the electric charges on the
CE (Beard, 1974; Wang and Pruppacher, 1977; Lai et al., 1978; Barlow and Latham, 1983; Wang et
al., 1983; Byrne and Jennings, 1993). However, most of these works have faced difficulties in
controlling all parameters impacting the CE. For instance, Beard (1974) do not measure the AP charge
; Lai et al. (1978) have a polydispersed AP size distribution, the relative humidity level is not provided
and the terminal velocity of the droplets is not reached ; Barlow and Latham (1983) use a
polydispersed AP size distribution and the relative humidity level significantly varies from 50 to 70 %
in their measurements; in the work of Byrne and Jeannings (1993) the droplet velocity does not reach
the terminal velocity. For these reasons, it is really difficult to find comparable CE measurements in
the literature as Barlow and Latham (1983) concluded after highlighting a discrepancy of few orders
of magnitude between all these authors. Nevertheless, Wang and Pruppacher (1977) and Wang et al.
(1983) screened the APs surface charge and the droplets size (as well as the relative humidity for Wang and
Pruppacher (1977)) but they consider only unlike signs between both droplets and APs. Thus, only
the Coulomb inverse square term in the analytical expression of the electrostatic forces can be
documented whereas the contribution of the short-range attractive term has not been experimentally
verified until now.

The purpose of this study is to overcome this lack of data by providing new CE measurements for
weakly and strongly droplets and APs charges with both negative and positive charge products, to
quantify the effect of the short-range attractive term on the CE since its contribution was previously predicted by modelling (Tinsley and Zhou, 2015; Dépée et al., 2019).

Thus, a novel experiment has been designed for this study. With this experiment, the influence of relative humidity can also be investigated and this was the object of the companion paper of this present work: Part I (Dépée et al., 2020).

In the first section of this paper, Part II, the experimental setup is detailed while the experimental method to evaluate the CE is described in the second one. Then, the measurements are presented and confronted with the correlation of Kraemer and Johnstone (1955) which accounts for attractive Coulomb interactions between droplets and APs. Another comparison is made in the last section with the Lagrangian model of Dépée et al. (2019) which provides a better CE evaluation since it can model every microphysical effect involved in the AP collection by cloud droplets (like Brownian motion, inertial impaction, interception, etc.) and their coupling. Since the experiments have been performed in a subsaturated air (relative humidity of 95.1 ± 0.2 %), we extend the Dépée et al. (2019) model by adding the thermophoretic and diffusiophoretic effects. Finally, this study aims to experimentally validate the Dépée et al. (2019) model to provide consistent theoretical CEs for a convenient incorporation in cloud models, pollution models, climate models, and so forth.

Figure 1 APs trajectories computed with the extended Dépée et al. (2019) model for a 50 μm droplet radius (A) and AP with various radii (a) and densities (ρ_{AP}). The air temperature (T_{air}) and the air pressure (P_{air}) are respectively -17 °C and 540 hPa. From Figure 1 A to F, the considered effects are the Brownian motion (A), the inertial impaction (B), the interception (C), the electrostatic forces with attractive (D) and repulsive (E, F) Coulomb forces. The droplet (q) and AP (q_{AP}) charges are labelled. In Figures 1 B to F - the red trajectories result in an AP collection. Adapted from Part I (Dépée et al., 2020).
1 EXPERIMENTAL SETUP

1.1 Overview

Figure 2 shows the In-Cloud Aerosol Scavenging Experiment (In-CASE) which has been built to study the influence of the electric charges on the CE. Droplets fall at their terminal velocity into a chamber through an AP flow of 1.5 l/min. The In-CASE’s chamber is subdivided into 3 parts: the injection head where droplets and APs are inserted; the collision chamber where droplets and APs interact with each other; the aerodynamic separator set at the bottom’s chamber impacts droplets into an impaction cup while uncollected APs go out the chamber toward a High Efficiency Particulate Air (HEPA) filter. For this latter stage, an Argon updraft assures that there are no AP that settle into the droplet impaction cup. More details on the In-CASE’s chamber can be found in Dépée et al. (2020).

APs are atomised from a sodium fluorescein salt solution ($C_{20}H_{10}Na_2O_5$). This molecule has been used for its significant fluorescent properties, detectable at very low concentrations (down to $10^{-10}$ g/l). Once generated, the APs flow through a diffusion dryer and a portion of the flow is then directed into a Differential Mobility Analyser (DMA; TSI 3080) to select APs following their electrical mobilities whereas the overflow ends in an exhaust. At the DMA’s outlet, the AP size distribution is assumed to be monodispersed (discussed in section 2.1). Thereafter, APs are electrically charged by a custom-designed field charger (section 1.4). Since the optimised AP flowrate in the charger is 1.5 l/min and the maximum AP flowrate in the DMA was 1.2 l/min during the experiments, a clean air flowrate is added at the charger’s inlet. Before the AP injection in the In-CASE’s chamber, the flow is humidified to assure a high relative humidity level inside the collision chamber (section 1.2). Before the AP collection on the HEPA filter, the APs flow through a low-energy X-ray neutraliser (< 9.5 keV, TSI 3088) to eliminate charge accumulation on this filter leading to AP deposition on the metallic walls of the filter holder.

Droplets are generated with a piezoelectric injector provided by Microfab (MJ-ABL-01 model) with an internal diameter of 150 µm - at 25 Hz to prevent droplets from coalescing. The generator is set in a 3D printing which is located in the injection head (Figure 5, Right). An electrostatic inductor is also placed in the 3D printing to charge droplets (section 1.5). The droplet size is measured during experiments through two facing portholes in the injection head. Further details can be found in Dépée et al. (2020) but note that the size distributions of the droplets generated by the piezoelectric injector are considered monodispersed since the droplet size dispersion is very low ($\sigma \sim 1\%$).

This In-CASE setup presented here is quite different from the other configuration regarding the relative humidity’s influence developed in Part I (Dépée et al., 2020).
1.2 Thermodynamic conditions in the In-CASE’s chamber

Thermodynamic conditions were set as constant as possible during experiments to get comparable CE measurements. The pressure in the In-CASE’s chamber was the atmospheric one and the global temperature for the campaign presented in this paper was $1.08 \pm 0.12 ^\circ C$. As referred in section 1.4 of Dépée et al. (2020), the chamber’s temperature is controlled through a cooling system which indirectly sets the relative humidity level in the chamber. Here, the temperature of the pure water in the humidifier placed before the In-CASE’s chamber (Figure 2) was increased to get a global relative humidity level of $95.1 \pm 0.2 \%$. Note that this relative humidity level was the maximum which could be reached with In-CASE. So, the contribution of the thermophoretic and the diffusiophoretic effects in the CE measurements was reduced as much as possible.

1.3 Droplet evaporation

The droplet evaporation was theoretically evaluated similarly to subsection 1.4.2.2 of Dépée et al. (2020). For a relative humidity level of 95 \%, it was found that the droplet radius decreases by less than 0.5 \% from the droplet generation to the bottom of the collision chamber. Thus, the evaporation in the In-CASE collision chamber was neglected for the discussions below.

1.4 AP charging

APs are electrically charged by passing through a custom-designed field charger adapted from Unger et al. (2004). The scaled geometry is presented in Figure 3. This charger is based on a system of electric discharges produced between a high potential tungsten wire and a grounded cylinder. A metallic converging portion is used at the charger’s outlet to trap ions and assure only charged APs can leave the charger. A Teflon ball ($\Omega=1$ mm) is set at the end of the tungsten wire to ensure there is no point effect between the wire and the ion trap. A large number of ions are then created and migrate between the two centimeters interelectrode space along the electric field lines. Finally, the APs flow through them and get charged by ion attachment.

![Geometry of the home-made AP charger based on Unger et al. (2004) (at scale).](image)

The charging relationships of the charger used during all experiments are presented in Figure 4. They provide the mean electric AP charge related to the potential at the tungsten wire for the 4 AP radii considered here. It results from ex situ experiments which are detailed in Appendix A. Note that APs are negatively charged through the discharge regime used (negative Trichel regime) and there is an electric potential where the AP charge saturates which is typical for field chargers (Pauthenier and Moreau-Hanot, 1932). These results were performed at an AP flowrate of 1.5 l/min which was found to maximise the AP penetration inside the charger and consequently the AP concentration inside the In-CASE’s chamber. Penetration tests - not presented in this study - were deduced by varying the AP flowrate in the setup detailed in Appendix A.

Figure 3 Geometry of the home-made AP charger based on Unger et al. (2004) (at scale).
1.5 Droplet charging

The droplets charge is controlled through an electrostatic inductor adapted from Reischl et al. (1977). Two parallel metallic plates are set at the droplet generator’s nozzle (Figure 5, left) – one plate connected to the neutral potential and the other one to a potential referred as $V_{\text{ind}}$. It induces an electric field ($E_{\text{ind}} \sim 10^2 - 10^3$ V/m) at the nozzle. Since sodium chloride is added to the pure water that feeds the piezoelectric droplet generator, this electric field can selectively attract negative or positive ions toward the nozzle where the droplet is formed, according to its sign. If $V_{\text{ind}}$ is negative, the positive sodium ions ($Na^+$) migrate toward the nozzle and the negative chloride ions ($Cl^-$) are repulsed from the nozzle and inversely if the potential is positive. Furthermore, the amplitude of the electric field ($E_{\text{ind}}$) sets the ion quantity in the droplet. Note that the sodium chloride concentration has no impact on the induced droplet charge if the ion number is large enough for the entire experiment time (Reischl et al., 1977) – 3.3 g/l was used here.

Figure 4 AP charging relationships used during experiments for the 4 AP radii ($a$) considered. Error bars represent the standard deviations in measurements.

Figure 5 (Left) Electrostatic inductor below the piezoelectric droplet generator. (Center) 3D printing containing droplet generator and electrostatic charger. (Right) Injection head at the top of the IN-CASE’s chamber containing the 3D printing.
A method to evaluate the droplet charge was developed in this study and is detailed in Appendix B. In Figure 6, the resulting charging relationship of the electrostatic inductor is presented. It gives the droplet charge \( Q \) as a function of the electrostatic inductor potential \( V_{\text{ind}} \). We note that the droplet generator produces highly electrically charged droplets since the droplet charge is evaluated to about -8,400 elementary charges, for a zero potential at the inductor plate \( (V_{\text{ind}} = 0 \, \text{V}) \). This is in line with Ardon-Dryer et al. (2015) which used a similar generator and measured up to \( 10^4 \) elementary charges on the generated droplets. Finally, this charging relationship is used during experiments to positively or negatively set the droplet charges. The electrostatic inductor and the droplet generator are placed into a 3D printing (Figure 5, center), this latter being placed in the injection head at the top of the In-CASE's chamber (Figure 5, right).

Figure 6 Charging low of the electrostatic inductor · colors identify different tests performed to ensure there is no droplet charge modification over time and manipulations. Error bars represent the standard deviation of the droplet radii evaluated. The parameter \( V_{\text{cap}} \) is the potential at the capacitor to measure the droplet radius (see Appendix B).

2 DATA ANALYSIS

2.1 Assumption of a monodispersed AP size distribution

As a reminder, APs flow through a DMA (Figure 2) to select APs following their electrical mobility. As explained in section 2.2 of the Part I (Dépée et al., 2020), several AP radii can actually be selected depending on their elementary charges given that they have the same electrical mobility. For example, with a selected AP radius of 100 nm at the DMA (considering one elementary charge on it), the double charged AP radii of 161.8 nm will also be selected.

Sometimes, the multiple charged APs cannot be neglected in the AP flow at the DMA’s outlet. The CE deduction is then more difficult (Dépée et al., 2020). Here, the aerodynamic impactor at the DMA’s inlet (referred as \( D_{50\%/2} \) · which is the radius where 50 % of the APs are impacted · is small enough compared to the double charged AP radius. This is summarised in the Table 1 for all selected AP radii used in the experiments. Thus, the AP size distribution at the DMA outlet is assumed to be monodispersed and the CE is deduced as follows.

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Table 1 AP selection parameters

<table>
<thead>
<tr>
<th>Selected AP radius by the DMA (single charged)</th>
<th>Double charged with the same mobility AP radius</th>
<th>AP flowrate in the DMA</th>
<th>Cut-off radius of the impactor at the DMA inlet ($d_{50%}/2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 nm</td>
<td>161.8 nm</td>
<td>1.2 l/min</td>
<td>140 nm</td>
</tr>
<tr>
<td>150 nm</td>
<td>253.7 nm</td>
<td>1.0 l/min</td>
<td>157 nm</td>
</tr>
<tr>
<td>200 nm</td>
<td>348.3 nm</td>
<td>0.6 l/min</td>
<td>213 nm</td>
</tr>
<tr>
<td>250 nm</td>
<td>444.3 nm</td>
<td>0.4 l/min</td>
<td>268.5 nm</td>
</tr>
</tbody>
</table>

2.2 Collection efficiency definition

The collection efficiency ($CE$) is calculated from the equation (1):

$$CE(a, A, q, Q, HR) = \frac{m_{AP,d}}{m_{AP,available}}$$

(1)

Where $m_{AP,d}$ is the AP mass collected by all droplets which is directly measured by fluorescence spectrometry analysis of the droplets collected in the impaction cup, which is located at the bottom of the In-CASE chamber (Figure 9 of Dépée et al., 2020). $m_{AP,available}$ is the mass of available APs in the volume swept by all droplets - evaluated with the equation (2):

$$m_{AP,available} = \pi (A + GroF(RH) \times a)^2 \times F_d \times \Delta t \times H_{eff} \times C_{m,AP}$$

(2)

With $F_d$ - the droplet generation frequency, $\Delta t$ - the experiment duration (on average 4 hours and a half in this campaign), $a$ - the AP dry radius, $GroF$ - the growth factor depending on the relative humidity ($HR$). This latter characterises the hygroscopicity of the sodium fluorescein salt - further details related to its evaluation can be found in section 1.4.2 of Dépée et al. (2020). $H_{eff}$ is the effective height of interaction between APs and droplets calculated with the equation (3):

$$H_{eff} = \frac{U_{AP}}{U_{AP} + V_{in-case}} H_{in-case}$$

(3)

With the AP flow velocity ($U_{AP}$) equal to 1.3 cm/s (for an AP flowrate of 1.5 l/min), the droplet terminal velocity ($U_{AP,\infty}$) assumed to be equal to 25 cm/s and the In-CASE collision chamber’s height ($H_{in-case}$) of 1 meter.

In equation (2), the mean AP mass concentration ($C_{m,AP}$) in the In-CASE collision chamber is evaluated from the fluorescence spectrometry analysis of the HEPA filter. It is given by the equation (4) where $Q_{in-case,c}$ is the AP flowrate going through the In-CASE collision chamber.

$$C_{m,AP} = \frac{m_{AP,\infty}}{\Delta t \times Q_{in-case,c}}$$

(4)

2.3 Uncertainties

Uncertainties are not detailed in this paper but were addressed in Part I, section 2.3 (Dépée et al., 2020).
3 RESULTS AND DISCUSSIONS

3.1 Extension of the Dépée et al. (2019) model

CE measurements are compared to the model of Dépée et al. (2019) which models the electrostatic forces \(F_{\text{elec}}\) between droplets and APs in the CE calculation. Since the global relative humidity level was 95.1 ± 0.2 % in all experiments, the thermophoretic \(F_{\text{th}}\) and the diffusophoretic \(F_{\text{df}}\) forces were also considered to get the theoretical CE values. Indeed, Dépée et al. (2020) showed that the contribution of these two effects for a comparable relative humidity level is significant. Thus, the Dépée et al. (2019) model is extended here by replacing the resulting velocity at the AP location \(U_{\text{f@AP}}\) in their Equation 6 by the new equation (5):

\[
U_{\text{f@AP}}(t) = U_{\text{f@AP}}(t) + \frac{r_p}{m_p} (F_{\text{buoy}} + F_{\text{df}} + F_{\text{elec}} + F_{\text{th}})
\]

(5)

Where the analytical expressions of \(F_{\text{buoy}}\) is detailed in equation system (9), \(F_{\text{df}}\) and \(F_{\text{th}}\) in Dépée et al. (2020) · equations (12) · and \(F_{\text{elec}}\) is defined in equation (7):

\[
F_{\text{elec}} = \frac{q^2}{4\pi \varepsilon_0 A^2} \left( \frac{1}{r^2} \right)^{\frac{3}{2}} + \frac{1}{r^2} \times \frac{Q}{q} \mathbf{u}_r
\]

(6)

With \(\varepsilon_0\) · the permittivity of the free space, \(\mathbf{u}_r\) · the unit vector in the radial direction from the droplet centre to the AP centre, \(r^*\) · the distance between the AP and droplet centres, normalised by the droplet radius \(A\).

3.2 Collection efficiency measurements

The CE measurements for various charges are presented in Table 2 for the 4 AP wet radii \(d_{\text{wet}}\) considered in this study. The droplet \(Q\) and AP \(q\) charges are also identified by number of elementary charges. The global temperature was 1.08 ± 0.12 °C for a global relative humidity level of 95.1 ± 0.2 % and a droplet radius of 48.5 ± 1.1 μm. Note that the wet AP density depends on the one of sodium fluorescein salt and water. Equation (1) of Dépée et al. (2020) yielded a density of about 1116 kg m⁻³.

| \(d_{\text{wet}}\) (μm) | \(Q/|Q|\) (|Q|) | 6.0 × 10⁻⁴ | 3.0 × 10⁻⁴ | 5.0 × 10⁻⁴ | 0 ± 6.0 × 10⁻⁴ | −5.0 × 10⁻⁴ | −1.0 × 10⁻⁴ | −3.0 × 10⁻⁴ |
|-----------------|----------------|------------|------------|------------|----------------|------------|------------|------------|
| 175 ± 3         | −10 ± 1        | 3.91 × 10⁻² | 2.44 × 10⁻² | 3.47 × 10⁻² | 4.17 × 10⁻³ | 5.58 × 10⁻³ | 9.81 × 10⁻⁴ | 2.55 × 10⁻⁴ |
|                 | −20 ± 2        | 6.77 × 10⁻² | 3.47 × 10⁻² | 6.99 × 10⁻³ | 5.07 × 10⁻³ | 4.25 × 10⁻³ | 9.17 × 10⁻⁴ | 4.12 × 10⁻⁵ |
| 260 ± 4         | −11 ± 1        | 2.41 × 10⁻² | 1.30 × 10⁻² | 3.25 × 10⁻³ | 2.97 × 10⁻³ | 2.14 × 10⁻³ | 1.34 × 10⁻³ | 1.93 × 10⁻⁴ |
|                 | −30 ± 3        | 7.91 × 10⁻² | 2.31 × 10⁻² | 7.96 × 10⁻³ | 5.75 × 10⁻³ | 3.47 × 10⁻³ | 2.57 × 10⁻³ | 4.97 × 10⁻⁵ |
| 346 ± 4         | −10 ± 1        | 2.24 × 10⁻² | 8.98 × 10⁻³ | 3.03 × 10⁻³ | 1.86 × 10⁻³ | 1.84 × 10⁻³ | 1.05 × 10⁻³ | 5.20 × 10⁻⁴ |
|                 | −34 ± 3        | 4.58 × 10⁻² | 1.40 × 10⁻² | 5.39 × 10⁻³ | 3.91 × 10⁻³ | 2.90 × 10⁻³ | 2.23 × 10⁻³ | 3.60 × 10⁻⁵ |
|                 | −71 ± 7        | 9.17 × 10⁻² | 3.25 × 10⁻² | 1.70 × 10⁻³ | 7.33 × 10⁻³ | 5.51 × 10⁻³ | 2.88 × 10⁻³ | 2.21 × 10⁻⁵ |
| 432 ± 5         | −22 ± 2        | 3.74 × 10⁻² | 1.49 × 10⁻² | 3.22 × 10⁻³ | 2.49 × 10⁻³ | 1.85 × 10⁻³ | 2.44 × 10⁻³ | 1.25 × 10⁻⁴ |
|                 | −52 ± 5        | 7.62 × 10⁻² | 4.13 × 10⁻² | 1.13 × 10⁻³ | 3.23 × 10⁻³ | 3.23 × 10⁻³ | 4.17 × 10⁻³ | 1.06 × 10⁻⁴ |
|                 | −90 ± 9        | 1.77 × 10⁻¹ | 3.55 × 10⁻² | 1.83 × 10⁻² | 6.90 × 10⁻³ | 4.75 × 10⁻³ | 4.56 × 10⁻³ | 2.43 × 10⁻⁵ |
3.2.1 Effect of the product of the droplet and AP charges on the collection efficiency

The CE measurements for a wet AP radius of 432 nm are presented in Figure 7 as a function of the product of the droplet \((Q)\) and AP \((q)\) charges. An important charge influence is measured, increasing or decreasing the CE up to two orders of magnitude for large negative or positive charge products, respectively, compared to the theoretical CE value disregarding the electrostatic effects (dashed line in Figure 7). This is due to the Coulomb inverse square term in the electrostatic forces’ equation (6) which dominates – attracting or repulsing the APs from the droplet depending on the fact that AP and droplet charges have unlike or like signs.

For small positive charge products (approximately \(q \times Q \leq 10^6 |e| x |e|\)), an increase of CE with a factor of more than three is measured compared to the theoretical CE value without electrostatic forces. This fact truly emphasises the contribution of the short-range attractive term in equation (6) which attracts the APs toward the droplet even though the droplet and AP charges have like signs. Indeed, as previously stated, this term prevails for small charge products (Dépée et al., 2019).

Note that the same observations can be made for the other wet AP radii, with a measured influence of the electric charges on CE up to four orders of magnitude.

Figure 7 CE measurement as a function of the product of the droplet \((Q)\) and AP \((q)\) charges for the wet AP radius of 432 nm. Color code informs about the AP charge. The dashed line represents the theoretical CE value disregarding the electrostatic forces (given the air parameters 1 °C, 1 atm, 95% of relative humidity).

3.2.2 Effect of the AP charge on the collection efficiency for a neutral droplet

In Figure 8, the CE measurements for a neutral droplet are presented for the 4 wet AP radii – referred by the color code - with the respective theoretical CE values without electrostatic forces (the dashed lines).

Note that the contribution of the electrostatic forces seems insignificant for an AP charge of about -10 elementary charges and an AP radius of 346 nm and 260 nm as well as an AP of 432 nm with -20 elementary charges. Indeed, these measurements are very close to the theoretical ones with no consideration of electrostatic forces. Several microphysical effects have probably an equivalent
contribution on the CE measurements such as electrostatic, thermophoretic and diffusiophoretic forces, in addition to AP diffusion, weight and inertia.

Nevertheless, for the 4 AP radii, an increase of the CE considering more elementary charges on the APs is measured - even though the droplet is neutral (or within uncertainties weakly charged). For example, given an AP radius of 346 nm, the CE is multiplied by almost a factor 4 when the AP charge increases from -10 to -71 elementary charges. It highlights the contribution of the short-range attractive term in equation (6), showing the presence of a surface charge distribution on the droplet formed by the partial influence of the AP electrostatic field on it. In the current case, this is the only contribution since the droplet is neutral and the Coulomb inverse square term is zero in equation (6).

This is an important result since to our knowledge, there is no experimental observation of the short-range attractive term on the CE in the previous studies of the literature.

For a given AP charge, an increase of the CE is measured when the AP radius decreases, probably due to the increase of the electrical mobility of APs. This is in line with the numerical results of Dépée et al. (2019) even though electrostatic effects are not the only contribution involved in this CE increase. Indeed, the Brownian motion of the APs increases for smaller APs and enhances the collision between the droplet and APs. Moreover, the curve slope could be increased for a decrease of the AP radius since the electrical mobility increases - but this trend is not visible in Figure 8. It can be due the uncertainties on the CE measurements, the droplet neutralisation and the AP charge.

![Figure 8](https://doi.org/10.5194/acp-2020-832)

Figure 8 CE measurement as a function of the AP charge \( q \) for the 4 wet AP radii (Color code). The droplet is neutral. The dashed line represents the theoretical CE value disregarding the electrostatic forces (given the air parameters 1 °C, 1 atm, 95% of relative humidity).

3.2.3 Comparison with existing models

In the next subsections, the CE measurements are confronted to two different models in order to evaluate their robustness and the modelling of the observed effects.

3.2.3.1 Kraemer and Johnstone (1955) model

To describe the impact of the electric charges on the CE, there is the well-know correlation of Kraemer and Johnstone (1955), summarised in equation (7):
With \( \eta_{\text{air}} \) - the dynamic viscosity of air, \( C_u \) - is the Stokes-Cunningham slip correction factor (defined in Appendix A of Dépée et al. (2019)) and \( \Delta U \) the droplet fall velocity relative to the AP fall velocity.

This latter is assumed to be equal to \( |U_{a,\infty} - U_{a,\infty}| \) where \( U_{a,\infty} \) is the AP settling velocity.

Since this correlation models the contribution of the attractive Coulomb forces on the CE, only the CE measurements with a negative charge product are considered. In Figure 9, the parity plot of the modelled CE from the correlation of Kraemer and Johnstone (1955) as a function of the measured CE is presented. The horizontal error bars are the measurement uncertainties while the vertical ones are the extreme theoretical CE values considering the extreme droplet and AP charges (by adding or subtracting the charge uncertainties). It is shown that the correlation of Kramer and Johnstone (1955) accurately describes the observation for the large charge products (red color) but the discrepancies between model and measurement increase when the charge product decreased (when color goes to blue). Indeed, the less AP and droplet are electrically charged, the more the model underestimates the CE compared to the observations. This is due to the formula which only models the attractive Coulomb forces and disregards the other effects like the AP weight, the AP inertia and the AP diffusion which tend to increase the CE as well as the diffusiophoretic and the thermophoretic forces (Dépée et al., 2020). Consequently, the correlation gives better agreement for large charge products where the attractive Coulomb forces dominate the other effects on the AP collection. This case illustrates the strong interest of using Lagrangian models like the one of Dépée et al. (2019) which considers all microphysical effects involved in the in-cloud AP collection and especially their coupling.

Note that Wang et al. (1983) also compared their CE measurements with this correlation, finding good agreement since they considered between \(-10^7\) and \(-10^8\) elementary charges on droplets and between 1 and 13.5 elementary charges on APs. So, their charge products were larger than the ones used in the present study and they had no combined effect - the attractive Coulomb force was by far the only significant contribution. It can explain why their comparison with the correlation of Kraemer and Johnstone (1955) are better than the ones presented in Figure 9. Since most of the measurements of Wang et al. (1983) are for a droplet radius of 250 \( \mu \)m, they are not compared to the present ones which are significantly much smaller (\( \lambda = 48.5 \pm 1.1 \mu \)m).
3.2.3.2 Dépée et al. (2019) extended model

In Figure 10, the parity plot of the modelled CE from the extended model of Dépée et al. (2019) as a function of the measured CE is presented. The modelled CE are calculated from the experimental parameters (AP density, air temperature, pressure and relative humidity as well as the sizes and charges) and the CE values less than $10^{-5}$ are set to $10^{-5}$ to avoid an excessive computation time (Dépée et al., 2019). The horizontal error bars are the measurement uncertainties while the vertical ones are the theoretical CE values considering the extreme droplet and AP charges (by adding or subtracting the charge uncertainties). The color code corresponds to the different droplet radii studied.

It appears that there are as many data points above the parity curve as below, meaning that the model overestimates as much as underestimates the observations. Thus, it can be assumed that there is no missing or unnecessary microphysics effects in the CE modelling. Moreover, the mean difference between the modelled CEs and the 70 measured CEs is 66 %. This is a reasonable value for a microphysics parameter such as the collection efficiency which varies several orders of magnitude, especially since the value was calculated disregarding the different uncertainties (error bars in Figure 10) and was as a result over-evaluated.

Nevertheless, 6 data points seem inconsistent with discrepancies between model and measurements from 150 to 1000 %, occurring for the smallest CE values in Figure 10 (lower left). Note that the discrepancies should be even worse since the modelled CEs, set to $10^{-5}$, are actually much lower. By examining these data points, it appears that the measured AP masses in the droplet impaction cup $m_{\text{AP},d}$ in equation (1) - are very close to the detection limit of the spectrometer used. Moreover, for the experimental conditions, the model predicts AP masses in the droplets lower than the detection limit since the Coulomb inverse square term in equation (6) was very repulsive. So, the assumption can be made that a pollution occurred during the various steps of the protocol (end of experiment, disassembly of the chamber’s bottom to reach the droplet impaction cup, change of room for the analysis, etc.). Note that the detection limit of the spectrometer is $10^{-15}$ kg (for the nominal analysis volume considered), which only represents ten APs with a dry radius of 250 nm deposited on the droplet impaction cup. Thus, it exists an important uncertainty in these CE measurements related to a possible contamination which is difficult to quantify. To reduce it, it would be necessary to work in a cleanroom or increase the experiment duration to avoid detection problem. However, for these data points the experiment duration was almost 6 hours (without mentioning the preparation, the purging and the cleaning durations) and, beyond this duration, stability problems of the piezoelectric droplet generator were frequent.

However, a reasonable agreement between the extended model of Dépée et al. (2019) and the CE measurements are observed. As a reminder, the mean discrepancy was over-evaluated at 66 % which is suitable to describe a microphysical parameter varying on several orders of magnitude for the collection efficiency. Furthermore, if the 6 inconsistent values are removed - the mean discrepancy on the 63 remaining CE measurements decreases from 66 to 38 %.

The 38 % of discrepancy between the Dépée et al. (2019) extended model and the measurements can be attributed to the dispersion of the AP charge distribution. Indeed, it was not possible to characterize the AP charge distribution which remains an important uncertainty. Moreover, the AP size distribution was assumed to be monodispersed but a dispersion exists, even if very small, which depends on the spectral bandwidth of the DMA. This one can induce some larger (or smaller) APs inside the AP charger which can get an electric charge significantly larger (or smaller) than the predicted one since the charging process is roughly proportional to the AP surface. Then, in the IN- CASE chamber, some larger (or smaller) APs with a larger (or smaller) electric charge can interact with the droplets and notably change the final AP mass collected by the droplets during an experiment ($m_{\text{AP},d}$). Another possible explanation is the differences in temperature and relative humidity between the top and the bottom chamber, respectively less than 1 °C and 4 % (addressed in Dépée et al. (2020)). It could induce local discrepancies during the AP travel time in the chamber in term of AP density (through the hygroscopicity) or thermophoretic and diffusiophoretic forces which can change the likelihood of being collected by the droplets and then slightly change $m_{\text{AP},d}$. See Dépée et al. (2020) for a discussion of the influence of these two latter forces on the CE.
CONCLUSION

In-CASE (In-Cloud Aerosol Scavenging Experiment) was developed to conduct a series of experiments evaluating the contribution of microphysical effects on the AP collection by falling cloud droplets. For this purpose, all the parameters influencing the collection efficiency (CE) are controlled - i.e. the AP and droplet sizes, the AP and droplet electric charges and the relative humidity. A first campaign was performed to study the influence of the relative humidity which is the topic of the Part I (Dépée et al., 2020). This current study was dedicated to a second topic - aiming the impact of the electric charge on the CE. Furthermore, the CE measurements allow to validate existing models like the Lagrangian one of Dépée et al. (2019) which considers all microphysical effects involved in the AP collection by cloud droplets. Indeed, the literature lacks baseline data to get a suitable comparison with the modelling since most of the previous studies failed to control all parameters influencing the CE like the AP and droplet sizes and charges as well as the relative humidity (Beard, 1974 ; Lai et al., 1978 ; Barlow and Latham, 1983 ; Byrne and Jennings, 1993). Even though some studies stand out (Wang and Pruppacher, 1977 ; Wang et al., 1983), no one examined the influence of the electrostatic forces when the droplet and AP charges had like signs. Thus, the short-range attractive term from the analytical expression of the electrostatic forces - equation (6) - used in the current Lagrangian models (Tinsley and Zhou, 2015 ; Dépée et al., 2019) has never been experimentally validated or at least emphasised.

In the new measured CE dataset, the APs and droplets are accurately charged through custom-made droplet and AP chargers detailed above. Since both charge polarities are found in clouds (Takahashi, 1973), the droplets were negatively as well as positively charged during experiments. Moreover, several amounts of elementary charges on the droplet were considered to represent a neutral droplet but also the weakly and strongly charged droplets respectively found in stratiform and convective clouds (Takahashi, 1973). The AP charge varied from the neutralisation to -90 ± 9 elementary charges depending on the AP size to represent different charge encountered in the atmosphere, particularly the ones of radioactive APs. Note that radioactive APs are known to get positively charged (Clement and Harrison, 1992) whereas the APs were negatively charge in this work, through the charging regime used in the AP charger (for integrity of the tungsten wire over time). Nevertheless, since we got the relation $F_{\text{elec}}(q, -Q) = F_{\text{elec}}(-q, Q)$ in equation (6), the CE measurements with the same $\frac{q}{Q}$ ratios are equivalent, assuming this analytical expression is validated by the measurements. The thermophoretic and diffusiophoretic effects were reduced as much as possible by maximising the
relative humidity during experiments at 95.1 ± 0.2 %. Since Dépée et al. (2020) measured a
contribution for a comparable relative humidity level, these two forces were added to the Dépée and
Part I model. Finally, 4 radii of moist AP were used from 175 ± 3 to 432 ± 5 nm for one droplet
radius of 48.5 ± 1.1 μm.

From the 70 measurements obtained, an influence of the electric charges of 4 orders of magnitude
on the CE was observed, strongly increasing or decreasing the CE for large charge products,
respectively negative or positive. An increase of the CE was also measured by considering more
elementary charges on the APs even though the droplets were neutral (within uncertainties). This
observation is an important result since it emphasises the contribution of the short-range attractive
term in the electrostatic forces (equation (6)). It validates a surface charge distribution on the
droplet, formed by the partial influence of the AP electric field on it, which has never been
experimentally shown, to our knowledge, in the literature before.

The CE measurements with opposite signs on the droplet and AP were compared to the correlation
of Kraemer and Johnstone (1955), giving good agreements for large negative charge products where
the Coulomb attractive forces prevail over the other dynamic effects. This is in line with the work of
Wang et al. (1983) who also obtained good agreements, considering another droplet radius (250 μm)
and larger negative charge products. However, in the present study, an increase of the discrepancies
between the correlation and the measurement was measured when reducing the number of
elementary charges. This is due to the electrostatic forces not being the only effect involved in the
AP collection. There is actually a coupling of electrostatic, diffusiophoretic and thermophoretic
forces as well as the AP diffusion, weight and inertia. Thus, when the charge product is not strong
enough (gets significantly smaller than 10^7 |e| x |e|), Lagrangian models as the one of Dépée et al.
(2019) remain the best estimation of the CE.

Finally, the CE measurements were also compared to the extended model of Dépée et al. (2019),
showing a really good description of the observed effects. Indeed, the mean discrepancy of the
modelling and the 70 measurements was 66 % which is suitable for a microphysical effect varying on
several orders of magnitude like the collection efficiency. This value was even better when 6
inconsistent measurements, probably contaminated, were disregarded as it decreases from 66 % to
38 %. Moreover, note that the model overestimates as much as underestimates the observations so
that the discrepancies probably result from remaining uncertainties (like the dispersion of the AP
charge distribution) instead of a missing microphysical effect in the CE modelling.

To conclude, 70 new CE measurements are now available considering the influence of the electric
charges, showing significant differences with the previous CE measurements and theoretical values
from the literature which disregard the electrostatic forces. Thus, it appears to be essential to study
the impact of the new baseline data in a cloud-model like DESCAM (Detailed SCAvenging Model,
Flossmann, 1985) to examine the influence of the electric charges on the total wet AP removal in the
atmosphere. It could strongly affect the atmospheric AP removal since cloud droplets are known to
be charged (Takahashi, 1973) as well as the atmospheric AP, even more when APs are radioactive.
Indeed, Dépée et al. (2019) estimates that the electric charge of the radioactive APs emitted after
the Fukushima accident in 2011 was up to 600 elementary charges. Thus, AP removal could be
substantially affected by the electrostatic forces in-cloud and significantly change the ground
contamination after a discharge of radioactive materials from a nuclear accident. Since the new
Lagrangian model of Dépée et al. (2019) showed an accurate description of the influence of the
electric charges (and also of the relative humidity, studied in Part I (Dépée et al. (2020)) on the CE,
this latter constitutes a simple, convenient and rapid manner to obtain a CE evaluation for its
incorporation in cloud models.
Appendix A - AP charger

A.1 AP charging relationship’s acquisition

The AP charging relationships were obtained by performing ex situ experiments with the setup presented in Figure 11. A nominal AP flow goes through the charger with a monodispersed AP size distribution. At the charger’s outlet, the flow of charged AP is subdivided - 0.6 l/min is directed to a Condensation Particle Counter (CPC; TSI 3787) to deduce the concentration number of AP in the charger ($C_{\text{N,AP}}$) while the other part goes toward an electrometer to measure the current ($I_{\text{elec}}$) due to the charge evacuation. Before entering the CPC, APs are neutralised to avoid any deposition on the metallic walls of the CPC and then the AP flow passes through a diffusion battery to filter the fine particles produced during the discharges inside the charger. The mean AP charge ($\langle q \rangle$) was then calculated from the equation (8) with the elementary charge ($e$) and the AP flowrate in the electrometer ($Q_{\text{elec}}$):

$$\langle q \rangle = \frac{I_{\text{elec}}}{e \times C_{\text{N,AP}} \times Q_{\text{elec}}}$$

Several AP flowrates in the charger ($Q_{\text{charger}}$) were considered to study the AP penetration. When $Q_{\text{charger}}$ was less than 0.7 l/min, clean air was added before the CPC to maintain a CPC flowrate of 0.6 l/min - this part is presented in the red dashed rectangle in Figure 11. From these experiments, it was found that $Q_{\text{charger}}=1.5$ l/min maximises the AP penetration through the charger.

![Figure 11 Setup to obtain the AP charging relationship. The red dashed rectangle is the part added to study the AP penetration through the charger.](https://doi.org/10.5194/acp-2020-832)

A.2 Validation

The setup (Figure 11) was conducted with the charger turned off to measure the mean AP charge after the DMA. It was found one elementary charge on APs which validates that the multiple charged APs are stopped at the DMA’s inlet by the aerodynamic impactor. Thus, the assumption made that the AP size distribution is monodispersed after the DMA is justified. The AP charge was also analysed during 5 hours - no AP charge modification was measured over time. Moreover, the saturated AP charges visible in Figure 4 for a tungsten wire potential less than -12.5 kV was also compared to the theoretical values of Pauthenier and Moreau-Hanot (1932) - giving a good agreement.

Note that two other characterizations were made during these ex situ experiments like the determination of the ion current between the grounded cylinder and the tungsten wire (Figure 3) or the discharge frequencies - these both parameters are related to the tungsten wire potential. These curves were used to precisely identify the discharge regime of the charger (Unger, 2001) - the negative Trichel regime which provides a large discharge frequency and then a spatially homogeneous particle charging around the tungsten wires.
Appendix B - Droplet charging relationship obtention

B.1 Overview

The Figure 12 presents the setup used in ex situ experiments to measure the droplet charge where the charging relationship in Figure 6 comes from. The 3D printing containing the droplet injector and the charging system (detailed in section 1.5) is set above a capacitor composed of one neutral potential plate and another plate connected to a high potential \( V_{\text{cap}} \). In this latter, pictures are obtained by optical shadowgraphy to get the droplet trajectories. The electric field \( E_{\text{cap}} \) induced in the capacitor disturbs the droplet motion according to its electric charge. Thus, the droplet charge is evaluated by finding the one which fits the best the theoretical droplet trajectory deduced from the 2nd Newton’s law and the measured droplet trajectories. A Faraday cage ensures the electric field at the capacitor \( E_{\text{cap}} \) has no effect on the electric field at the electrostatic inductor \( E_{\text{ind}} \). Since this is not a proper Faraday cage because of the holes for droplets and camera, a horizontal metallic perforated plate is added below the 3D printing and connected to the neutral potential to prevent the electric field \( E_{\text{cap}} \) from changing the droplet charge.

![Figure 12 Setup to obtain the droplet charging relationship. (Left and Center) 3D view and (Right) schema (not at scale)](https://doi.org/10.5194/acp-2020-832)

B.2 Droplet charge evaluation

A series of 200 pictures pairs, with each one dephased from the other by a known time-step \( \Delta t \), are obtained by optical shadowgraphy at the level of the capacitor. A circle Hough transform is then applied to evaluate the droplet centers in every picture - an example is given in Figure 13 (Left) where the two droplets from a picture are represented by two black crosses meanwhile the blue cross is the detected droplet from the coupled picture dephased by \( \Delta t \).

Then, the instantaneous droplet velocity \( \overrightarrow{U}_{D0}(t) = U_{D0x} \overrightarrow{u}_x + U_{D0y} \overrightarrow{u}_y \) at the first detected droplet position \( (D_0) \) of coordinates \( (x_{D0},y_{D0}) \) is calculated and the vertical velocity component \( U_{D0y} \) determines the droplet radius \( A \) by reversing the Beard (1976) model. Here, the circle Hough transform is not used to calculate the droplet radius since the camera zoom is at the lowest to get a large field - the uncertainty would be too large.

Finally, the theoretical droplet trajectories at the capacitor are deduced by solving the 2nd Newton’s law where the buoyancy force \( F_{\text{buoy}} \), the drag force \( F_{\text{drag}} \) and the electrostatic force \( F_{\text{Ecap}} \) related to the electric field \( E_{\text{cap}} \) at the capacitor are considered, summarised in equations 9:
\[
\begin{align*}
\frac{m_0 \, dU_D(t)}{dt} &= F_{\text{buoy}} + F_{\text{drag}} + F_{\text{cap}} \\
F_{\text{buoy}} &= -m_0 \rho_{\text{water}} - \rho_{\text{air}} \, g \, u_y \\
F_{\text{drag}} &= -\frac{C_D \pi \rho_{\text{air}} U_D^2 A^2}{2 \, \|U_D(t)\|} \\
F_{\text{cap}} &= Q \, E_{\text{cap}}/u_x
\end{align*}
\]

(9)

With \(U_D\) - the instantaneous droplet velocity vector at the computational time \(t\), \(\rho_{\text{air}}\) and \(\rho_{\text{water}}\) - the air and water densities, \(g\) - the acceleration of gravity, \(m_0\) - the droplet mass, \(Q\) - the droplet charge, \(C_D\) - the drag coefficient, \(u_x\) and \(u_y\) - the unit vectors in the cartesian coordinate system.

By projecting on the corresponding axis, it is obtained the system of equations (10) to solve:

\[
\begin{align*}
\frac{m_0 \, dU_{Dx}(t)}{dt} &= Q \, E_{\text{cap}} - \frac{C_D \pi \rho_{\text{air}} U_{Dx}^2 A^2}{2} \\
\frac{m_0 \, dU_{Dy}(t)}{dt} &= -m_0 \rho_{\text{water}} - \rho_{\text{air}} \, g - \frac{C_D \pi \rho_{\text{air}} U_{Dy}^2 A^2}{2}
\end{align*}
\]

(10)

Where \(C_{Dx}\) and \(C_{Dy}\) are the drag coefficient projections depending on the Reynolds number projections \(Re_x\) and \(Re_y\) in the cartesian coordinate system. Since \(Re_x \ll 1\) et \(Re_y \ll 2\) in the study, the drag coefficient projections are calculated from the analytical expression given by Hinds (2012) and summarised in equations (11):

\[
\begin{align*}
C_{Dx} &= \frac{24}{Re_x} \, \frac{12 \, n_{\text{air}}}{AU_{Dx} \rho_{\text{air}}} \\
C_{Dy} &= \frac{24}{Re_y} \, \left(1 + 0.15 Re_y^{0.687}\right) \, \frac{12 \, n_{\text{air}}}{AU_{Dy} \rho_{\text{air}}} \left(1 + 0.15 \, \frac{2A \, U_{\infty} \, \rho_{\text{air}}}{\eta_{\text{air}}} \, 0.687\right)
\end{align*}
\]

(11)

Note that the term \((1)\) in the Equations (11) is supposed as constant to simplify the resolution of the equations (9) - giving second order differential equations. This assumption is justified since \(Re_y\) is close to the unity and then \(C_{Dy} = \frac{24}{Re_y}\) remains suitable. The equation system to solve becomes, equations (12):

\[
\begin{align*}
\frac{m_0 \, dU_{Dx}(t)}{dt} &= Q \, E_{\text{cap}} - \frac{6 \pi \eta_{\text{air}}}{K_s} U_{Dx} \\
\frac{m_0 \, dU_{Dy}(t)}{dt} &= -m_0 \rho_{\text{water}} - \rho_{\text{air}} g - \frac{6 \pi \eta_{\text{air}} K_s}{K_3} U_{Dy}
\end{align*}
\]

(12)

After two consecutive integrations with the initial conditions \(\cdot U_{Dx}(t = 0) = U_{Dx0}, U_{Dy}(t = 0) = U_{Dy0}\) \((x_0(t = 0), y_0(t = 0)) = (x_{D0}, y_{D0})\), the analytical equations of the horizontal and vertical droplet positions, respectively referred as \(x_{th}\) and \(y_{th}\), are given in equations (13):

\[
\begin{align*}
x_{th}(t) &= Q \, E_{\text{cap}}/K_s + m_0 \left(\frac{Q \, E_{\text{cap}}/K_s}{K_3}\right) \left[1 - e^{-\frac{K_3}{m_0}}\right] + x_{D0} \\
y_{th}(t) &= -m_0 \rho_{\text{water}} - \rho_{\text{air}} g t + m_0 \left(\frac{U_{\infty,A} + m_0 (\rho_{\text{water}} - \rho_{\text{air}})}{K_3 \rho_{\text{water}}} g\right) \left[1 - e^{-\frac{K_3}{m_0}}\right] + y_{D0}
\end{align*}
\]

(13)

Where \(E_{\text{cap}} = -\varphi\, \text{rad}(V) = \frac{V_{\text{cap}}}{0.01} \text{ V/m.}\)

As presented in Figure 13 (Left), for every pair of pictures, the droplet charge \((Q)\) is then evaluated by looking for the theoretical droplet trajectory from the Equations (13) which fits the best with the observed droplet positions. In the given example (Figure 13, Left), the fitted theoretical trajectory - for \(V_{\text{ion}} = -32.25 \text{ V}, V_{\text{cap}} = -629.5 \text{ V}, A = 49.5 \mu\text{m}\) and the air temperature \(T_{\text{air}} = 292.55 \text{ K}\) - illustrated by the red line is obtained for a droplet charge \((Q)\) of \(+9.10 \times 10^4 \text{ |e|}\). Finally, this method is applied...
for the 200 picture pairs to get the mean droplet charge value - visible in Figure 13 (Right). Note that the standard deviation of the 200 $Q$ values gives the error bars in Figure 6.

Terminal velocity measurement, (Right, Middle) Droplet radius evaluation by reversing the Beard (1976) model and (Right, Bottom) droplet charge deduction for a series of 200 pictures pairs. Mean and standard deviations for the corresponding parameters are presented.

**B.3 Validation**

The method presented at the previous section is possible as long as the droplet has reached its terminal velocity. As mentioned in Dépée et al. (2020) and visible in Figure 4 (Left) of the same paper, droplets are generated at a velocity larger than their terminal velocity. It has been found that a distance between the droplet generator and the capacitor of 15 cm was large enough to allow droplets to reach their terminal velocity. In the setup in figure 12, this requirement prevails.

An experiment was performed to ensure that reversing the Beard (1976) model was a suitable method to evaluated the droplet radius. For this purpose, the same droplet train was recorded in optical shadowgraphy with a camera zoom at the lowest and at the greatest to respectively apply the Beard (1976) model inversion and the circle Hough transform. In all tests, it was found a discrepancy of less than 2 % between the two methods, giving overevaluations as well as underevaluations when comparing one to the other.

Also, the disturbance of the electric field at the capacitor ($E_{cap}$) on the vertical droplet velocity was studied. $E_{cap}$ was then turned on and off to investigate the change in vertical droplet velocity. It was found that during tests, $E_{cap}$ reduced the vertical velocity up to 1.3 %. This situation was for a droplet charge ($Q$) and a capacitor potential ($V_{cap}$) both negative. Some other tests also showed that the droplet vertical velocity was increased up to 0.3 %, for a droplet charge and a capacitor potential of unlike sign. Since these two extreme cases respectively represent a underevaluation of less than 0.7 % and an overestimation of less than 0.2 % of the droplet radius - this effect was neglected.

Finally, two other validations can be formulated by examining the Figure 6. First, several capacitor potentials ($V_{cap}$) were used in the tests - from -629.5 to -477.4 V - giving the same charging relationship. The Faraday Cage is consequently reliable, there is not impact of the electric field ($E_{cap}$) on the droplet charge. Secondly, in the four tests the droplet radius varies from 47.0 to 51.2 μm. Thus, the droplet charging system is independent of the droplet size and droplet evaporation.
References


