Triboelectrification of Granular Matter as a Function of Particle Count

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***Abstract* - During experiments measuring the triboelectrification of spherical particles rolling down an inclined plane, it was noted that total charge on the particles and sometimes the sign of the charge varied as the number of particles increased. An equilibrium value of *Q/m* for the particles was reached fairly quickly as the number of particles was incremented. This suggests that particle – particle triboelectric interactions and/or plane charge saturation tend to dominate the overall triboelectric interaction over particle – plane interactions for more than a relatively few numbers of particles.**

I. INTRODUCTION

The Electrostatics and Surface Physics Laboratory (ESPL) at the Kennedy Space Center (KSC) and the Space Processes and Experiments Division (SPED) at Glenn Research Center (GRC) were engaged with DEM Solutions, Inc. in an Innovative Partnership Program (IPP) project. This project will incorporate electrostatic and advanced mechanical forces into DEM Solutions' discrete element modeling software, EDEM™ [1][2]. EDEM models the interaction and body forces of granular matter to simulate particulate flow.

To support this IPP project, the ESPL performed inclined plane/spherical particle triboelectric experiments to determine *Q/m* and the triboelectric charge generation constant, α [1][2]. To better understand the triboelectric charging characteristics of granular systems, a series of experiments were performed where the particle count was incremented from one particle to larger numbers. This paper will discuss the set-up and results of these experiments. Then possible physical explanations of the data will be discussed. Finally a summary and description of possible future work will be presented.

II. EXPERIMENTAL SET-UP AND DATA

A. Experimental Apparatus

An inclined plane triboelectric apparatus was developed to triboelectrify granular matter by causing the particles to roll down an inclined plane into a Faraday cup [1]. Planes and particles of varying materials were procured for these experiments. The spherical particle materials are: 1.0 mm borosilicate glass, 2.0 mm borosilicate glass, 3.0 mm borosilicate glass, 2.4 mm Nylon 6/6, 2.4 mm Polytetrafluoroethylene (PTFE), 1.6 mm Acrylic, 2.4 mm Copper, 3.2 mm High Density Polyethylene (HDPE), and 3.2 mm Stainless Steel. The plane materials are: Aluminum, Nylon 6/6, and PTFE. The plane materials were chosen so that both ends of the triboelectric series [3] are covered (PTFE – negative end, Nylon 6/6 – positive end) and a conductive metal. The Aluminum plate was ungrounded for all experiments. The experimental apparatus is shown in Fig. 1.

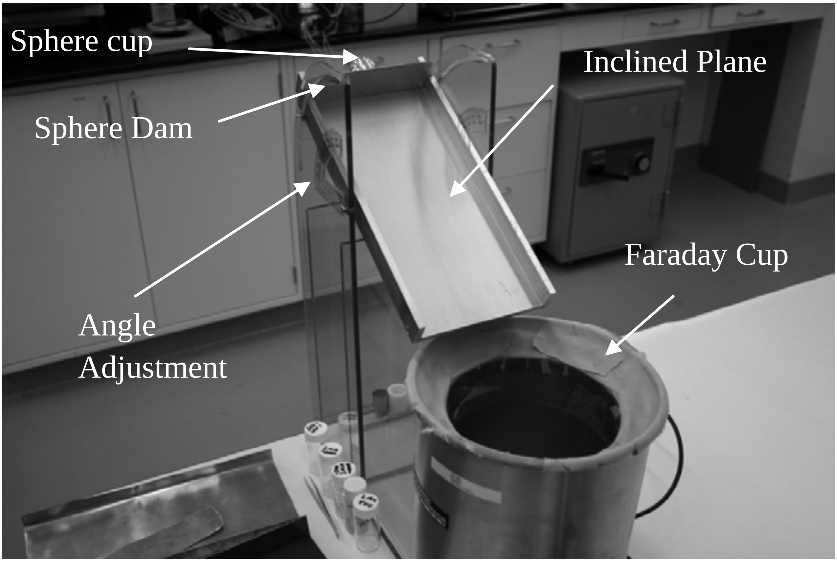

Fig. 1. Inclined plane triboelectric apparatus showing the base Aluminum plane, particle cup, dam, and Faraday cup.

B. Single Sphere Experiments

Inclined plane triboelectric experiments were performed using only one sphere of each of the sphere materials (Glass, Nylon 6/6, PTFE, Acrylic, Copper, HDPE, and Stainless Steel). Three series of experiments were performed with the spheres on planes of Aluminum, Nylon 6/6, and PTFE. This covers a metal and opposite ends of the triboelectric series [3]. A total of 210 experiments were performed.

All Spheres and plane materials were cleaned with isopropyl alcohol prior to each series of experiments. The spheres, planes, and other components were fully discharged prior to each experiment with a 3M air ionizer. The experiment was repeated ten times per sphere and plane combination. The data was averaged and standard deviations were calculated. A summary of charge and contact time data is given in the table below.

TABLE 1: CHARGES ON SINGLE SPHERE EXPERIMENTS

Plane →	Aluminum		Nylon 6/6		PTFE	
Sphere ↓	Q(nC)	t(s)	Q(nC)	t(s)	Q(nC)	t(s)
2.0 mm Glass	0.01	0.58	-0.21	0.61	0.10	0.59
2.4 mm Nylon 6/6	0.01	0.61	-0.20	0.59	0.10	0.54
2.4 mm PTFE	-0.08	0.59	-0.18	0.58	0.10	0.55
1.6 mm Acrylic	-0.06	0.67	-0.16	0.66	0.10	0.65
2.4 mm Copper	0.02	0.57	-0.19	0.55	0.10	0.54
3.4 mm HDPE	0.02	0.53	-0.14	0.60	0.09	0.58
3.4 mm Stainless Steel	-0.06	0.54	-0.13	0.57	0.11	0.57

This data is shown graphically in Figs. 2 – 4.

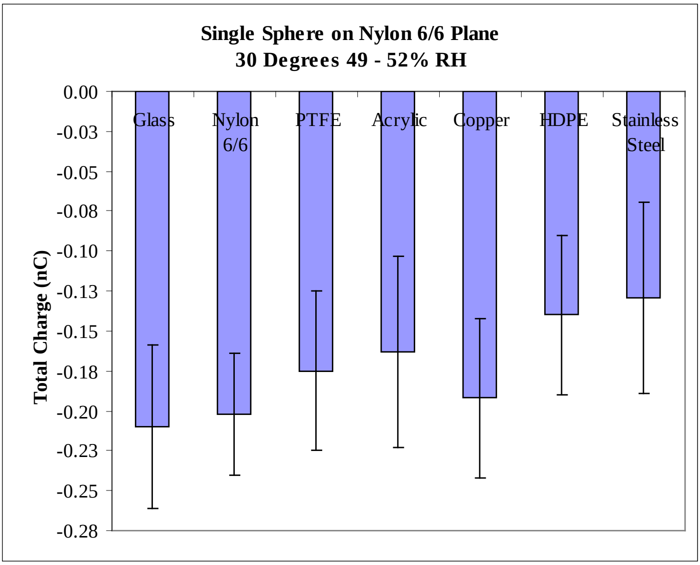

Fig. 2. . Total Q on single spheres for a Nylon 6/6 plane at 30°. Error bars are ± one standard deviation.

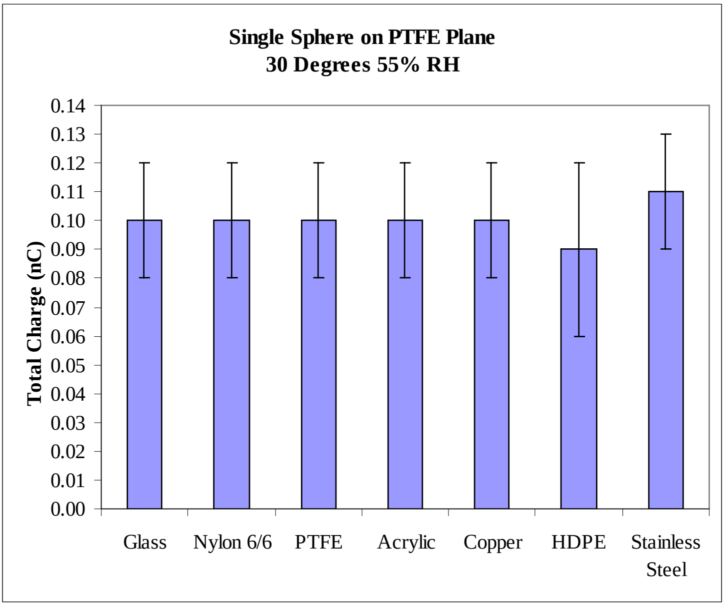

Fig. 3. Total Q on single spheres for a PTFE plane at 30°. Error bars are ± one standard deviation.

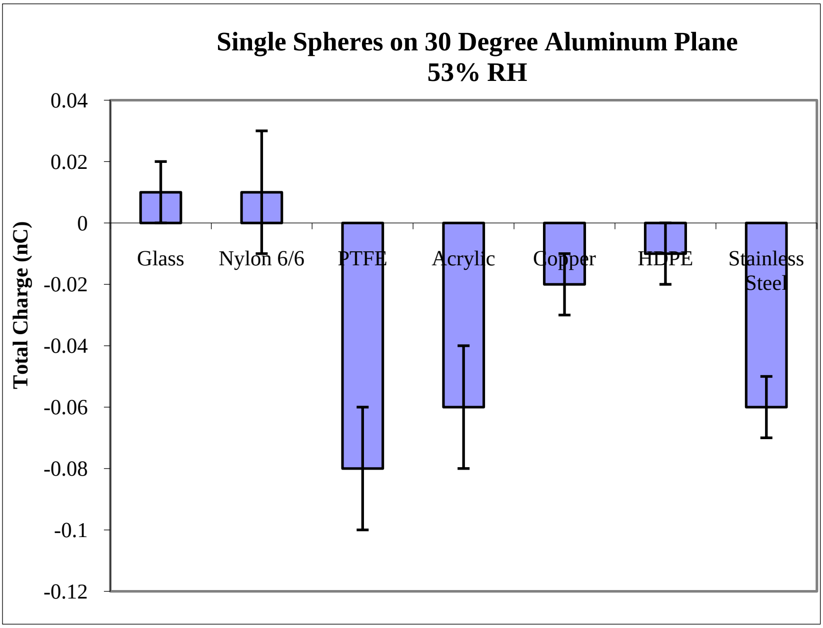

Fig. 4. Total Q on single spheres for an Aluminum plane at 30°. Error bars are ± one standard deviation.

C. Triboelectric Experiments with Incremented Sphere Counts

2.0 mm Glass Spheres – PTFE Plane

The sphere increments for this experiment were N = 1, 2, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80. The glass spheres charged (+) against PTFE as expected. The total charge versus N is given in Fig. 5. The expected linear response of Q versus N was obtained which was easily curve fit to a linear equation.

What was unexpected was the slope of the resulting graph. For one glass sphere, the average total charge was measured to be 0.12 nC. For two glass spheres, with double the surface area, a total charge of ~ 0.24 nC would be expected and so forth for increasing N or

$$Q = q_1 N \tag{1}$$

where q_1 is the measured charge on one sphere. A graph of the above data versus Eq. (1) is shown in Fig. 6. As can be seen, the slope of Eq. (1) is greater than that of the experimental data.

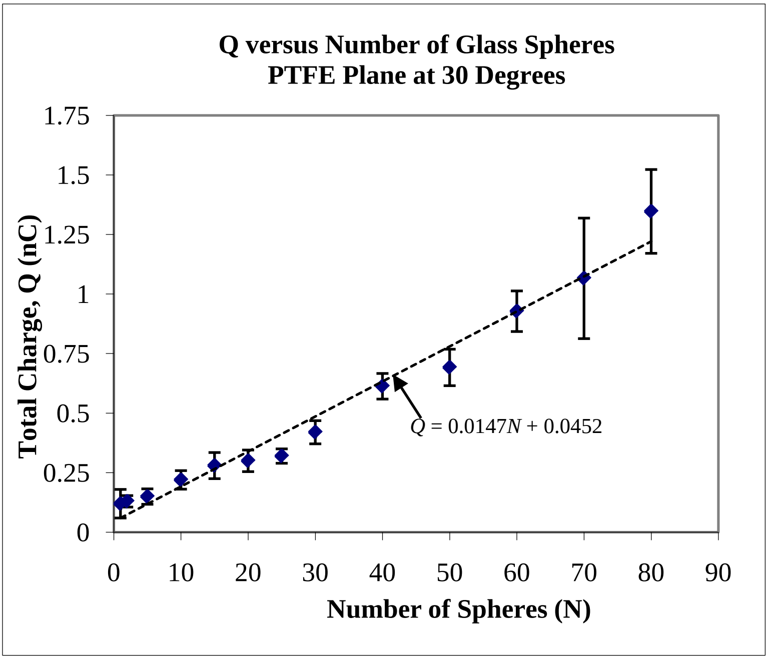

Fig. 5. Total charge for 2.0 mm glass spheres on a PTFE plane at 30° with a linear fit curve. Error bars are ± one standard deviation.

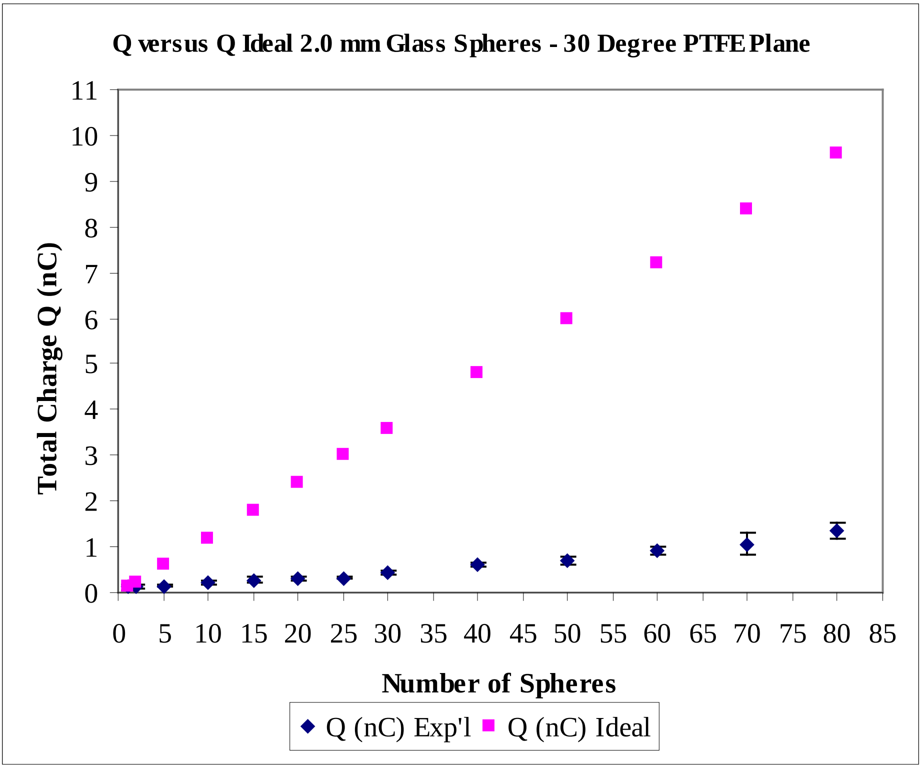

Fig. 6. Total charge versus number of spheres for experimental data and Eq. (1).

The resulting curve in Fig. 6 reaches an almost constant value for *Q/m* past about 10 spheres.

Nylon 6/6 Spheres – PTFE Plane

It was noted in the previous set of experiments that the *Q* versus *N* curve became constant around N = 15 spheres so the sphere increments for this experiment were *N* = 1, 2, 5, 10, 15. The Nylon 6/6 spheres charged positive against PTFE as expected with total *Q* increasing with *N*. This data is shown in Fig. 7. The Nylon 6/6 spheres charged strongly against the PTFE and an exponential curve fit was obtained for the data.

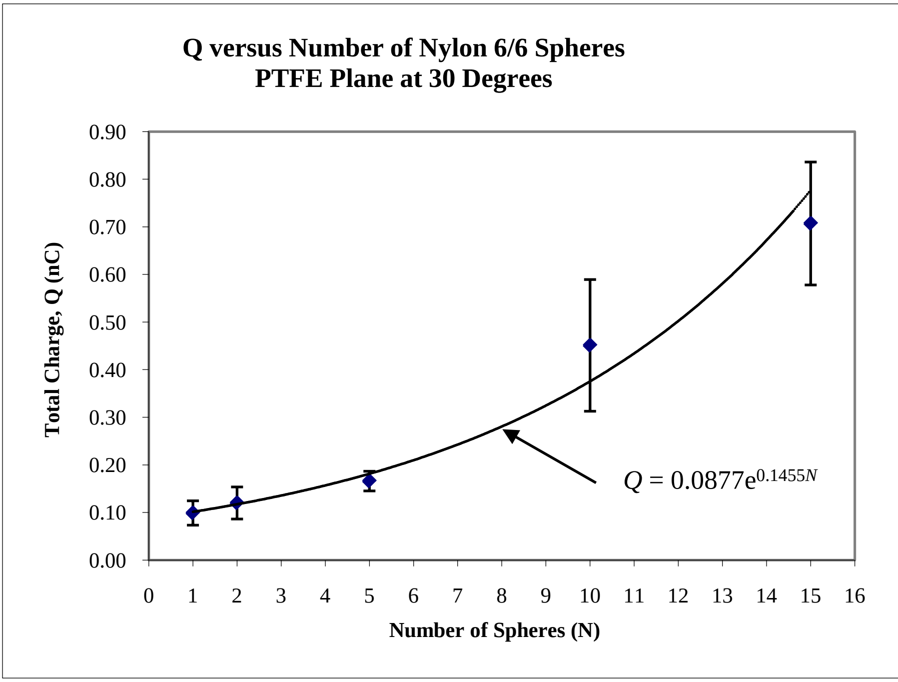

Fig. 7. Total charge versus number of spheres for Nylon 6/6 sphere tribocharged on a 30° PTFE plane. An exponential fit equation was found for the data. Error bars are ± one standard deviation.

Comparing the data to ideal results calculated from Eq. (1) shows that the ideal curve has a higher slope than experimental data. This comparison is shown in Fig. 8.

PTFE Spheres – PTFE Plane

The number of spheres for these experiments was the same as for the Nylon 6/6 above. For these experiments, the total charge measured on 1, 2, and 5 spheres was positive in sign but negative for 10 and 15 spheres. The overall slope of the data is negative as shown in Fig. 9. The change in sign between the 5 sphere experiment and the 10 sphere experiment in this series is perhaps indicative of the growing influence of particle-particle triboelectric interaction as the particle count is incremented versus particle-plane triboelectrification.

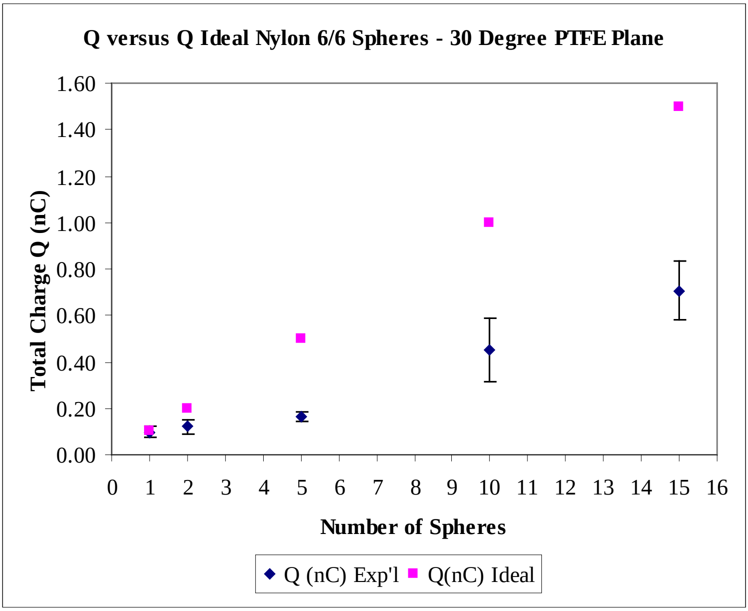

Fig. 8. Total charge versus experimental data and the ideal result calculated from Eq. (1).

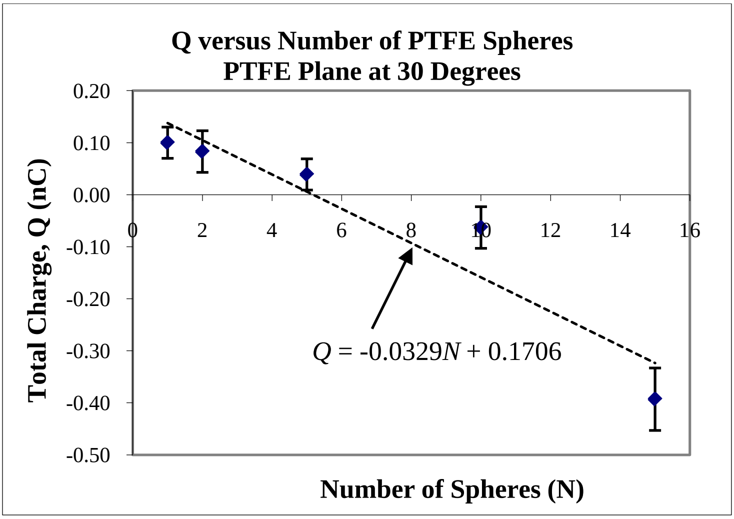

Fig. 9. PTFE spheres tribocharged on a 30° PTFE plane. Initial spheres charged positive while subsequent sphere counts charged negative. A linear curve fit equation is shown. Error bars are ± one standard deviation.

Comparing the experimental data to the ideal charging using the concept of Eq. (1), shows a dramatic difference in slopes. This is shown in Fig. 10. The average positive charge measured on one PTFE sphere does not relate to the total negative charge accumulated on higher counts of PTFE spheres. In other words, the total charge on higher multiples of one sphere has a linear relationship but not of the same slope, i.e., the total charge is not *N* times the charge measured on one PTFE sphere neither in magnitude or, as it turns out, for many PTFE spheres in sign.

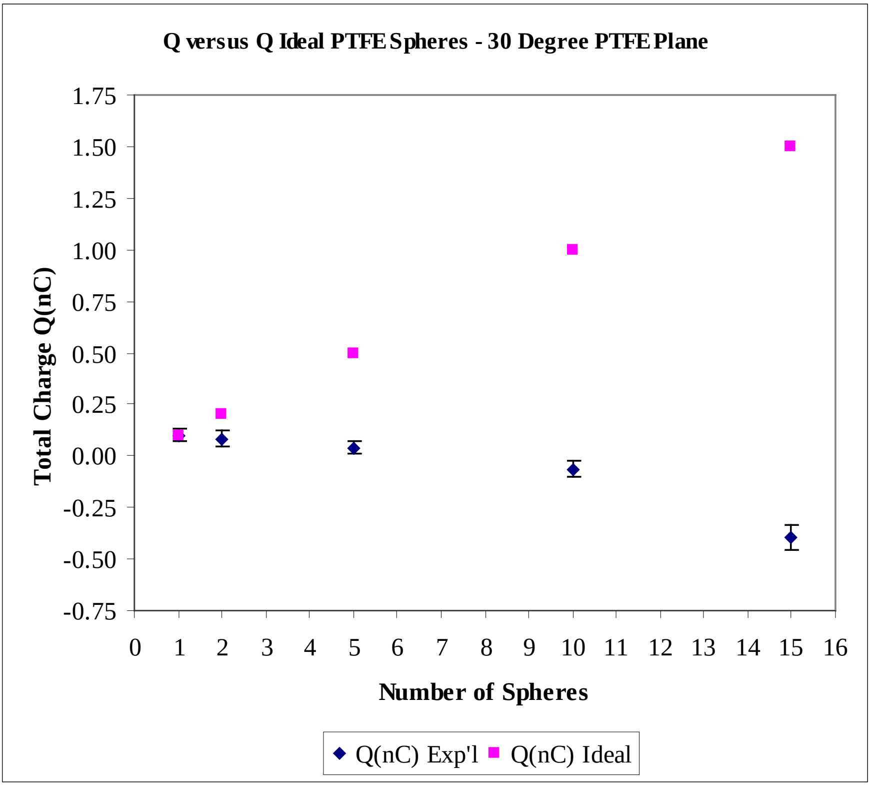

Fig. 10. Total charge versus experimental data and ideal values calculated from Eq. (1).

2.0 mm Glass Spheres – Nylon 6/6 Plane

The sphere increments for these experiments are 1, 2, 5, 10, 15, 20, 25, and 30. For these experiments, the total average charge measured on 1, 2, and 5 spheres were all negative while for higher values of N, the average charge was positive. The data is linear and is shown in Fig. 11. This linear trend is consistent with the positive charge recorded for 250 glass spheres in previous experiments. The slope of the experimental data will diverge from the slope of the ideal data based on the charge of one glass sphere.

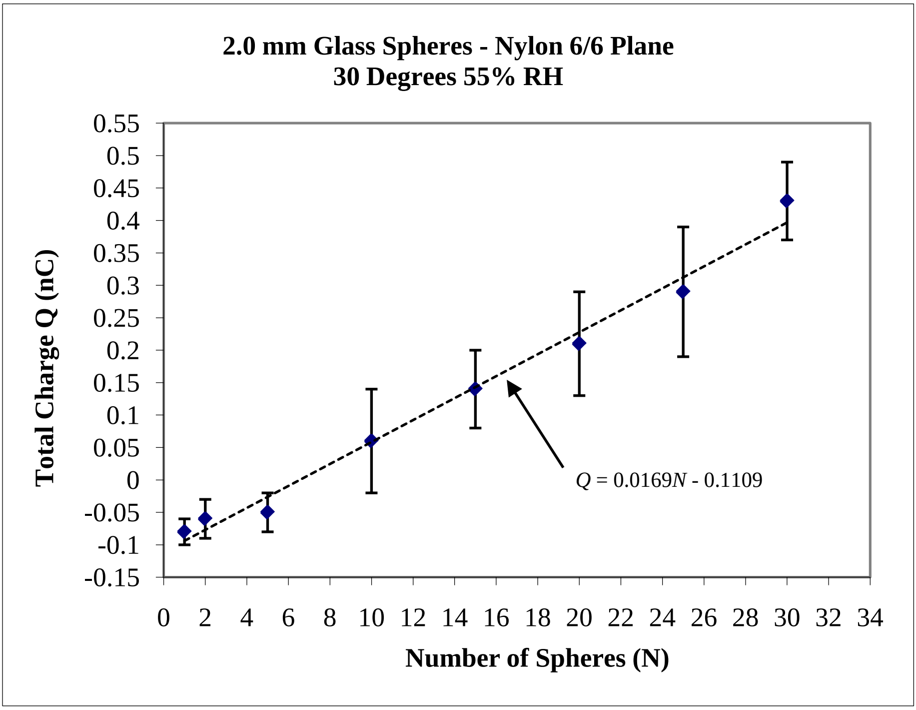

Fig. 11. Total charge versus number of spheres for 2.0 mm glass spheres tribocharged on a Nylon 6/6 plane. A linear fit curve is shown. Error bars are ± one standard deviation.

Nylon 6/6 Spheres – Nylon 6/6 Plane

As for glass, the Nylon 6/6 sphere count sequence was initially 1 – 30. However, little triboelectric charging was noted during these experiments. To determine if this trend continued, more experiments were performed with the following sphere counts – 40, 50, 100, 150, 200, and 217. The Nylon 6/6 spheres were accidentally spilled prior to this experiment and only 217 of the 250 were found. Between sphere counts of 30 and 40, the average total charge became increasingly positive and approached values measured for 250 Nylon 6/6 spheres triboelectrified on a Nylon 6/6 plane in previous inclined plane experiments. This expanded data set is graphed in Fig. 12. Further experimentation is planned for sphere counts between 30 and 40 to investigate this apparent tribocharging transition.

3.0 mm Glass Sphere – PTFE Plane

To help determine the effect of sphere size, the experiments with glass spheres on a PTFE plane were repeated with 3.0 mm glass spheres. The sphere number sequence is 1, 2, 5, 10, 15, 20, 25, 30. As expected, the glass spheres charged positive against the PTFE plane. Unlike the linear curves for other spheres, this data was best fit by an exponential function. This data is graphed in Fig. 13.

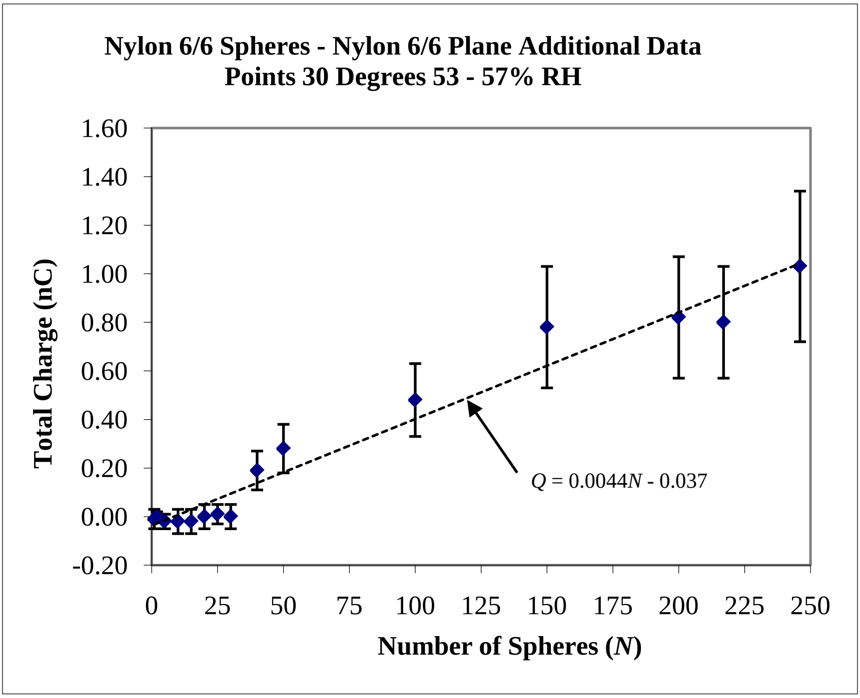

Fig. 12. Total charge versus number of spheres for Nylon 6/6 spheres triboelectrified on a 30° Nylon 6/6 plane. A linear equation was found for the data though the fit is poor for values of N lower than 40. Error bars are ± one standard deviation.

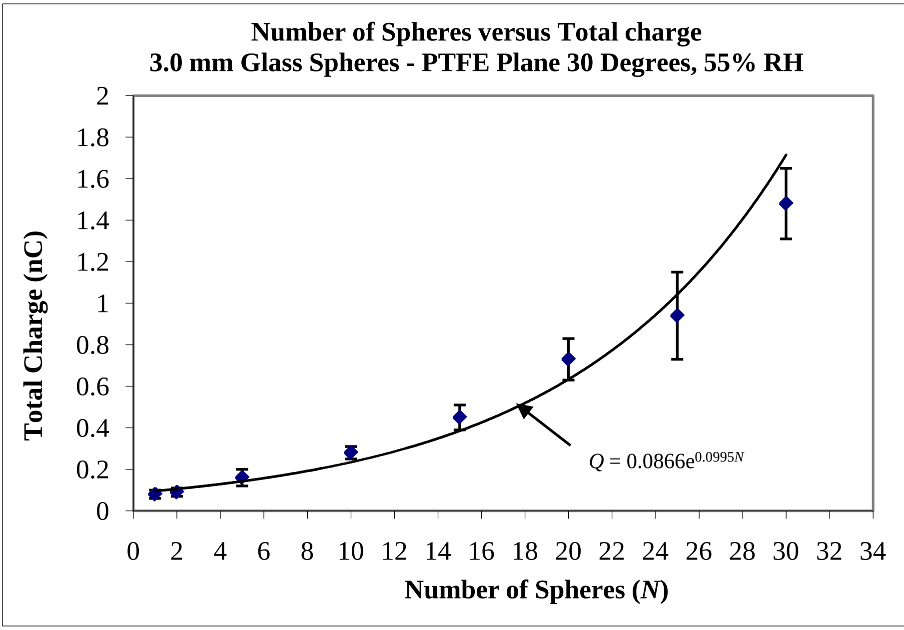

Fig. 13. Total charge versus number of spheres for 3.0 mm glass spheres tribocharged on a 30° PTFE Plane. The data was fit to an exponential function. Error bars are ± one standard deviation.

The data for 2.0 mm and 3.0 mm glass spheres were graphed together for comparison in Fig. 14. The larger surface area of the 3.0 mm spheres allows a larger charge to accumulate. Although the 2.0 mm data fits a linear function well, an exponential function was fit to the data to compare to the exponential function of the 3.0 mm data.

1.0 mm Glass Spheres – PTFE Plane

To further determine size effects, 1.0 mm borosilicate glass spheres were obtained for triboelectric experimentation with the inclined plane apparatus. This was a difficult experiment in that the charge accumulated on such small particles was at the lower limit of sensitivity for the Faraday cup's nanocoulomb meter, hence large error bars. However, a linear trend was observed like the 2.0 and 3.0 mm spheres. This data is shown in Fig. 15.

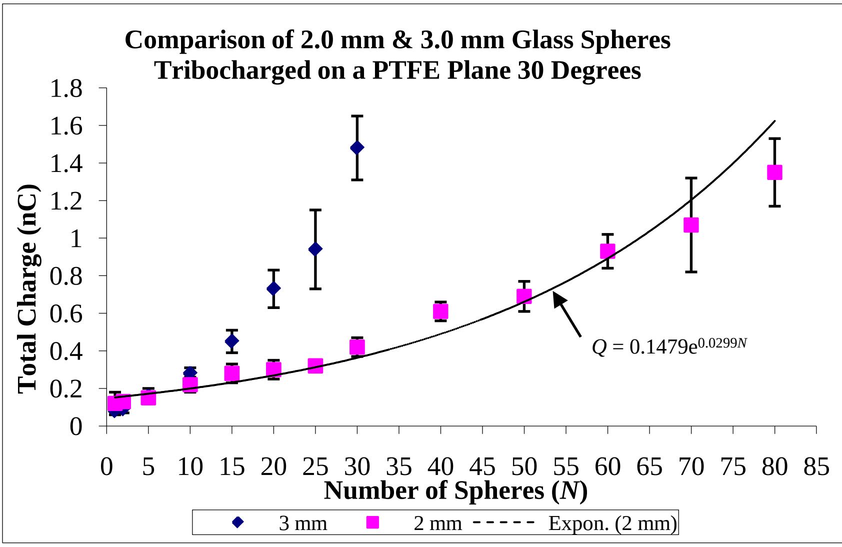

Fig. 14. Comparison of total charge versus number of spheres for 2.0 mm and 3.0 mm glass spheres tribocharged on a 30° PTFE plane. Error bars are ± one standard deviation.

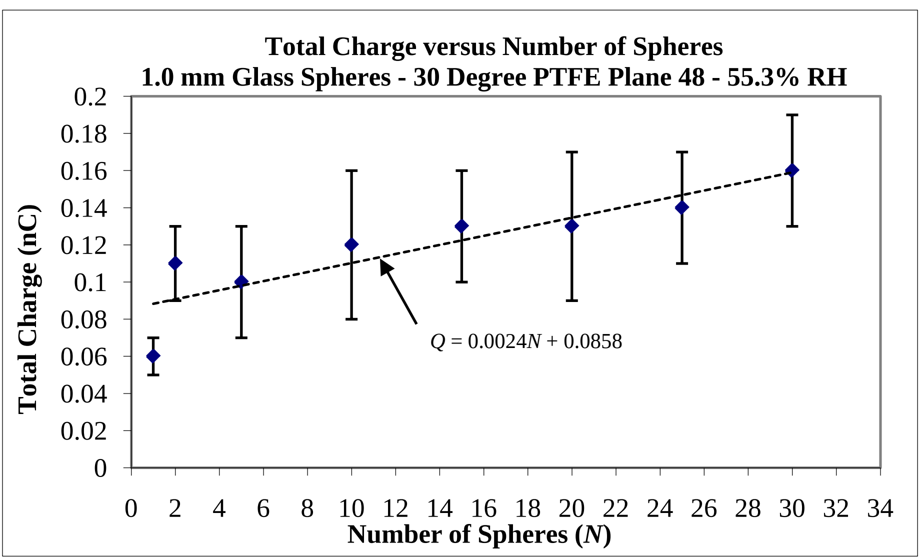

Fig. 15. Total charge versus number of spheres for 1.0 mm diameter glass spheres rolling down a 30º PTFE plane. Error bars are ± one standard deviation.

The 1.0 mm glass data is graphed with the 2.0 and 3.0 mm glass sphere – PTFE plane data to compare all three borosilicate glass – PTFE plane series of triboelectric experiments. This graph is shown in Fig. 16. As can be seen in Fig. 16, the magnitude of the triboelectric charging on the glass spheres increases with diameter, hence surface area. In Fig. 15, the 1.0 mm glass sphere triboelectric charging data was fit to a linear curve. It was noted that this data could also be fit with reasonable accuracy to an exponential curve like the 2.0 and 3.0 mm glass data. This exponential curve is given in Fig. 16.

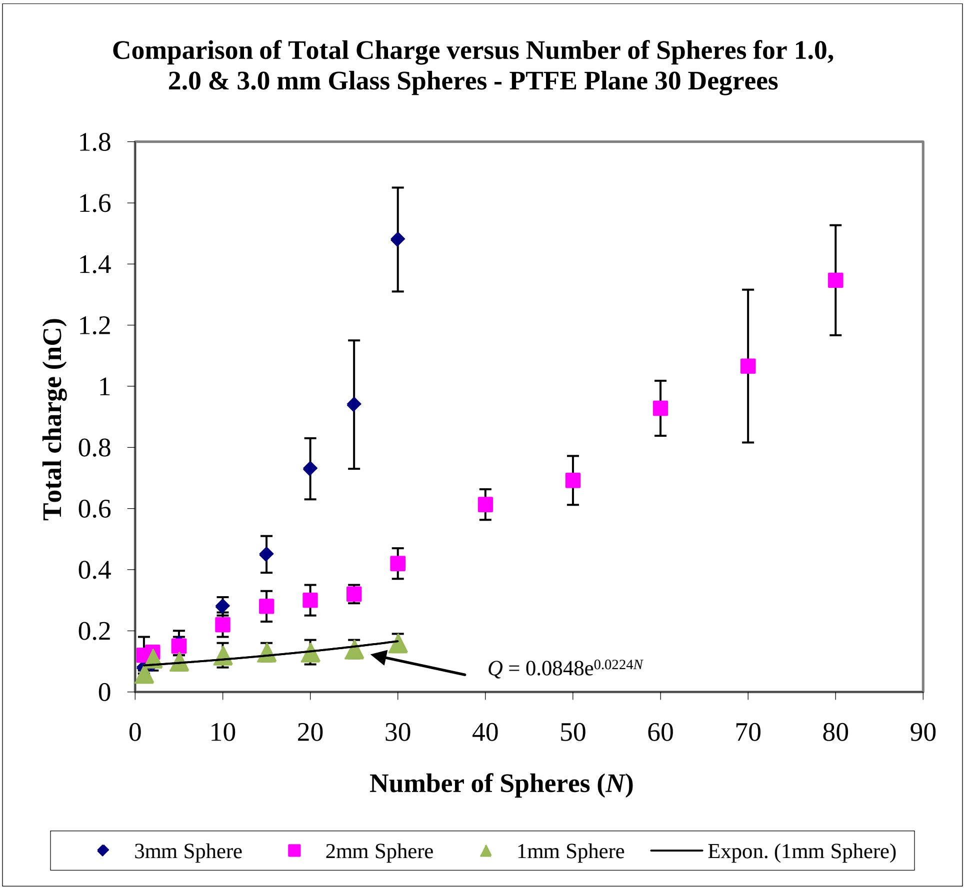

Fig. 16. Comparison of 1.0 mm, 2.0 mm, and 3.0 mm Borosilicate glass sphere – PTFE plan triboelectric charging data. Error bars are ± one standard deviation.

III. CONCLUSION AND SUMMARY

Triboelectric data was taken first on single particles rolling down an inclined plane, then on many particles incremented as described in section II. The resulting triboelectric data was for the most part expected with reasonable linear or exponential Q versus N curves obtained. What was not expected was that the slopes of many of the Q versus N curves were not equivalent to an ideal slope where the total charge Q of N particles was equal to the average charge measured on one particle times N. Indeed, for one case, PTFE spheres triboelectrified on a PTFE plane, the charge on particle counts 1, 2, and 5 were positive, while the total charge on particle counts 10 and 15 were negative (Figs. 9 & 10).

Several possible explanations for these phenomena present themselves. One explanation could be the possibility of some contamination on the surface of the spheres, the inclined plane, or both. All the subject materials were of commercial grade purchased from local vendors but were cleaned thoroughly with a non-residue leaving detergent and rinsed with deionized water. Surface contamination was mitigated by keeping all materials in the same laboratory environment during experimentation, limited human handling, and cleaning of all surfaces with isopropyl alcohol (IPA) after each experiment.

A second possible explanation is a change in ambient relative humidity. However, relative humidity in the lab was fairly constant, varying only a few percent during the period of these experiments. Therefore the small variation of relative humidity is not considered a significant perturbation on the average charges measured.

Another, more likely explanation is that at relatively low values of N, particle – particle tribocharging dominates or at least mitigates particle – plane tribocharging. As the particles travel down the inclined plane they will tribocharge against it and against each other.

Further experimentation is required to better quantify the observed phenomena. Such experiments would vary relative humidity or would be performed in vacuum to determine the effect of environment on the total charge generated. Also, sphere counts would be taken beyond the levels reported here to determine if the same trends continue.

Overall, evidence has been presented that indicates that the triboelectric charging characteristics of one or a few particles against a surface may not necessarily relate either in magnitude or sign to the triboelectric charging characteristics of many particles. This result has implications for any process that includes the tribocharging of granular matter.

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