DRUG DEVELOPMENT AND INDUSTRIAL PHARMACY, 18(14), 1505-1526 (1992)

AN EXPERIMENTAL INVESTIGATION OF TRIBOELECTRIFICATION IN COHESIVE AND NON-COHESIVE PHARMACEUTICAL POWDERS

P.A. Carter, G. Rowley, E.J. Fletcher*, E.A. Hill**, School of Pharmaceutical and Chemical Sciences, *School of Computing and Mathematics, Sunderland Polytechnic, Sunderland, **Glaxo Operations U.K. Ltd., Barnard Castle.

ABSTRACT

A detailed experimental investigation has been undertaken of the triboelectrification process of the pharmaceutical excipient alpha-lactose monohydrate and selected drugs. Particle charge studies involved the design and construction of an apparatus to incorporate pneumatic powder feed, triboelectric charging via a cyclone separator and simultaneous powder charge (Q) and mass (M) measurements using a modified Faraday well. Preliminary studies showed the charging of the selected materials to be unaffected by relative humidity up to 84%, due to the very low hygroscopicity of the powders. Experiments using lactose size fractions with brass, steel and cellulose contact charging surfaces conducted at different feeder gas pressures, gave net electronegative specific charge values (Q/M) for the metal surfaces, and electropositive values for cellulose. Specific charge increased linearly with gas pressure for the metals, and non-linearly for cellulose. Samples of micronised lactose and beclomethasone dipropionate (BDP) showed more tendency than unmicronised samples to adhere to the contact surface which resulted in more complex charging processes. A novel system to analyse the charge and mass data in further detail was developed, giving relative Q/M values at unit time intervals. It is proposed that this will overcome the

limitations of reliance on the final net specific charge value. Preliminary results indicated differences in the charging mechanism for lactose in contact with the two metal surfaces.

INTRODUCTION

Particle agglomeration in pharmaceutical powders has led to problems in attaining satisfactory drug content uniformity(1-3), and electrostatic forces have been identified in playing a role in cohesion/adhesion processes(4). During powder handling operations such as mixing or pneumatic conveying, particles invariably acquire an electrostatic charge due to interparticulate and particle/contact surface collisions. The net charge on a powder sample may be electropositive or electronegative, and is often derived from a complex bipolar system(5). Triboelectrification or contact charging has been shown to be influenced by several factors, including particle size and shape, nature and work function of the contacting surface and particulate material, contact area and frequency, surface purity, and atmospheric conditions(6). Although the process is not fully understood, it is generally accepted that charging occurs as a result of electron transfer between materials of different electrical properties(7), although other workers(8) have related charge transfer to the chemical nature of the solid surface, particularly when polymer surfaces are involved.

Very little detailed work has been undertaken with pharmaceutical systems although charging of excipients and selected drugs has been investigated with reference to particulate mixing(9,10).

The principal aims of this work were to design and construct a suitable apparatus for the investigation of triboelectrification in both cohesive and non-cohesive pharmaceutical powders, and to investigate the mechanisms of charging by analysis of the data produced by continuous measurement of Q and M with time (t). The continuity of measurement should give greater insight about the charging mechanisms, particularly for bipolar charging.

MATERIALS

Lactose B.P. 45-90 µm size fraction (Dairy Crest, M.M.B.)

Lactose B.P. 355-500 µm size fraction (D.M.V., Veghel.)

Lactose B.P. micronised (Glaxo Operations U.K. Ltd.)

Beclomethasone dipropionate (BDP) micronised (Glaxo Operations U.K. Ltd.)

Salbutamol sulphate unclassified (Glaxo Operations U.K. Ltd.)

The size fractions were prepared by sieving using B.S. (Endecott) test sieves agitated on a Rotap machine. The size fractions were air-jet sieved to remove small particle contamination, and the effectiveness of this process was confirmed by optical microscopy. The micronised materials were prepared using a fluid energy mill.

METHODS

Particle Characterisation

Detailed particle characterisation was considered to be an essential step in the study of the triboelectrification process, since it is known that particle properties may affect the charging process.

Differential Scanning Calorimetry

This technique utilised a DSC 1B (Perkin Elmer) and was used to establish suitable drying temperatures for both lactose and BDP. The alpha-lactose monohydrate thermograms indicated that drying at temperatures between 90° and 100°C caused loss of the water of crystallization, whereas for BDP, drying at temperatures up to 120°C produced no alteration in the crystal structure.

Moisture Analysis

Moisture uptake determined by a gravimetric method and a Moisture Evolution Analyser (Du Pont Instruments) was < 0.3% w/w at up to 84% relative humidity (RH) at 20°C for both lactose and BDP.

Triboelectrification experiments were therefore conducted under ambient conditions since it was established that the samples were relatively non-hygroscopic.

Surface Area Determination

Surface area values of 2.99, 2.82 and 0.29 m^2/g were obtained for BDP, micronised lactose and lactose B.P. (unclassified) respectively, using the volumetric method of low temperature nitrogen adsorption (Flowsorb II 2300, Micromeritics).

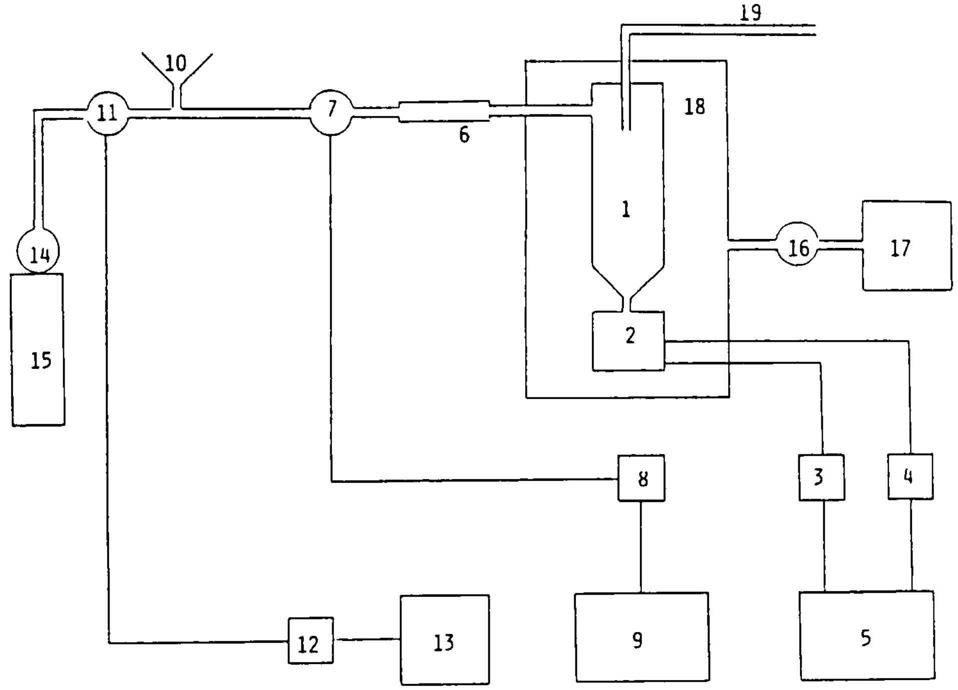
Particle Size and Shape

The arithmetic mean Feret diameter for BDP and micronised lactose was 1.65 and 2.05µm respectively when determined by optical and electron microscopy using image analysis (Quantimet, Cambridge Instruments). It was apparent from the electron microscopy that these values were for agglomerated particles. Direct measurement of primary particles from photomicrographs gave mean Feret diameters of approximately 0.5µm for both micronised powders. Shape was determined by measuring the length:breadth ratio and the area/perimeter^2 which gave arithmetic mean values of 1.50 and 0.05 respectively for both micronised powders. Qualitatively, the shape would be described as "square-circular".

Particle Charging Investigations

Apparatus

Powder charge studies involved the design and construction of the apparatus illustrated in Figure 1. The powders were pneumatically conveyed from a feeder system along a horizontal cylindrical pipe connected to a cyclone separator which acted as



1. *Cyclone separator*
2. *Faraday well with connections*
3. *Strain gauge indicator.*
4. *Electrometer*
5. *Flatbed recorder*
6. *Radioactive source*
7. *Fibre optic system*
8. *Amplifier for fibre optic system*
9. *Flatbed recorder*
10. *Venturi feeder*
11. *Pressure transducer*
12. *Amplifier for pressure transducer*
13. *Digital readout for pressure transducer*
14. *Gas tank pressure control*
15. *Gas tank with pressure gauge*
16. *Vacuum gauge*
17. *Vacuum pump*
18. *Vacuum chamber*
19. *Exhaust pipe for cyclone separator*

FIGURE 1

Schematic of Apparatus

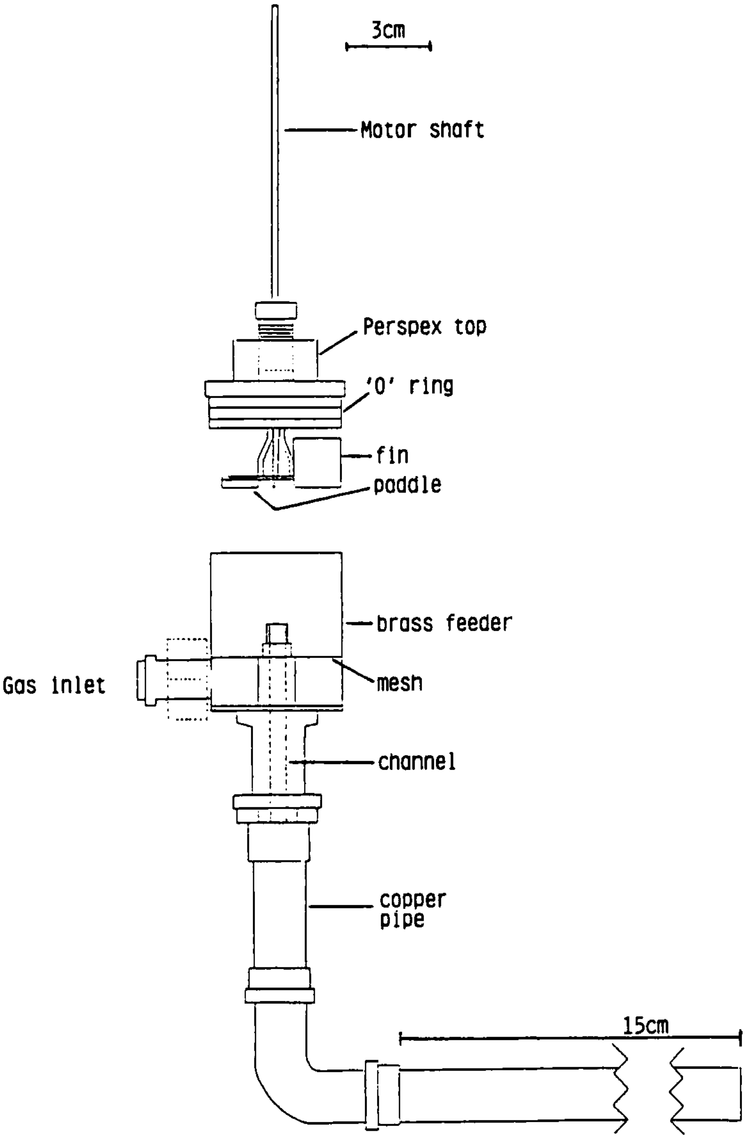


FIGURE 2
Fluidised Bed Feeder

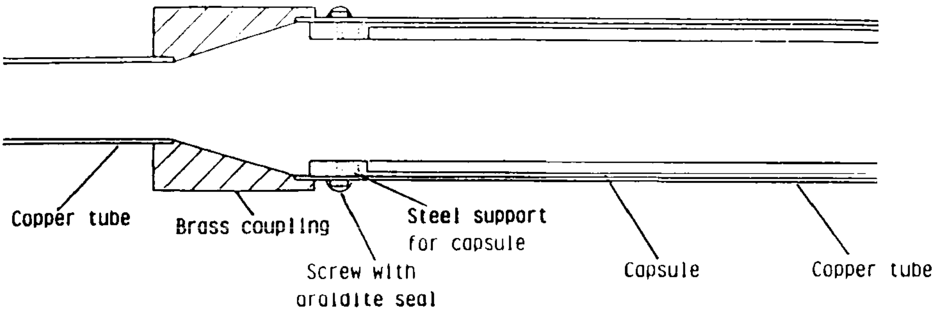


FIGURE 3
Capsule containing ^{85}Kr gas installed in copper tube.

the charging surface. A fibre optic probe located in the pipe provided limited information of the powder mass flow and a radioactive charge neutraliser stabilised the particle charge prior to entry into the cyclone. The powders were separated from the carrier gas (dry Nitrogen) by the cyclone and collected in the Faraday well and the charge (Q) and mass (M) measured continuously using an Electrometer and Strain gauge system connected to a chart recorder. The system was earthed and enclosed in a vacuum chamber in order to perform experiments in a controlled atmosphere when required.

Feeder System

A venturi feeder was found to be satisfactory for the free flowing lactose size fractions, and a fluidised feeder (Figure 2) was designed to deliver the micronised particles in a controlled manner. The efficiency of powder delivery from the fluidised feeder was approximately 70% of the sample weight.

Radioactive Charge Neutraliser

Figure 3 illustrates the main components of the neutraliser. Two capsules each of 10mCi activity were housed diametrically opposite on the inside wall of copper tube. The beta particles from the ^{85}Kr source create an electrically conductive atmosphere consisting of bipolar ions, and charged powder particles may be discharged by capturing ions of opposite polarity. The effectiveness of the system was confirmed with a constant residual charge on the powder samples emerging from the neutraliser, irrespective of the previous charging conditions or type of powder. The particle residence time was increased by increasing the internal diameter of the neutraliser. The gas pressure drop within the neutraliser was an advantage for coarse non-cohesive powders, but caused reduced transport efficiency for micronised powders and hence it is recommended that the diameter of the pipe for the neutraliser should be the same as for the feeder pipe.

Faraday Well

Figure 4 shows the essential features of the Faraday well designed for this study. The sign and magnitude of the charge was monitored by a Keithley 610C Electrometer (Keithley Instruments) and the mass was measured by a strain gauge bridge system connected to a digital strain indicator (Strainstall Ltd.). The increase in charge and mass were recorded simultaneously using a twin channel chart recorder.

Selected mass-time and charge-time curves were traced and digitised using a graphics tablet (Summagraphics MM 1201) interfaced with a computer. Following curve fitting using the method of cubic spline polynomial interpolation, the data points were processed and displayed in a spreadsheet showing Q, M, dQ/dt, dM/dt, dQ/dM and Q/M at unit time intervals. Q and M values were also computed as a percentage of the maximum Q and M values respectively, allowing %Q, %M and %Q/M versus time curves to be plotted on the same graph (when multiplied by a suitable factor) following parabolic filtering to reduce point scatter. Hence, the % Q/M versus time curve represented the cumulative Q/M ratio with time. From this data, the average Q/M value over one second intervals was calculated for every 0.5s interval by linear interpolation over the interval ± 0.5s. This was done by substracting %Q values at (t + 0.5)s and (t - 0.5)s and then dividing by corresponding %M values obtained by the same method.

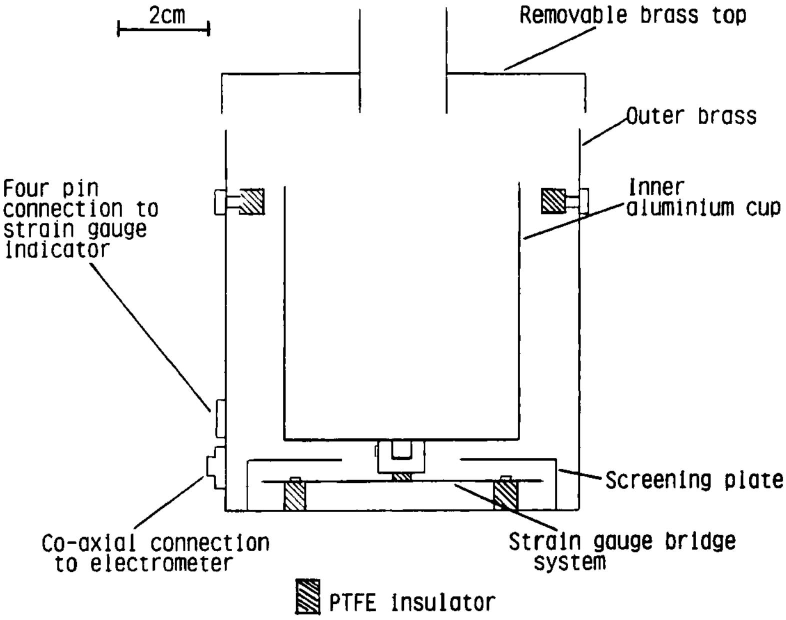


FIGURE 4

Faraday Well

RESULTS

Triboelectrification of Lactose Size Fractions

Preliminary studies confirmed that the charge of the relatively non-hygroscopic lactose was unaffected by relative humidity in the range (0-84%) and the results described here are for samples stored and charged under ambient conditions.

Electrostatic charge generation was found to decrease with increased moisture levels(11,12) due to alteration of the surface properties of the particulate material, however since there is a lack of information and uncertainty about these effects in particulate systems, detailed studies are now being undertaken in these laboratories.

Riffled samples (1g) were conveyed from the venturi feeder at pressures in the range 0.76 - 11.40 psi and the results for

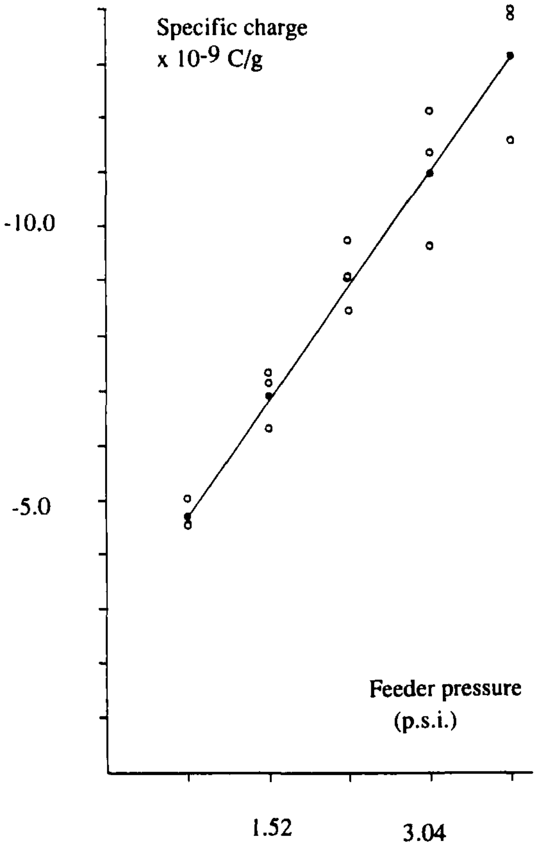


FIGURE 5

Specific charge versus pressure for 355-500μm size fraction and brass cyclone.(o), experimental (●), mean result.

the final mean specific charge (Q/M) following triboelectrification at each given feeder pressure using either a brass or stainless steel cyclone are shown in Figures 5-8.

In all cases both charge and mass versus time followed a smooth curve up to a maximum value corresponding to completion of an experimental run. This maximum value was used to calculate the specific surface charge values in Figures 5-8. A limitation of this, and all previous work, is that only the final charging values are used, whereas it would be more valuable to measure charge continuously during the triboelectrification process.

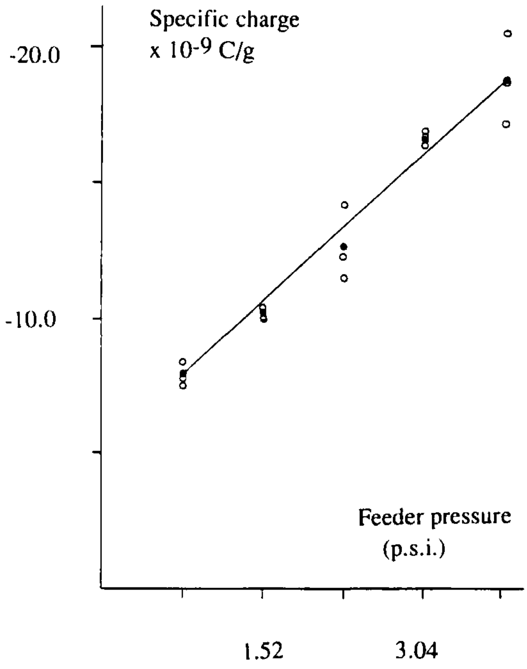


Figure 6

Specific charge versus pressure for 355-500μm size fraction and steel cyclone. (o), experimental (●), mean result.

Linear relationships are shown with correlation coefficient (r) and slope (m) values of 0.9998 (r) and 2.79 x 10^{-9} (m) for brass and 0.9952 (r) and 3.69 x 10^{-9} (m) for the steel system for the 355-500μm particles and 0.9733 (r) and 15.77 x 10^{-9} (m) for brass and 0.9768 (r) and 22.96 x 10^{-9} (m) for steel with the 45-90μm size fraction.

Higher electronegative values were obtained for both size fractions when in contact with steel compared with brass.

Charging experiments with a non-metallic contact surface were achieved by spray coating the inner surface of the steel cyclone with cellulose generated from an aerosol paint. Figure 9 shows that the net charge values attained with the 355-500μm

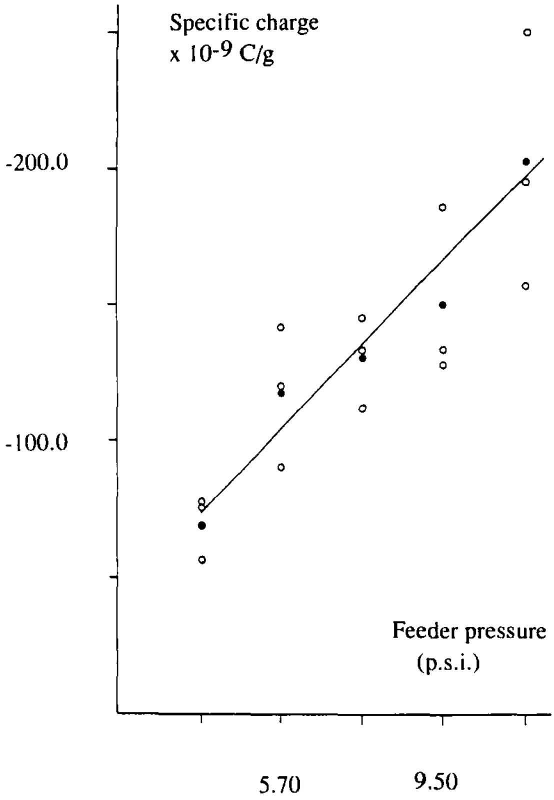


FIGURE 7

Specific charge versus pressure for 45-90µm size fraction and brass cyclone. (o), experimental (●), mean result.

particles in contact with the cellulose surface are positive, with a non-linear relationship between Q and pressure over the range 0.76-3.80 psi.

Relative Q/M versus time curves are shown in Figures 10 and 11 taken from triboelectrification experiments using the lactose 355-500µm particles with steel and brass surfaces respectively.

The relative Q/M versus t curves show a gradual increase in Q/M for steel and a gradual decrease in Q/M for brass.

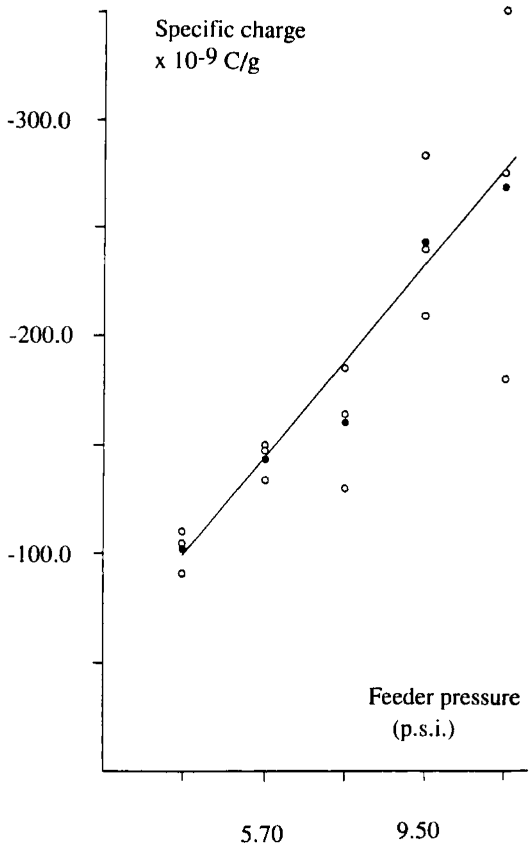


FIGURE 8

Specific charge versus pressure for 45-90μm size fraction and steel cyclone. (o), experimental (●), mean result.

Triboelectrification of Micronised Lactose, BDP and Salbutamol Sulphate

Micronised lactose was conveyed at pressures in the range 0.46-6.90 psi from the fluidised feeder into the brass cyclone and the results are shown in Figure 12, whereas selected results for BDP and salbutamol sulphate are shown in Table 1 along with those for micronised lactose for comparison.

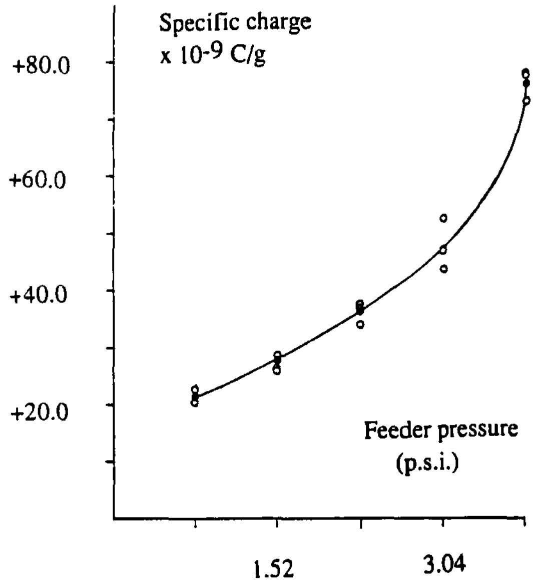


FIGURE 9

Specific charge versus pressure for 355-500μm size fraction and cellulose cyclone. (o), experimental (●), mean result.

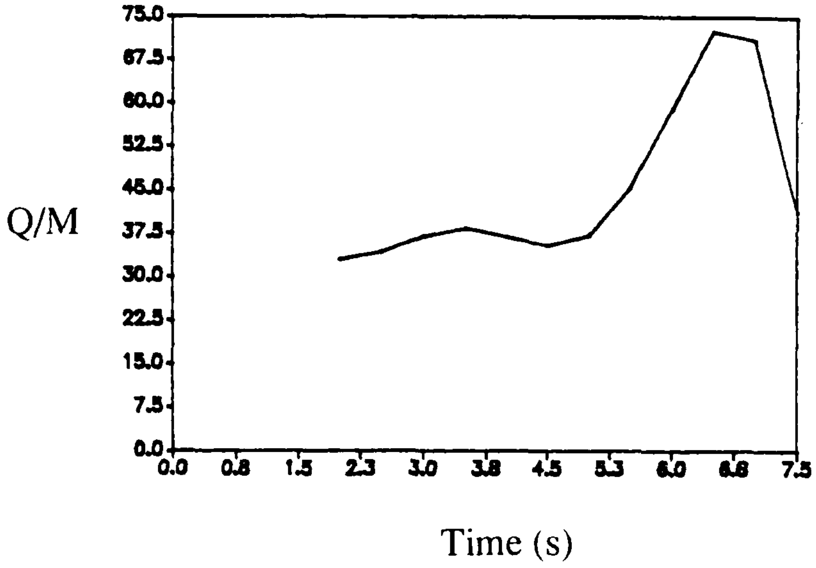


FIGURE 10

Example of relative Q/M versus t curve using steel surface (1.52 psi).

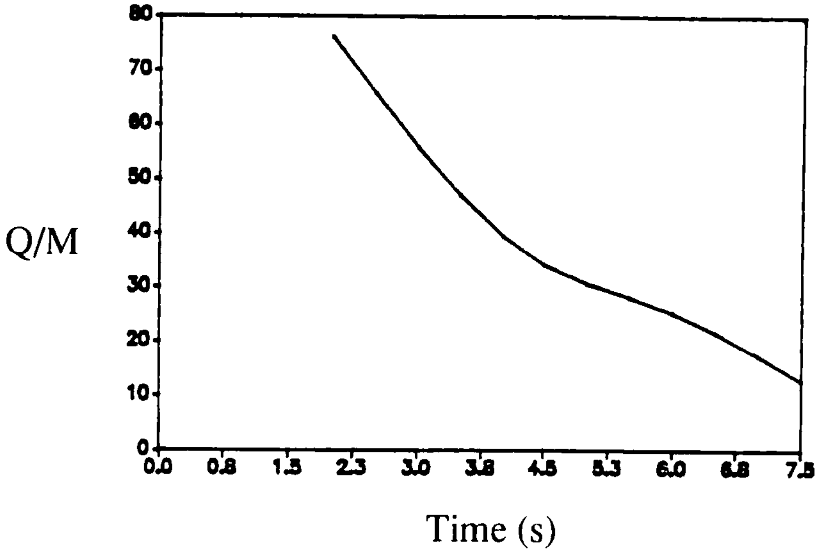


FIGURE 11
Example of relative Q/M versus t curve using brass surface (2.28 psi).

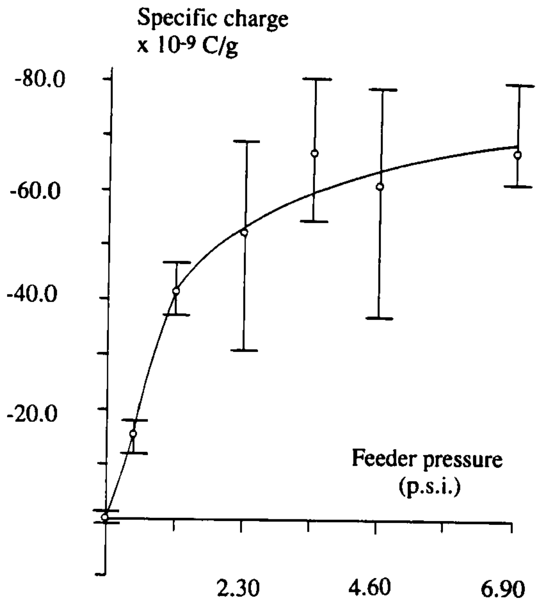


FIGURE 12
Specific charge versus pressure for micronised lactose. The vertical bars represent the spread of five determinations.

TABLE 1

Mean specific charge values x 10^{-9} C/g at a fluidised feeder pressure of 8.68 psi. Each result a mean of five determinations with the 95% confidence limits shown.

Charging surface	Salbutamol sulphate	Lactose (micronised)	BDP (micronised)
Brass	+27.3 (19.2)	-112.1 (34.7)	-540.6 (152.8)
Steel	-24.5 (41.7)	-133.4 (65.8)	+55.4 (238.2)

The results from Figure 12 and Table 1 show more complex charging tendencies than those for the lactose size fractions since the charge values for micronised lactose approach a maximum at higher feeder pressures.

Salbutamol charged electropositively with brass and both electropositively and electronegatively with steel, whereas BDP acquired a very high electronegative charge with brass but was also both electronegative and electropositive with steel.

DISCUSSION

Generally, the results show differences in charging tendencies due to particle size and type, nature of contact surface, and the effects of particle adhesion to the contact surface.

The significant increased specific charge values with the smaller (45-90µm) lactose size fraction (Figures 5-8) can be attributed to the greater particle number density providing an overall increase in available surface area for charge transfer than with the larger (355-500µm) size fraction. Stainless steel was found to impart a higher electronegative charge on the lactose particles than brass, an effect that could be related to the work function of the two metals, where the work function is defined as the minimum energy required to extract a free electron from the surface of the material. Elsdon and Mitchell(8) found stainless steel to have a lower work function than brass and hence would more readily donate electrons to materials with lower Fermi levels, i.e. materials with lower energy electrons. When contact is made between a metal and metal/semiconductor, equilibrium is reached when the Fermi levels are equated, and this is achieved by electron transfer down the potential step from the material with the higher to that with the lower Fermi level. The results emphasized the different charging tendency of the lactose 355-500μm particles with the different surfaces. Mean maximum Q/M values of -13.23, -18.76 and +76.80 x 10^{-9} C/g were obtained for brass, steel and cellulose respectively, the magnitude of charge from the cellulose being significantly higher and representing a complex charging process possibly involving chemical (ionic) groups(8) in addition to very different triboelectrification conditions. A triboelectric series given in the literature(13) places brass/steel at the electropositive end and insulator materials such as PVC and cellulose at the electronegative end. This implies that metals will generally donate electrons and insulators receive electrons in contact with other materials within the series. Table 2 shows the theoretical maximum Q/M values for lactose particles at the condition of incipient breakdown in air, calculated from:

$$Q = 1.03\ .10^{-4} \cdot r^{1.7} C \quad \text{(Equation 1)}$$

where r = radius of spherical particle.

Equation 1(6) assumes spherical particles whereas in this work the particles were characterized as "square-circular" by microscopic techniques. Calculations for micronised samples are more difficult since the value of r could be that for primary particles or for agglomerates, and in Table 2 the results were calculated using the former. In addition, irregular shaped particles will have regions of higher curvature than spheres and corresponding higher surface charge densities following redistribution of charge across the particle surface.

TABLE 2
Theoretical maximum Q/M ratio for lactose.

Particles	Maximum Q/M value (C/g)
Lactose micronised	9.79×10^{-4}
Lactose 45-90µm	1.05×10^{-5}
Lactose 355-500µm	9.52×10^{-7}

The charge values obtained in this work were lower than the theoretical maximum values suggesting a complex process of charge and discharge during triboelectrification. The lower charge values obtained may be an indication that the particle-surface contact was of limited intimacy due to particle asperites, agglomeration and contact surface roughness. These factors along with particle deformation, adhesion and contact surface will affect the charging process and need to be investigated in more detail before the role of triboelectrification in powder handling operations can be understood.

Increased velocity of lactose particles as a result of increased feeder gas pressure caused an increase in particle charge values which could be attributed to three effects:

i) Increased contact pressure resulting in elastic/plastic deformation. This would increase the available area for charge transfer(14).

ii) Higher particle-surface collision frequency as a result of increased turbulence in the cyclone.

iii) Decreased particle-surface separation time providing less chance of charge leakage down the potential gradient on separation(4) and hence minimising charge loss to the contact surface.

It has been suggested(15) that the charge transfer time is as low as 10^{-6}s when considering impact of a particle onto a metal surface, and the relaxation time may be calculated using $\rho\varepsilon$, where ρ and ε are particle resistivity and permittivity respectively. The relaxation time describes the time taken for the charge to redistribute itself over the particle surface, away from the contact area. Permittivity and resistivity were calculated from experimentally determined values for capacitance and resistance respectively. The relaxation times calculated from these results were 1.70s for lactose, 3.28s for BDP, and 1.27s for salbutamol and these values were much greater than typical particle-surface contact times. Localised charging may limit the net particle charge by decreasing the particle/contact surface potential gradient in the contact area.

Micronised powder samples exhibited more complex charging patterns than those for larger size fractions, and Figure 12 for micronised lactose shows an increase in electronegative charge up to a maximum value (approximately -65.0×10^{-9} C/g) occuring at approximately 3.0 psi, contrasting with the linear plots (Figures 5-8) for the non-cohesive powders. In addition to particle agglomeration, there is a strong interaction between the micronised samples and the contact surface. Particle adhesion to the inner cyclone wall was minimal for the larger size fractions but extensive for the micronised samples, thus altering the contact surface for the micronised particles, from metal to powder coated metal. The % w/w of the micronised lactose samples deposited in the Faraday well ranged from 47-59 at the lower pressures to 25-36 at the higher pressures due to greater adhesion to the metal surfaces. For the lactose size fractions, there was little adhesion and values >90% were obtained for the mass deposited at the higher pressures. The maximum Q/M value for the micronised lactose was thus lower than the theoretical value of 9.79×10^{-4} C/g and it was postulated that particle-particle interactions were responsible for compensating the charge, with Figure 12 showing an approach to an equilibrium bipolar charging system. In addition, calculations relating to particle motion within the cyclone estimated a minimum mean free path of 22, 1.85 and 0.057cm for the 355-500µm, 45-90µm size fraction and micronised lactose respectively. These values relate to the minimum distance a particle has to travel before it encounters another particle and clearly show the increased likelyhood of particle-particle interactions with the micronised powder. This, along with the increased particle adhesion to the contact surface, contributes to the complex charging process in these systems.

Table 1 shows the charge values for BDP and salbutamol sulphate and indicates the very different charging tendencies of the two materials. Both BDP and micronised lactose were found to have similar particle/agglomerate size distributions and surface areas (Section 2.2.1) but showed very different charging tendencies, for example, BDP acquiring a very high electronegative charge in contact with brass (-540.6×10^{-9} C/g) compared to the micronised lactose (-122.1×10^{-9} C/g). The wide range of charge values (Table 1) for salbutamol and BDP in contact with the steel surface indicates that the net charge could have electropositive and electronegative values. These results provide evidence for bipolar charging and indicate the limitations of the use of final net charge in particle charge investigations.

These preliminary results illustrate the complexities and difficulties when conducting charging experiments with different materials. Blythe and Reddish(16) investigated the charging of particles <1mm diameter and concluded that with fine particles the electrostatic forces of attraction were greater than gravitational and hydrodynamic forces, and that particle-particle contacts were liable to give a mixture of electropositive and electronegative particles which would lead to an overall decrease in net charge.

The relative Q/M values at unit time intervals (Figures 9 and 10) revealed differences in the charging mechanism for lactose and the two contacting surfaces. The resultant net charge on the particles was found to decrease with time with the brass surface and increase with time for the stainless steel surface. Differences in the relative number of electropositive and electronegative particles for the two surfaces would explain these effects, and further work is needed for a more detailed explanation. The development of this technique along with a new technique for the investigation of bipolar charging in powders is now being undertaken in these laboratories.

CONCLUSIONS

A new practical technique for measuring the charging tendencies of powders in contact with selected surfaces has been developed which provides continuous monitoring of particle mass and charge simultaneously. Test results have shown a level of sophistication in which differences in charging tendencies due to particle size, type and charging surface have been established. This work will enable powders, in particular pharmaceutical drug and excipient systems, to be studied under controlled conditions with a detailed analysis of the charge/mass data.

REFERENCES

1. Train, D., Pharm. J., 185, 129, (1960).

2. Orr, N.A., Hill, E.A., and Smith, J.F., Int. J. Pharm. Tech. and Prod. Mfr., 1, (2), 4, (1980).

3. Orr, N.A., and Sallam, E.A., J. Pharm. Pharmacol., 30, 741, (1978).

4. Cole, B.N., Baum, M.R., and Mobbs, F.R., Proc. Inst. Mech. Eng., 184, 3c, 77, (1969/70).

5. Kunkel, W.B., J. Appl. Phys., 21, 820, (1950).

6. Bailey, A.G., Powder Tech., 37, 71, (1984).

7. Vick, F.A., Br. J. Appl. Phys., Supp. No. 2., 4, s1, (1953).

8. Elsdon, R., and Mitchell, F., J. Phys. D. Appl. Phys., 9, 1445, (1976).

9. Staniforth, J.N., and Rees, J.E., J. Pharm. Pharmacol., 34, 69, (1982).

10. Staniforth, J.N. and Ahmed, H.A., Brit. Pharm. Conf., Keele, (1989).

11. Smeltzer, E.E., Weaver, M.L., and Klinzing, G.E., Powder Tech., 33, 31, (1982).

12. Vincent, H., J. Elect., 18, 113, (1986).

13. Ally, M.R., and Klinzing, G.E., Powder Tech., 44, 85, (1985).

14. Coste, J., and Pechery, P., J. Elect., 10, 129, (1981).

15. Masuda, H., Komatsu, T., and Ilnoya, K., AIChe. J., 22, 3, 558, (1976).

16. Blythe. A.R., and Reddish, W., Electrostatics 79, London, 107, (1979).