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Measurement of triboelectric charging of moving micro particles by means of an inductive cylindrical probe

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Abstract
We present a method based on induced currents in a cylindrical probe which allows analysis of the micro-particle charging processes in an aerosol. The micro particles were triboelectrically charged by passing through a dielectric tube coaxially mounted into the probe. The cylindrical probe enabled the quantification of particle charging without prior calibration of the probe. An analytic model was developed for the description of the measured induced currents and implemented into a computer simulation program. The combination of model simulations and an appropriate experimental setup revealed comprehensive data for the determination of the particles' electric charge against time of flight through the tube. In methodological proof of principle experiments, the formations of particle clouds with charges of different signs were observed using magnetite micro particles.

Introduction

Micro and nano particles are of increasing interest for the development of new materials and novel technologies. Many types of such particles are as a rule electrically charged [1] or gain their electric charge during production or processing cycles. In these cases the electric charge is not constant and depends on the conditions of particle transport and storage. On the other hand, the ability to produce charged particles has the advantage that these particles can be manipulated by means of electric fields.

A significant contribution to the electric charging of micro and nano particles is caused by triboelectric charging resulting from contacting surfaces of different materials during transport or production processes. Due to the complexity of these motions and the physical surface–particle interactions, it is nearly impossible in practice to precisely predict the resulting electric particle charge. Therefore, it is important to determine the electric charging of particles experimentally and non-invasively without interference to the transport procedure.

A typical method for the determination of the electric charge is based on collecting particles in a Faraday cup [2]. In this method, the integral of the measured induced current along time results in the induced charge, which is equal to the charge of the particles in the Faraday cup. However, this method does not allow *in situ* determination of the charge of moving particles, i.e. for instance controlling charging conditions of particle flows in a running production apparatus.

In previous attempts to improve the analysis of electric characteristics of moving micro particles, a circular inductive probe was utilized and implemented in particle flow systems without any restriction on particle motion [3–7]. A grid of electrodes has also been employed to determine the velocity and electric charge of cosmic dust particles [8]. There are, however, inflicted several problems concerning the interpretation of the measured induced currents from such probes. On the one hand, the total induced charge was smaller than the real charge of the particles, which required additional complex calibration measurements; on the other hand, unambiguous conclusions from experimentally determined currents against time could not always be drawn.

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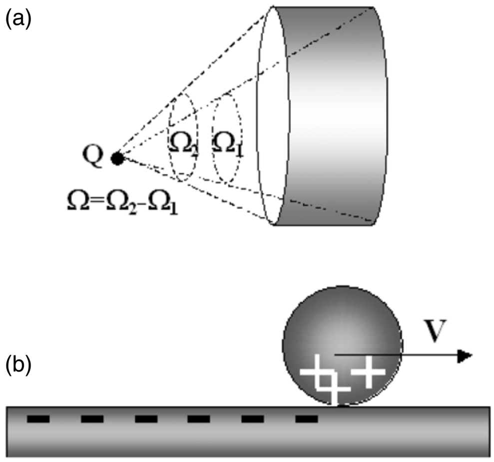

Figure 1. (*a*) Schematic to the definition of the solid angle Ω in the case of a metal ring and (*b*) schematic representation of triboelectric charging of a particle and the surface.

An analytic model was developed, in which the charge distribution of a discontinuous dust flux in a circular probe was determined by extracting and estimating only the height of current peaks [9, 10].

Furthermore, Armour-Chélu and Woodhead investigated the charging process of particles in gas flows in tubes as well as the influence of humidity, temperature and particle size [11, 12]. The conclusions on the influence of these factors were derived from the comparison of electric signals in the inductive circular probe before and after applying these factors.

In this paper we propose another approach using an inductive metal probe of cylindrical shape. We demonstrate that this setup can overcome the calibration and interpretation problems of current measurements for single micro particles or corresponding particle clouds. By means of the probe introduced here, triboelectric charging of particles can be examined *in situ* and non-invasively in a running flow stream without additional calibration procedures.

1. Principles of charge measurement and simulations

1.1. Analytical model for the induced current in a cylindrical probe tube with triboelectric charging of a micro particle or particle cloud

The ratio between the induced charge in a cylindrical metal probe and the electric charge of a particle can be determined by a numerical solution of the Poisson equation with appropriate boundary conditions. Taking into account the simple geometry in our case, an analytical model based on the Gaussian theorem is suggested and applied to the interpretation of typical experimental results. The Gaussian theorem says that the flux of the electric field E produced from an electric charge Q through the surface S is equal to $Q\Omega$, whereas Ω is the solid angle under which the borders of the surface S are seen from the position of the charge Q (Figure 1(*a*)). In our special approach, Q corresponds to the electric charge of a moving particle or a compact particle cloud. With the induced charge Q_{ind} on the surface S being equal to the flux of the electric field E through the surface S, the relation between the induced charge Q_{ind} and the particle charge Q can be obtained by

$$Q_{\mathrm{ind}} = -Q\frac{\Omega}{4\pi}. \tag{1}$$

In the case of a Faraday cup, $\Omega = 4\pi$ and thus $Q_{\mathrm{ind}} = -Q$. In the case of a particle moving past an arbitrarily shaped probe, the solid angle $\Omega(t)$ is a function of time t. By differentiating equation (1) with respect to time, the equation for the induced current results to

$$I_{\mathrm{ind}} = \frac{\mathrm{d}Q_{\mathrm{ind}}}{\mathrm{d}t} = -\frac{1}{4\pi}Q\frac{\mathrm{d}\Omega}{\mathrm{d}t}. \tag{2}$$

In the case of an additional triboelectric charging of the micro particle or particle cloud whilst passing the probe, the charge $Q(t)$ is also a function of time t. For the particle–surface interaction sketched in figure 1(*b*), the following equation for the induced charge in the probe is obtained:

$$Q_{\mathrm{ind}} = \frac{1}{4\pi}\int_{t_0}^{t}\frac{\mathrm{d}Q}{\mathrm{d}t}\Omega\,\mathrm{d}t - (1-\eta)\frac{Q\Omega}{4\pi}. \tag{3}$$

The first part of equation (3) represents the charge in the cylindrical probe induced by the triboelectric charging of the surface. The upper limit for the integral over time is the time variable, which corresponds to the location of the particle relative to the probe. The second part describes the charge in the cylindrical probe induced by the motion of the particle, whose charge is not constant in time. The 'phenomenological' coefficient η determines the degree of influence of both the equation parts on the induced charge in the probe. Calculations have shown that this coefficient helps to describe the complex diversity of the observed experimental dependences of the induced current in the probe. Although the microscopic mechanism of this coefficient is not yet completely understood, it can be assumed that η is connected to a delocalization of the negative and positive charges on the contact surface. During transport, a particle accumulates its total triboelectric charge in the narrow area of its contact region, whereas the inverse charge is spread over the surface along the particle surface contact trail. Since the particle is moving in a gas or air environment, additional gas discharging effects around the contact regions have to be considered [13–16]. The induced charge due to the particle motion can vary according to the radial position in the cross-section of a cylindrical tube [12].

Following from (3), the equation for the induced current is derived as

$$I_{\mathrm{ind}} = \eta\frac{1}{4\pi}\frac{\mathrm{d}Q}{\mathrm{d}t}\Omega - (1-\eta)\frac{1}{4\pi}Q\frac{\mathrm{d}\Omega}{\mathrm{d}t}. \tag{4}$$

If the coefficient $\eta = 0$, the first part of equation (4) is cancelled out. Physically, this means that the emerging charges on the surface and the particle compensate each other. Equations (2) and (4) are utilized in simulations.

1.2. Simulation of induced currents in a cylindrical probe without triboelectric particle charging

In the following it is assumed that a positively charged particle passes a grounded cylindrical probe of length L with constant

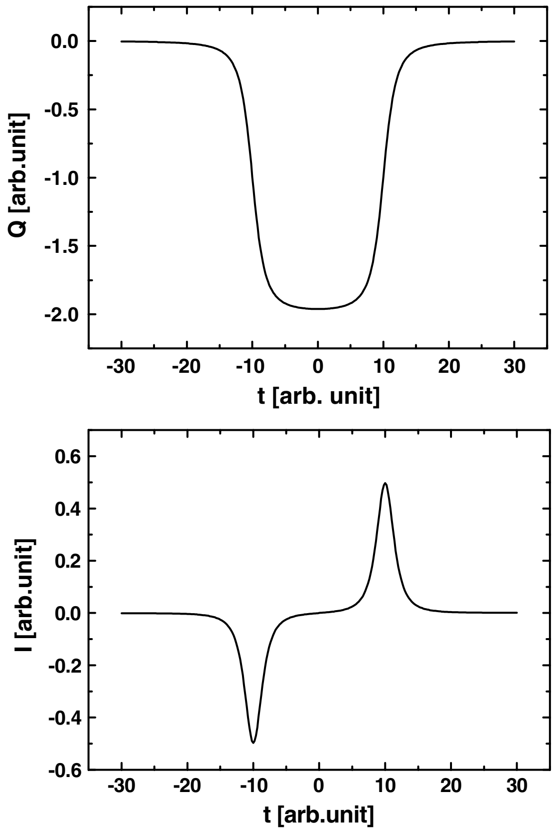

Figure 2. Induced charge $Q(t)$ (top) and induced current $I(t)$ (bottom) in a grounded cylindrical probe with a positively charged particle passing through with constant velocity (inlet at $t = -10$ a.u.; outlet at $t = 10$ a.u.).

velocity v and without contacting the probe's surface. A typical graph of the induced charge $Q_{\text{ind}}(t)$ against time is shown in figure 2 (top). At $t = -10$ a.u. (arbitrary time units) the particle enters the probe cylinder, at $t = +10$ a.u. it leaves the probe cylinder. The induced charge has a maximum value in the middle of the tube, because exactly at this point the solid angle Ω reaches its maximum. By differentiating the function $Q_{\text{ind}}(t)$, the induced current $I_{\text{ind}}(t) = \mathrm{d}Q_{\text{ind}}/\mathrm{d}t$ can be calculated (figure 2, bottom). The two maxima of the induced current $I_{\text{ind}}(t)$ arise when the particle passes the probe tube apertures. The interval Δt between these maxima depends on the particle's velocity v and the geometrical length L of the probe tube. Obviously, the integral of induced current over time from negative infinity to $t = 0$ equals the absolute value of the total induced charge at the middle of the tube length. If the probe length is much larger compared with the cross-section of the cylinder apertures, that is $\Omega(0) \to 4\pi$, the particle charge equals the induced charge in the middle of the cylindrical probe.

Assuming an accelerated motion of the particle through the probe tube, the induced current $I_{\text{ind}}(t)$ also shows two peaks. However, due to the resulting asymmetry in $Q_{\text{ind}}(t)$, the shape and size of the second peak differ from the first one: the absolute maximum of the second peak increases with a decreasing width compared with the first one.

Another interesting example is the motion of two particles (or two compact particle clouds) with opposite signs. The corresponding simulated graphs of induced charges and currents are shown in figure 3. The resulting curves of the induced current are the sum of two 2-peak distributions with different amplitudes (figure 3, bottom), according to the charge and the relative time delay of the two particles. Integrating corresponding parts of the induced current over time, the charges of both particles (particle clouds) can be estimated.

1.3. Simulation of the induced current in a cylinder probe tube with triboelectric charging of particles

We have simulated the induced charges and currents in a grounded cylindrical probe the length L, while an accelerated micro particle or compact particle cloud, respectively, is moving through a dielectric tube coaxially mounted within the grounded probe tube (figure 4). At the probe inlet (in figure 5 at $t = -15$ a.u.) the particle is assumed to have a constant positive charge. Further positive triboelectric charging occurs when the particle contacts the surface of the dielectric tube (e.g. a glass tube). In the simulation, a dependence of the particle charge $Q \sim t^2$ was assumed. In figure 5, the resulting induced current is illustrated for different values of the coefficient η. The graphs are the sum of the induced current from the first part in equation (4) (dotted line, 'surface current') and the induced current from the second part in equation (4) (dashed line, second part in equation (4), 'particle current'). At smaller coefficients, e.g. $\eta = 0.3$, the 'particle current' predominates. It consists of two peaks (very small positive: left, and large negative: right) comparable to the curves in figure 2. However, the absolute heights of the peaks at the inlet and outlet of the probe tube differ considerably due to charging effects during particle motion through the probe tube.

With increasing η, the part of the 'surface current' increases. This induced current exhibits two features: the first feature is the behaviour of the total current when the particle is moving inside the probe. The solid angle Ω changes in this region relatively slowly and, therefore, the current curve is proportional to the time differentiation of the charge. The second feature is the slow decrease of the induced current after the particle has left the tube. The total current in this region consists only of the 'particle current'.

A similar effect appears when a polarized particle cloud passes the probe tube with additional triboelectric charging (figure 6). The simulated particle cloud consists of two parts, a first and negatively charged bigger part as well as a second and positively charged smaller part (as in figure 3, top right). Here, additional negative triboelectric charging takes place with a coefficient $\eta = 0.6$. The short linear region between the first and the second peak qualitatively corresponds to the linear region between the first small and the second bigger peak in figure 5 with $\eta = 0.3$.

2. Experimental results and discussion

The experimental set up is schematically shown in figure 4. Triboelectric charging of particles was examined in a Duran50 glass tube with a constant inside diameter of 0.2 cm and in a conical tube made of soda-lime glass. The soda-lime glass tube was about 18 cm long with a linearly decreasing inside diameter from 0.7 cm to 0.25 cm. We used commercial

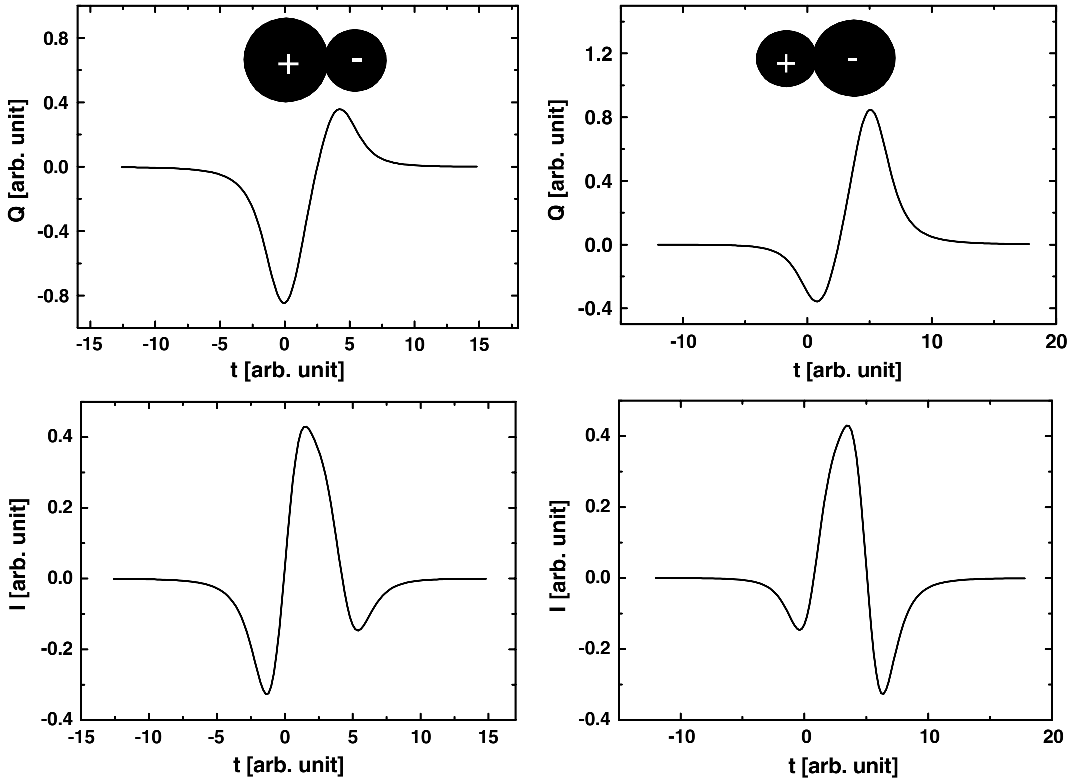

Figure 3. Induced charge $Q(t)$ (top) and induced current $I(t)$ (bottom) in a grounded cylindrical probe with a polarized particle cloud of two oppositely charged components. The cloud is not subjected to any additional triboelectric charging during its motion in the probe.

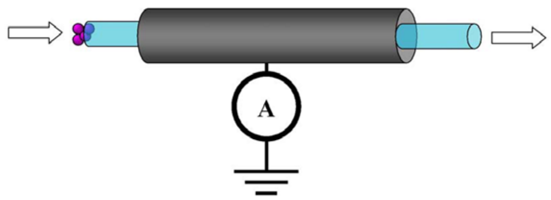

Figure 4. Schematic representation of the experimental setup for measuring the induced current and charge in a grounded cylindrical probe with a particle cloud moving through a coaxially mounted dielectric tube.

(This figure is in colour only in the electronic version)

laser printer toner particles (OKI Systems GmbH, Düsseldorf, Germany) with a mean diameter of 10 μm, and magnetite particles of a magnetite powder with a size distribution from 1 μm to 45 μm (Hewlett Packard, Germany). A cylindrical brass tube with a length L of 18 cm and an inside diameter of 9 cm was utilized as probe, in which the glass tubes were mounted coaxially. The particles were put at the end of the glass tube. To this end was connected a compressed air unit with a mechanical valve. After opening the valve, the particles were accelerated so that they reached a velocity of above 50–70 m s^{-1} at the outlet of the glass tube. The relative air humidity of the compressed air was below 5%.

The induced currents of laser printer toner particles accelerated with compressed air are shown in figure 7. Obviously, the toner particles are charged positively in contact with Duran50 (figure 7(*a*)) and negatively with the soda-lime glass tube (figure 7(*b*)). The measured curves can be described qualitatively by comparison with the graphs simulated with $\eta = 0.96$ (figure 5): we observed the two features obtained from the simulations: a linear behaviour inside of the probe as well as a slowly decreasing edge as the particles are leaving the probe tube. Based on the simulation (see section 1.3), we can explain the linear behaviour of the induced current in the tube. Inside the long tube, the variation of the angle Ω of the moving particles is relatively small. Thus, only the first term in formula (4) describes the induced current dependence of time in the tube. The I_{ind} is proportional to the time derivative of the particle charge in this term. It is now obvious that the linear time dependence of induced current results from the quadratic time dependence of the particle charge $Q \sim t^2$ because the term does not include other parameters depending on time.

The dependence $Q \sim t^2$ could be interpreted from an energetic point of view. The physical work A performed during particle charging can be written as the product of the friction force F_{tr} and the path of the particles L along the probe tube: $A = F_{\text{tr}}L$, whereas L is proportional to the acceleration, i.e. $L \sim t^2$. If the electric energy of the particles is $E_{\text{el}} = Q\Delta\varphi/2$, with Q as particle charge and $\Delta\varphi$ as potential difference at contact, the following estimate can be given:

$$Q\Delta\varphi \sim F_{\text{tr}}t^2. \qquad (5)$$

As a consequence, if the triboelectric charging occurs at constant $\Delta\varphi$, the dependence $Q \sim t^2$ is confirmed.

Figure 8 shows the measured currents induced by accelerated magnetite particles in the probe tube. In the dielectric Duran50 tube, (figure 8(*a*)) nearly no charging of the magnetite particles was observed. The integral over the current curve is small. Compared with the simulations (figure 3),

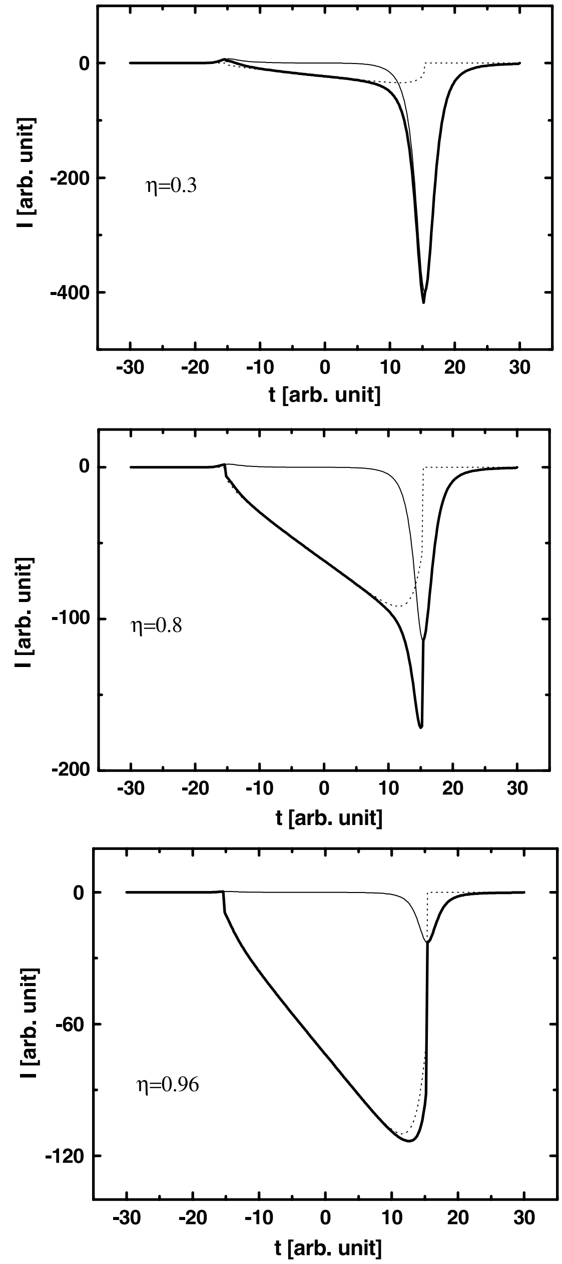

Figure 5. Simulation of the induced current (straight line) in a grounded cylindrical probe tube with a particle cloud passing through a coaxially mounted dielectric tube. Whilst passing the cylindrical probe, an additional positive triboelectric charging occurs. The three examples correspond to different values of coefficient η with dotted lines resembling the first part and the thin solid lines the second part of equation 4.

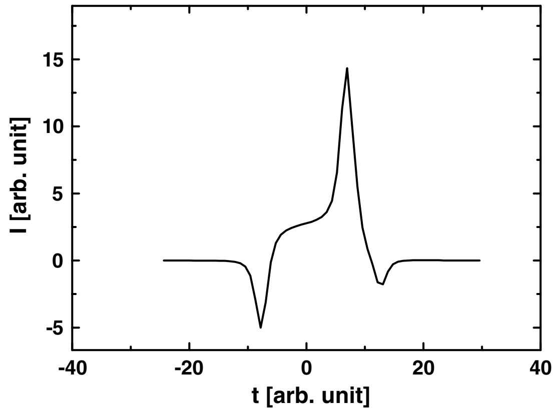

Figure 6. The induced current simulated for a grounded cylindrical probe with a polarized particle cloud (see charge distribution in figure 3) passing through a coaxially mounted dielectric tube ($\eta = 0.6$).

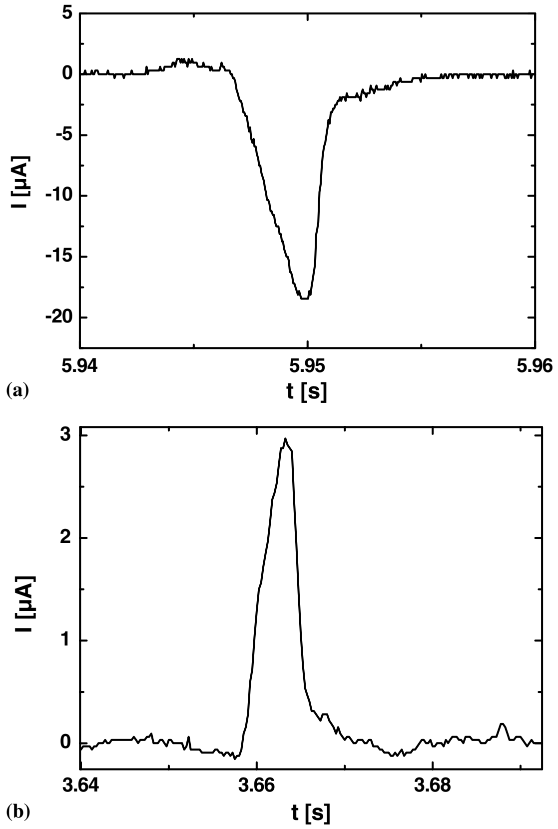

Figure 7. Induced currents measured with a brass probe for laser printer toner particles passing through a coaxially positioned dielectric tube of Duran50 glass (*a*) and soda-lime glass (*b*).

we can conclude that here a magnetite particle cloud was polarized during acceleration. The first and smaller part of the particle cloud was charged negatively, the second and bigger one positively. Such a charge distribution might emerge from the asynchronous separation of the particle collective from the surface of the glass outside of the probe. This is analogous to the charging of microdrops created from discontinuous fluid flows [2].

Since the integral of the induced current is positive, the magnetite particles are charged negatively within the conical tube of soda-lime glass (figure 8(*b*)). The measured curve is qualitatively comparable to the simulated curve in figure 6, where an additional triboelectric charging of a polarized particle cloud was assumed.

In contrast to the dielectric toner particles, magnetite particles have a smaller coefficient η. This could be explained by the fact that magnetite particles have a conductivity of about 10% of iron. The conductivity could enable a transfer of the charge at the surface into the particle's bulk decreasing the charge at the particle's surface and thus any discharging effects.

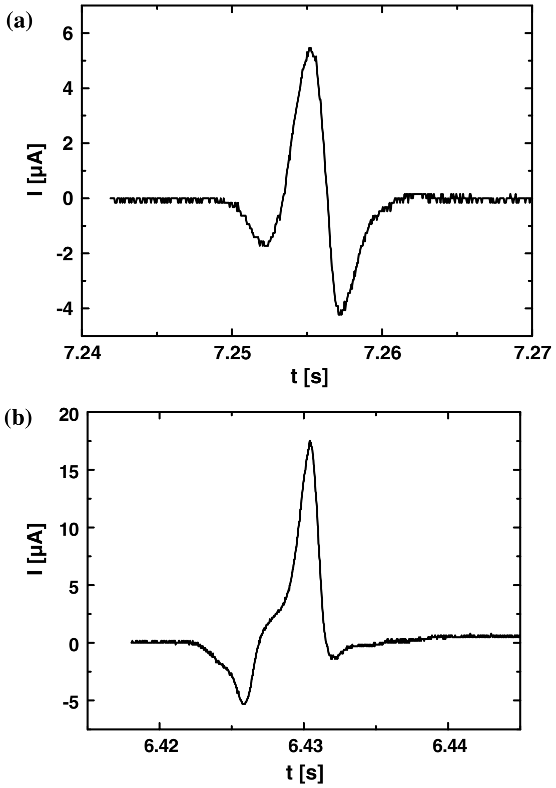

Figure 8. Induced currents measured with a brass probe for magnetite particles passing through a coaxially positioned dielectric tube of Duran50 glass (*a*) and soda-lime glass (*b*).

3. Conclusion

In this paper, we present a novel non-invasive and dynamic method for the investigation of triboelectric charging of particles as they are moving through dielectric tubes. In doing so, the electric charge of particles can be quantified without prior calibration of the induced current, as long as the inductive probe can be assumed to have the shape of a long tube. In fact, this method is well suited for determining Q/m values of micro and nano particles, as long as the particle mass passing the probe can also be measured (e.g. by a particle filter). Moreover, the cylindrical probe could be used to calibrate other probes of different materials and shapes.

We further developed an analytic model including a phenomenological coefficient for the description of the measured induced currents. With this coefficient, we were able to simulate a huge diversity of measured current, which could indicate a certain microscopic relevance of this parameter. This model in combination with experimental data allows for the determination of the time dependence of a particle charge. In acceleration experiments based on the theoretical and experimental findings presented here, we have observed that magnetite particle clouds show an analogous behaviour to fluid droplets developing opposite signs during droplet generation.

Acknowledgments

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