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Dynamic particle-surface tribocharging: The role of shape and contact mode☆

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ABSTRACT

Triboelectric particle charging features in many industrial processes. Dynamic particle-surface contact is the key charging mechanism in many types of particle tribocharger. Models of dynamic charging have tended to assume that the particle is spherical, but experiments have shown that particle shape can strongly influence the charging behaviour. We review some experimental work, then present a simple two-dimensional model of the dynamic contact charging of an elliptical particle, of varying roundness ratio, with a flat surface. A rich variety of contact modes (sliding, rolling, tumbling) are captured, each producing distinctive charging behaviour.

1. Introduction

Triboelectrification is a ubiquitous feature of many dry particulate systems [1–3]. It can manifest itself in a variety of ways, including adhesion to vessels or pipe walls [4], changes in dispersion or aggregation behaviour [5,6], or discharges, leading to significant explosion hazards in dry powder systems [7]. Tribocharging of particulates can also be exploited in processes such as photocopier toner handling [8] and dry triboelectric separation [3,9–13]. In the latter process, the components of a mixed particulate are given different charges by contact or friction. The components are then separated by passing the differentially-charged mixture through an electric field.

Contact interactions in particle processing systems can occur either between particles or between a particle and another object, usually the vessel or conduit wall [14]. This paper deals with the second of these mechanisms. It is well known that the mechanical nature of the interaction between a particle and a solid surface strongly influences the exchange of charge. For instance, tribocharging tends to increase with the interaction energy, and sliding contact tends to transfer more charge than simple normal contact [2]. The reasons for these trends are usually multiple and complex. Charge exchange during single particle-surface impacts has previously been studied in some detail [15–20], and some attention has also been paid to the exchange of charge between a continuous flow of particulate material and a solid surface [21,22]. Both formal studies and anecdotal accounts from industry agree that the broad 'character' of the particle-surface contact has a strong effect on the exchange of charge. The present author has been advised on a number of occasions by industrial practitioners that some tribochargers are only effective if the particles can be made to 'slide' on the tribocharging surface. These accounts raise as many questions as they answer - for instance, in this context, what exactly constitutes 'sliding'? Is continuous contact the most important factor, or is the presence of slip, as opposed to rolling, more important? As another example, pneumatic cyclones represent a very effective means of tribocharging coarse mineral particulates prior to separation, e.g. [23,24]. Measurements of charge transfer in cyclones suggest qualitative differences in charging behaviour for different modes of contact (i.e. sliding, rolling or bouncing) between the particles and the inside of the cyclone [25]. The operation and design of cyclone tribochargers need to be informed by these considerations if they are to be used effectively. Similar considerations also govern the design and operation of other types of tribocharger [26], and of conveying systems where triboelectric effects are important.

Formal studies of sliding particulate charging on flat surfaces [21,22] have begun to answer these questions. In these studies, the mode of particle-surface contact was observed closely, using high-speed video footage, as the particles travelled down a flat tribocharging chute. These observations were compared with measurements of the resulting charge. Quantitative characterisation of the contact mode was provided by measuring the instantaneous fraction of particles in contact with the surface, the proportion of particles that were in continuous contact with the surface, and the proportion that were rolling during contact (as opposed to maintaining a fixed orientation). It was confirmed that

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the time the particles spent in actual contact with the surface (as distinct from the time they took to traverse the chute) was an important determinant of the transferred charge, as expected. Since contact time was in turn determined by whether the particles bounced on the surface (as opposed to rolling or sliding), the presence or absence of bouncing was clearly critical to determining the charge. On the other hand, one would expect the instantaneous normal force during contact, and thus the contact area, to be larger for bouncing than for continuous rolling or sliding. There was also some evidence that the very fact of non-continuous contact somehow limited the charge, perhaps due to gas breakdown discharge during separation of the particles from the surface [16,17]. Apart from these two factors, it was concluded that the distinction between rolling and fixed-orientation contact was critical to the charge transfer. A rolling particle progressively makes its entire accessible surface area available for charging, whereas a particle that slides with a fixed orientation only presents a limited portion of its surface for charging. On the other hand, assuming that the particle is non-spherical, the average instantaneous contact area for fixed-orientation sliding will tend to be larger than the average contact area for rolling, since the most stable fixed orientations will tend to be those that present the least curved part of the particle to the charging surface. Given the multiplicity of possible factors affecting the charge transfer, it is hardly surprising that these studies were unable to definitively determine the contribution of each, nor answer several other important questions regarding the charging process. For instance, no light was shed on the age-old question of whether sliding contact is inherently different to static contact in this context.

The studies discussed above strongly reinforced the importance of particle shape. The shape directly determines the contact area and pressure, and is also one of the key factors affecting the contact mode (rolling, sliding, bouncing, tumbling), thereby also having a strong indirect effect on the contact time, force and area. The model developed in [22,27] incorporated only a crude estimate of the average contact area for a rolling irregularly-shaped particle. Furthermore, no attempt was made to understand the effect of varying particle geometry on contact mode.

In this paper, we attempt to understand the effect of particle geometry on dynamic particle-surface tribocharging a little better by modelling a rather idealised system whose behaviour depends on a relatively small number of dimensionless variables. By initially exploring particle charge behaviour in this deliberately limited parameter space, we hope to develop a structure around which to build more sophisticated and realistic models in the future. The present model is two-dimensional, and the particle shape is restricted to an ellipse of varying roundness ratio. The simplest available models of elastic and inelastic contact (including friction) between the particle and the surface are used to calculate the linear and rotational motion of the ellipse. Two separate charge transfer models are used. In both cases, the particle is assumed to be a perfect insulator, and the flat surface a perfect conductor. The first is a simple capacitive static contact model. The second is slightly more complex, and includes a frictional charging term. It is important to provide a disclaimer at the outset: this frictional charging component has not been physically validated for any real system. It is designed to be as simple as possible, and broadly physically plausible. The same disclaimer applies to the model as a whole. At this stage, its purpose is illustrative and exploratory rather than predictive – a useful tool for gaining physical insight rather than a definitive quantitative model.

2. Model

2.1. Particle motion

The model particle is an ellipse, long axis $2a$ and short axis $2b$. The ‘roundness ratio’ $\varepsilon(\equiv b/a)$, the reciprocal of the aspect ratio, is the main means of characterising the particle geometry. Two sets of coordinates are used; the unprimed coordinates (x,y) refer to the directions tangential and normal to the flat surface, and the primed coordinates (x',y') are external horizontal and vertical coordinates, as shown in Fig. 1. The position of the centre of the ellipse is denoted (x_0,y_0). The angle between these systems (the tilt of the surface) is β. The anticlockwise angle between the long axis of the ellipse and the surface is denoted φ, and the anticlockwise angle formed by the contact point, the ellipse centre and the long axis is denoted θ, as shown. The distance from the ellipse centre to the contact point is r, and the local radius of curvature of the ellipse surface at the contact point is r_c. The geometric relationships between these lengths and angles are given in the Appendix.

The component of the external force on the particle tangential to the surface is denoted F_0^T, while the normal component is denoted F_0^N. Similarly, the tangential component of the contact force is F_c^T, and the normal component is F_c^N. Note that the direction of the arrows in Fig. 1 is that of the typical force vector in each case; F_0^N and F_c^T as shown would have negative numerical values in the present coordinate system. For all of the simulations performed here, the external force on the particle is assumed to be due to gravity, and to act in the negative-y' direction. In this case,

$$F_0^T = mg\sin\beta; F_0^N = -mg\cos\beta. \tag{1}$$

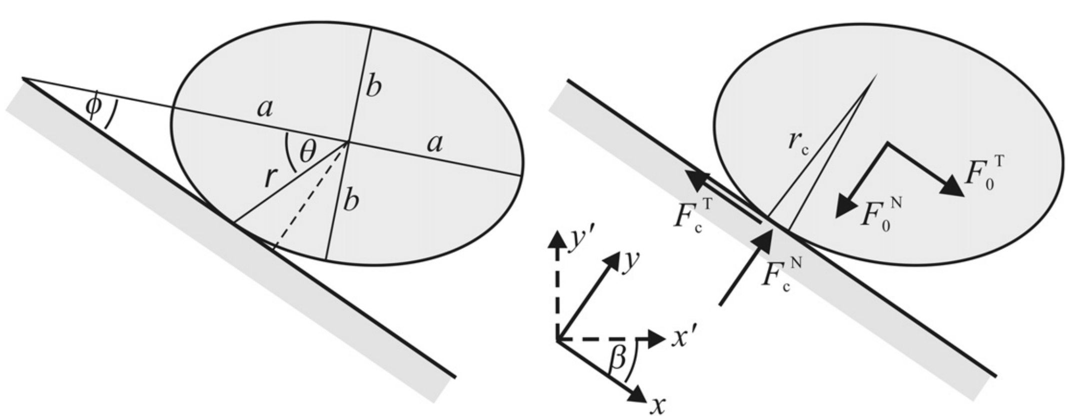

Fig. 1. Schematic of a two-dimensional elliptical particle in contact with a tilted surface, showing the coordinate axes, the important geometric quantities, and the forces on the particle.