Interaction of a ballistic probe with gaseous media

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Abstract. Free-flying metal probes are used to determine charge densities in gaseous media containing free charge or low density plasma. The trajectory of the probe is ensured either by gravity or by propelling the probe to a certain velocity at the launch site. While travelling, the probe charge changes from its launch-site magnitude to that related to the space charge density existing along the trajectory. The degree to which the probe’s arrival-site charge magnitude matches the space charge density in the area of interest depends on the probe shape and on the charge exchange processes between the probe body and the medium. The paper studies a probe acting as a free-flying charge carrier in air, and discusses the problems that may lead to an imbalance between the charge collected by the probe in the area of interest and the charge measured at the arrival site. The analysis and the described experiments are of the ballistic type: a small, triboelectrically pre-charged metal probe was propelled on a horizontal path, and the charge carried by the probe was measured at several points along the trajectory by means of contact-free induction rings; the initial and final charges were determined by static Faraday cups. A charge disparity was found under certain conditions, and its degree explained by the effects of the charge carrier potential. The studied probe charges ranged from 10 to 50 nF, and the fly-times needed to cross a one-meter path ranged from 20 to 40 ms. The probe to gas charge exchange experiments and their analysis yielded conditions under which the probe lost approximately 10 % of its charge. The results of our study may be of interest to those who intend to use the free-flying probe technique for the determination of space charge density.

1. Introduction
In the ballistic method, the degree of the space charge imbalance is determined from the charge collected by a free-flying metal probe. The unintrusiveness of the method allows the investigation of the variety of environments that are sensitive to the use of common measuring instruments.

Pauthenier and Moreau-Hanot [1] described the ballistic method in 1932—they determined the density of unipolar space charge using a gravity driven, metal, spherical charge carrier. Similar method was used to determine the field strength in precipitators with flat plate [2] and cylindrical [3] geometries. Analytical data related to the ballistic method were also published [4].

The gravity-imposed probe trajectory limitations can be overcome by using other methods of propulsion. Precipitator corona parameters were measured using a steel, spherical probe propelled by an air gun into a Faraday cup [5]. Similar propulsion was used in a study of low density plasma in which the probe charge was determined with two Faraday cups [6].

If the interaction of the probe with an object is to be scrutinized, such as in “the speed of approach” experiments, a pre-charged probe is used. The interaction of a triboelectrically pre-charged probe with a grounded plane was studied in 2000 by Zaharia [7].

In ballistic measurements, the motion and charge of the probe have to be known. Usually, the trajectory presents no problems, but the probe’s charge might, since it cannot be easily
manipulated. As it is evident that, in a given medium, a probe’s ability to carry charge depends predominantly on its size, we have studied the problem using a probe pre-charged by the triboelectrification between polytetrafluorethylene (PTFE) and lead [8]. The pre-charged probe was propelled along a horizontal trajectory and the charge on it measured by induction with two dynamic Faraday rings [9]. By varying the magnitude of the probe pre-charge, we have arrived at conditions, where the probe charge measured at the arrival site was found to be smaller than that measured at the launch.

2. Theoretical Part
A probe shaped as a thin, flat circular disc (figure 1) is assumed to be flying with velocity $v_p$, with its centre following trajectory $x$. The space probed by the disc contains free positive ions and electrons, with densities $n_+$ and $n_-$. The probe, by interaction with the free charge carriers, collects charge at a rate given by

$$\frac{dq}{dt} = \int_S \int J \cdot dS = \int_S \int e (n_+ - n_-) v_p \cdot dS,$$

(1)

since the current density $J$ is given by the imbalance between the encountered positive ($n_+$) and negative ($n_-$) charge carriers.

If the disc is always perpendicular to the axis of flight ($\alpha = 90^\circ$), equation (1) becomes

$$\frac{dq}{dt} = \int_S \int J dS = e (n_+ - n_-) v_p S_p.$$

(2)

A probe shaped as an axially aligned cylinder (with an effective area $S_p$) must be launched with an auxiliary apparatus to ensure its alignment.

Figure 1. Ballistic probe principle ($\hat{n}$, the normal to surface $S_p$; $n_+, n_-$, density of positive ions and electrons; $S_p$, probe’s effective cross section; $v_p$, probe’s velocity; $x$, coordinate; $\alpha$, angle; (+) and (−), free ion and electron).

Figure 2. Ballistic measurement (a, launching device; $l_1$, measured area; $l_2$, probe’s path; $m_1$, onset site; $m_2$, end-of-flight site; p, probe; $S_p$, probe’s cross section; $\rho_a$, atmospheric charge density; $\rho_m$, measured charge density).

Figure 2 shows a ballistic experiment comprising a probe launcher (a), and two measuring sites ($m_1$ and $m_2$) that yield information about the charges carried by the probe.

The charge density at each point in the area of interest is given as

$$\nabla \cdot D = \rho = \rho_a + \rho_m.$$

(3)

Free charge density $\rho$ consists of two main components, atmospheric charge density $\rho_a$ and the measured charge density $\rho_m$, given as

$$\rho_a = \rho_{a+} + \rho_{a-} \quad \rho_m = \rho_{m+} + \rho_{m-}$$

(4)
During the flight, the probe of cross section $S_p$ collects charge $q_p$ by interaction with the space charge density $\rho$, at a rate
\[
\frac{dq_p}{dt} = \rho \frac{dx}{dt} S_p.
\] (5)

Expression (5) determines the degree of the probe’s intrusiveness, since the perturbation that the probe causes in the medium is proportional to the degree of the probe-medium charge exchange.

At each point on the path shown in figure 2, the probe collects charge
\[
dq_p = \rho S_p \, dx,
\] (6)
and the total charge collected is
\[
q_p = \int_{x_0}^{x_2} \rho_a \, dx + \int_{x_1}^{x_2} (\rho_a + \rho_m) \, dx + \int_{x_2}^{x_3} \rho_a \, dx.
\] (7)

Usually, the charges in the noninteractive areas ($< x_0, x_1 >$ and $< x_2, x_3 >$) are taken to be negligible ($\rho \rightarrow 0$), and the expression (7) for the charge collected by the probe is simplified to
\[
q_p = \rho_m S_p \int_{x_1}^{x_2} dx = \rho_m S_p (x_2 - x_1),
\] (8)
which yields a charge $q_p$, collected by the pellet that has moved along a path $l_i = x_2 - x_1$.

A reasonable ballistic experiment must ensure that a minimum charge is exchanged between the probe and medium, and a negligible probe charge perturbance is experienced in the non-interaction area.

3. Experimental Part

![Figure 3](apparatus.png)

**Figure 3.** Apparatus (a, launcher; b, PTFE tube, length $l_1$; $fc_{1,2}$, fly-through Faraday cups (see figure 5); $l_2$, cups’ separation; $l_3$, tube to first cup distance; p, probe; $s_{1,2}$, cup outputs).

![Figure 4](probe.png)

**Figure 4.** Probe (pellet, caliber 0.22 in; dimensions in millimeters).

The apparatus used is shown in figure 3; it is comprised of a launcher (Crossman 2240) and a double-cone probe (figure 4), pre-charged by triboelectrification.

The triboelectrical charging was performed by interaction between the lead probe pellet and the polytetrafluorethylene launching barrel. Charging [10–13], resulting from the contact and separation between these two materials with work functions $\Phi_1$ and $\Phi_2$ and a low density of surface states $N_{ss}$ is given as
\[
Q = eN_{ss} A (\Phi_1 - \Phi_2)
\] (9)
where $\Phi_1$ and $\Phi_2$ are the work functions of the interacting materials and $N_{ss}$ the density of surface states. For the PTFE, the effective work function found by Davies [14] was applied ($\Phi_{PTFE} = 4.26$ eV); for lead, 3.94 eV was used [15]. The pellet’s charge at the exit from the barrel was consistently positive.
The charge on the free-flying probe was determined using several Faraday cups. The probe charge on the arrival site and the PTFE launch barrel were measured by two regular, pail-type Faraday cups. The charge on the flying probe and its velocity were determined with induction-type Faraday cups [9], shown in figures 5 and 6, since the dynamic Faraday cups yield both the charge and velocity of the interacting charged particle (figure 7). The Faraday cups were interfaced with a sampling oscilloscope (Tektronix TDS 3012B) with an in-house designed charge to voltage converter.

Figure 5. The fly-through Faraday cup (a, shield, 50.8 mm i.d., 11.4 cm length, copper; b, BNC connector; c, induction ring, 31.8 mm i.d., 10.2 cm length, copper).

Figure 6. The Faraday cup, amplifiers, and the guide tube used in the experiments.

4. Results and Discussion

Figure 7 (a) shows the induced charge waveforms from the fly-through Faraday cups for a narrow cup separation ($l_2 = 6.0$ cm). The ratio of the two pulse magnitudes is 0.91, normalized to the fly-through Faraday cup 1, representing a 9% difference in the probe signal amplitude.

Figure 7 (b) shows the induced charge waveforms from the wide separation of the fly-through Faraday cups ($l_2 = 95.0$ cm). The pulse waveforms fly-time separation is 35 ms, which corresponds to the average velocity of the pellet of 27 m·s$^{-1}$ (air propellant pressure of 27 Pa). The ratio of the two charges normalized to the fly-through Faraday cup 1 is 0.86 (from the magnitudes of the two pulses); this represents a 14% decrease in the signal magnitude.

As the probe charge was determined experimentally, probe capacitance is needed to obtain its potential. The capacitance and potential of an electrically isolated body can be obtained theoretically [9]; alternatively, it is often assumed that the capacitance of an object is approximately the same as the capacitance of an equivalent sphere—a sphere with the same surface area as the body of interest. The pellet dimensions make the total area of the probe $A_p = 150$ mm$^2$, yielding the equivalent-sphere radius 3.5 mm. The pellet’s capacitance can be estimated to be $C_p = C_s = 4\pi\varepsilon_0 R_s = 0.39 \times 10^{-12}$ F, and, for the pellet charge $Q_p$ ranging from $Q_p = 3 \times 10^{-9}$ C to $Q_p = 5 \times 10^{-9}$ C, the pellet potential range is $V_p = Q_p/C_p \approx 8$ to 13 kV.

The obtained potential exceeds the air corona discharge onset [16], which suggests that the flying probe will ionize the air. Further confirmation that the probe potential is sufficient for ionization of air is in figures 8 and 9 that show the corona onset and the sparking voltages for air. The corona onset for the pellet can be determined from the voltage-current characteristic (figure 8), measured for a system consisting of a biased pellet and a grounded plane.

Figure 9 is based on the work of Paschen [17], who in 1889 analyzed problems of the breakdown in gas; more recent data can be found e.g. in a book by von Engel [18]. Paschen’s semi-empirical
law has been derived for the “sparking” potential between plane parallel electrodes as

$$V_s = \frac{B (pd)}{\ln \left( \frac{A}{\ln \left( \frac{1}{1 \gamma} \right)} \right) + \ln(pd)}$$

where \(A = 1/\lambda_1\), \(B = V_i/\lambda_1\); \(\lambda_1\) is the mean free path at unit pressure \((p = 1\ \text{torr})\). Coefficient \(\gamma\) is given by the number of secondary electrons produced by each ion arriving at the cathode; the ionization coefficients \([18]\) \(A\) and \(B\) are listed in table 1.

The sparking voltage for the given media, both measured and calculated from equation (10) are plotted on linear scales in figure 9 in terms of the reduced pressure \(pd\), so it is only necessary to know the electrode gap \(d\) to obtain the sparking voltage \(V_s\) (listed in table 1). The spark voltage and the corona onset data confirm that an object, subject to its shape, will begin to ionize air when its potential approaches \(\sim 10^4\ \text{V}\). The corona onset values, measured for air, are similar to those found by Aubrecht [16].
Table 1. Paschen coefficients $A$ and $B$, and spark voltages for air.

| Medium | $A$ [cm $\cdot$ torr] | $B$ [m $\cdot$ Pa] | Range of validity $\frac{E}{p}$ [V $cm$ $\cdot$ torr] | Spark voltage $[V m$ $\cdot$ Pa] |
|--------|-----------------------|-------------------|---------------------------------|------------------|
| Air    | 15                    | 11.5              | 365                             | 274              | $100 - 800$ | $75 - 600$ | 9.2 | 8.5 |

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