Study of Velocity and Materials on Tribocharging of Polymer Powders for Powder Coating Applications

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Abstract— **Electrostatic powder deposition is widely used in a plethora of industrial applications ranging from the pharmaceutical and food industries, to farm equipment and automotive applications. The disadvantages of this technique are possible back corona (pin-like formations) onset and the Faraday penetration limitation (when the powder does not penetrate in some recessed areas). A possible solution to overcome these problems is to use tribochargers to electrostatically charge the powder. Tribocharging, or contact charging while two materials are in contact, is related to the work function difference between the contacting materials and generates bipolarly charged particles. The generation of an ion-free powder cloud by tribocharging with high bipolar charge and an overall charge density of almost zero, provides a better coverage of the recessed areas. In this study, acrylic and epoxy powders were fluidized and charged by passing through stainless steel, copper, aluminum, and polycarbonate static mixers, respectively. The particle velocity was varied to determine its effect on the net charge-to-mass ratio (Q/M) acquired by the powders. In general, the Q/M increases rapidly when the velocity was increased from 1.5 to 2.5 m/s, remaining almost constant for higher velocities. Charge separation experiments showed bipolar charging for all chargers.**

I. INTRODUCTION

Powder coating has proved its huge economical potential [1] based on its profitability, environmental aspects and excellent film characteristics. The main charging process used in industry is corona discharge. This mechanism is performed due to the controllable charging level of the particles, repeatability, unipolar charging, and produces good adhesion of particles to the substrate [2]. A typical corona discharge is characterized by a non-uniform electrostatic field between the tip of the corona gun and the grounded workpiece [3]. The particles are charged while passing through the corona region, where the air undergoes an electrical breakdown and becomes conductive, generating a dense cloud of free electrons and ions. The main inconveniences of corona charging are the Faraday penetration problem and the occurrence of back corona. A possible solution to these problems is tribocharging, which is another charging mechanism used in the powder coating industry. Although the tribocharging process has been extensively researched, there are still a series of problems and unknowns remaining to be solved.

In general, if two different materials are put into contact and then separated, they will become electrostatically charged due to an electron transfer between them. Due to the charge transfer, the two materials in contact will charge oppositely. There are three divisions of this phenomenon: metal-metal, insulator-insulator and metal-insulator contact. The first situation is rather simple and can be easily understood by the Fermi levels being brought to coincidence. Due to the difficulty in understanding the electron states in insulators, the second case is difficult to understand and control. The third system presents a high interest due to its possible industrial applications.

In general, tribocharging is more difficult to employ and predict than corona charging mainly due to a number of factors which influence this process. The most important are; humidity, surface roughness, material mechanical and electrical properties, and shape of the two materials in contact. For powder coating applications, there are some additional factors that characterize the particulate properties: particle size distribution (PSD), powder flow rate, particle velocity, surface profile of the impacting device, time of impact, and deposition of particles on the metal impactors.

The goal of this paper was to perform a study on the tribocharging properties of polymer powders by using static mixers made of different materials. The results are to be used in breaking the Faraday penetration barrier. Another objective is to establish correlations between the materials of the chargers, the velocity of the powders inside the chargers (the Reynolds numbers characteristic to the individual flow pattern) and the Q/M acquired by the particles.

II. EXPERIMENTAL PROCEDURE

The charging experiments were performed in a computer-controlled powder-coating booth to reduce the influence of the extraneous factors (temperature and humidity) on the final results. The temperature was kept uniform at 70 F ± 4%, and the humidity at 30 % ± 5 %.

Two powders were used, and had different chemical and size properties. The first one was an acrylic with a particle size distribution (PSD) of d_{10}= 12, d_{50} = 28, and d_{90} = 40 μm, and is typically used for the top clear coat in the automotive industry. The second powder was an epoxy gray industrial, currently used as primer, with a PSD of d_{10}= 14.73, d_{50} = 24.79, and d_{90} = 43.70 μm. The two powders were fluidized in a Nordson fluidizing bed for 10 minutes before each experiment, and transported from the fluidizing bed to the charging devices through a Venturi pump and a rubber hose.

For the tribocharging experiments, commercially available Ko-Flo static mixers were used, made of different materials; polycarbonate, 304 stainless steel, copper and aluminum. The diameter of the chargers is 2.54 cm and they have 6 inner metal elements used for impaction (Fig.1 (a)). To ensure a uniform powder cloud, a PTFE finger nozzle was attached to the chargers (Fig.1 (b)).

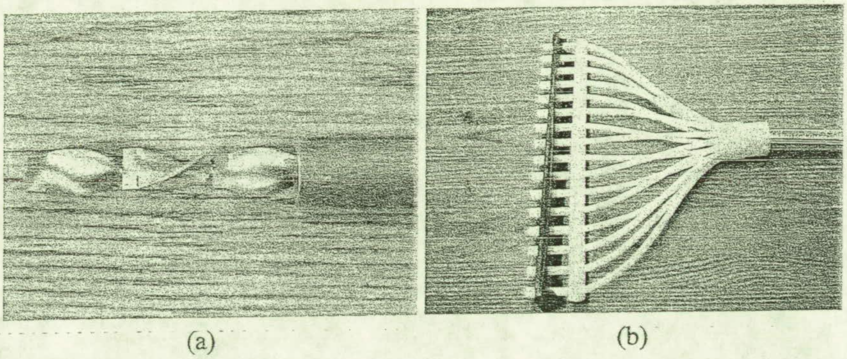
(a) (b)

Fig. 1. (a) The aluminum static mixer used to charge the powders and, (b) the PTFE finger nozzle

The powders were transported through the chargers by air stream at various flow rates and therefore at different velocities. The study intended to analyze the effect of the impaction and residence time of the powders inside the chargers on their charge-to-mass ratios (Q/M). The charging properties of the powders were analyzed by using a Faraday pail grounded through an electrometer for the net Q/M values and a charge separator for the charging polarities. For the Q/M measurements, a known mass of powder (M) was blown off inside the Faraday Pail while the charge level (Q) was measured by an electrometer. A charge separator was used to measure the ratios of positively and negatively charged powders. The instrument is composed of two V shaped copper plates (Fig. 2) with a variable voltage between them and connected to electrometers for measuring the charge of the collected powder. Throughout these experiments, the voltage between the plates of the electrometers was kept constant at 10 kV.

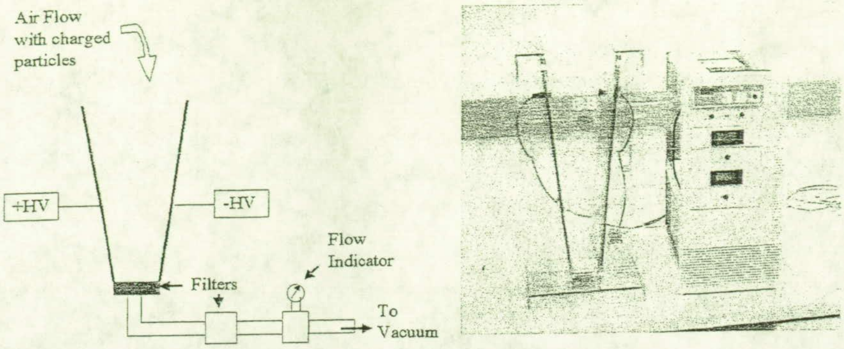

Fig. 2. The schematic and the picture of the charge separator used to separate species that are bipolarly charged

III. THEORETICAL DISCUSSION

A. Corona charging

The main advantages in corona charging are the constant and repeatable level of charge the particles acquire in this process. The most important disadvantages relate to the generation of high electric fields and necessity of high voltages as well as the back corona occurrence and Faraday penetration problems.

In the corona process, the air molecules are ionized, generating electrons and free ions. The electrons attach to the oncoming polymer particles, sprayed at different feed rates, and the powders will charge proportionally with the number of free charges generated during the discharge. Increasing the voltage will have a direct effect, causing an increase in the number of generated electrons and the powder Q/M. The charged particles move towards the grounded metal targets following the electrical field lines. For flat surfaces, uniform powder layers of variable thicknesses can be deposited. Serious problems are encountered when the surface to be coated is irregular with recessed areas. In this situation, the higher electrical field line density in certain areas will generate a thicker powder layer, while other areas will remain uncoated with negative effects on the corrosion resistance properties.

As the particles move along the electrical field lines, it is very important to study all the aspects related to the generation, geometry and intensity of these fields. It is known that during the corona discharge, an intense electrical field is generated between the corona tip and the grounded target. Another equally important field originates between the cloud of charged particles and the grounded workpiece to be coated. This happens for both corona and tribocharging mechanisms, and will be manifested as long as the cloud of powder particles coming out of the charging device has a net charge other than zero. Therefore in order to overcome the Faraday penetration limitation, the problem to solve is how to highly charge a powder, but without any net charge. A possible solution is to bipolarly charge the powder using the tribocharging mechanism.

The powder cloud as it leaves the charger is considered to be spherical (with a radius R) in order to simplify the mathematical calculations. From this perspective the charge density is given by eq. 1;

$$\rho_V = \frac{\sum Q}{V} = \frac{\sum Q}{\frac{4}{3}\pi R^3}, \tag{1}$$

where Q is the total charge and V is the volume of the powder cloud.

Applying Gauss's law to estimate the intensity of the electrical field E generated by the powder cloud;

$$\oint_S \vec{E} \cdot \vec{dA} = \frac{1}{\varepsilon_0} \int \rho_V dV \tag{2}$$

and considering the area of the cloud as being: $A = 4\pi R^2$, then;

$$E = \frac{\sum Q}{\varepsilon_0 A} = \frac{\rho_V \cdot \frac{4}{3}\pi R^3}{\varepsilon_0 \, 4\pi R^2} = \frac{\rho_V R}{3\varepsilon_0} \tag{3}$$

The total charge is given by the charge of the positive (q_+) and negative (q_-) powder fractions;

$$\sum Q = \sum q_+ + \sum q_- = \left(\frac{\sum Q}{M}\right) M \tag{4}$$

where M is the total mass of powder. Therefore,

$$E = \frac{\left(\frac{\sum Q}{M}\right)}{\varepsilon_0 \, 4\pi R^2} \left(\frac{1}{6} N \rho_p \pi d_p^{\,3}\right) \tag{5}$$

where N is the total number of particles, ρ_p is the density of the particles ($\approx$ 1200 kg/m^3) and d_p is the average particle diameter.

From equations (1) to (5) it can be observed that a powder cloud with a bipolar feature and a net Q/M approaching zero, there will be no electric fields generated, so the particles will penetrate and eventually deposit in the recessed areas. By depositing bipolarly charged particles, the back corona occurrence could be also greatly delayed given the lower electrical field intensity within the powder layer. The charging mechanism to be employed in order to obtain such charge characteristics of the particles is tribocharging.

B. *Tribocharging*

Tribocharging has been intensively studied for a number of years [4, 5]. There are a plethora of models that try to explain and model the charge transfer Q that occurs when a metal is put into contact with an insulator. The simplest one takes into consideration the difference in the Fermi levels;

$$Q = K\frac{(\varphi_1 - \varphi_2)}{e} \tag{6}$$

where φ_1 and φ_2 represent the work functions of the two materials and e is the electron charge. The work function of a solid is defined as the minimum energy required to extract an electron from the highest occupied energy level to the "vacuum level".

The work function difference was found, by some authors, to be in a direct correlation with the charge density σ [4];

$$\varphi_1 - \varphi_2 = \left(\frac{2\pi e\sigma}{\varepsilon_0 \varepsilon_r \rho}\right)^2 \tag{7}$$

where ε_0 is the permittivity of free space, ε_r is the dielectric constant of the material, and ρ is the volume density of the injected charge.

Other studies have taken into consideration the number of electron states per area (N_s) and the effective distance (z) between the materials in contact [4];

$$\varphi_1 - \varphi_2 = \sigma\frac{1 + (e^2 z N_s / \varepsilon_0)}{e N_s} \tag{8}$$

Although most of the studies consider the electrons to be the main charge carriers, some other authors give the charge transfer an ionic characteristic [6]. There is much controversy in the literature regarding the type of relationship between the charge density (or the charge transferred per unit area) in an insulator and the contact duration and the electronegativity properties of the two

The critical velocity has the form [9];

$$V_c = \frac{\beta}{d_a} \tag{9}$$

where β is a constant that depends on the two materials in contact and the system geometry.

The kinetic energy needed by the particle in order to bounce off while colliding with a surface is given by equation 10 [9];

$$E_{kin} = \frac{d_p A(1-e^2)}{2xe^2} \tag{10}$$

where A is the Hamaker constant, e is the coefficient of restitution (the ratio of the rebound velocity to the approach velocity) and x is the separation distance. In most of the situations, A and e depend only on the materials of the particles and surfaces.

In most situations, during impaction, the particles can deform and change their shapes, or in case of brittle materials, they can break and change their sizes. Due to all these factors, it is very important to correlate the velocity of the particles through the chargers to the charge they will acquire.

In time the impaction plates are coated by particles that did not bounce off, and therefore the charge acquired will decrease as the oncoming particles collide against other particles, instead of the metal surface. This is why the inner parts of the chargers have to be constantly cleaned.

IV. RESULTS AND DISCUSSION

The powder flow rate was increased successively from 0 to 4.5 m/s and the powder collected on grounded copper tubes was blown off inside a Faraday pail grounded through an electrometer. The results show the net charge-to-mass ratio (Q/M) decreased as the powder flow rate increased, while keeping the particle velocity through the chargers constant (Fig. 3). This result can be explained by the increase of the volume density of particles injected in the charger with a smaller probability for individual particles to collide against the metal inlets and become charged. This trend was observed for all the chargers.

The time of contact is related to the level of charge the particles acquire. The factor that controls the time the particles reside inside the charger and the time of impaction, is the velocity of the particles carried by the airflow. In consecutive experiments, the powder load was kept constant (about 70 g/min) and the airflow carrying the powder was increased. In this way the velocity of the particles increased proportionally to the increase in the airflow.

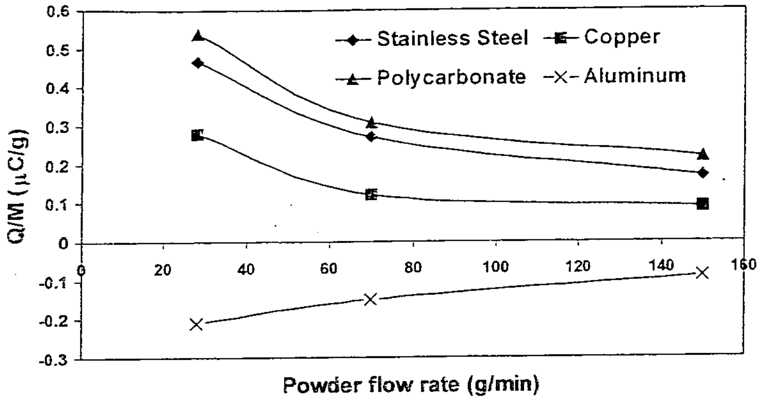

Fig. 3. Q/M variation with the powder flow rate for different chargers at an air velocity of 1.64 m/s

The experiments were repeated for different chargers made of different materials: polycarbonate, 304 stainless steel, copper and aluminum. The Q/M values of the powder deposited on the grounded copper tubes, for each charger material and each particle velocities were measured and are plotted in Fig. 4. As the velocity increased, the charge level acquired by the particles did not increase uniformly. In most cases, Q/M increased rapidly for velocities up to 3 m/s, and as the velocity is further increased, the Q/M values reached a plateau. The reduced residence time of the particles inside the chargers and inevitably the smaller impaction time can explain this behavior.

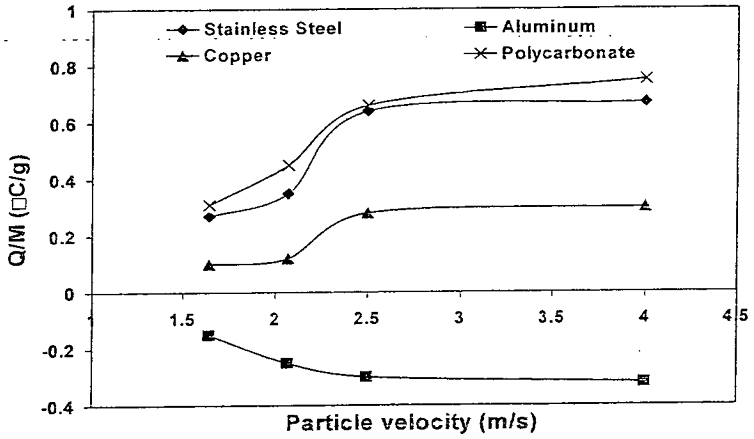

Fig. 4. Q/M variation with the particle velocity of the powder through different chargers. The powder flow rate was 70g/min

When the powder was charged against the stainless steel charger, the fastest Q/M increase was observed for velocities ranging from 2 to 2.5 m/s. This may be explained by the turbulent motion of the particles inside the charger. The Reynolds numbers Re, can be calculated by [9];

$$\mathrm{Re} = \frac{\rho_f V d}{\eta} \tag{11}$$

where ρ_f is the density of the fluid (air), V is the velocity of the particles, d is the diameter of the chargers, and η is the viscosity of air. Values obtained ranged from 2000 to 4000. This interval represents the transition region between the laminar-flow region to the turbulent one and generally is not very well defined. Usually in this interval, the friction coefficients between the fluid and the particles are very high, and there are a lot of eddies. The increase of the air velocity was achieved by increasing the airflow through the chargers, but the powder feed rate was kept constant. Therefore at high velocities, the powder cloud was more dispersed. This fact can explain the charge separation data plotted in Fig.5. For the situation where the stainless steel charger was used, more particles charge positively when the velocity increased.

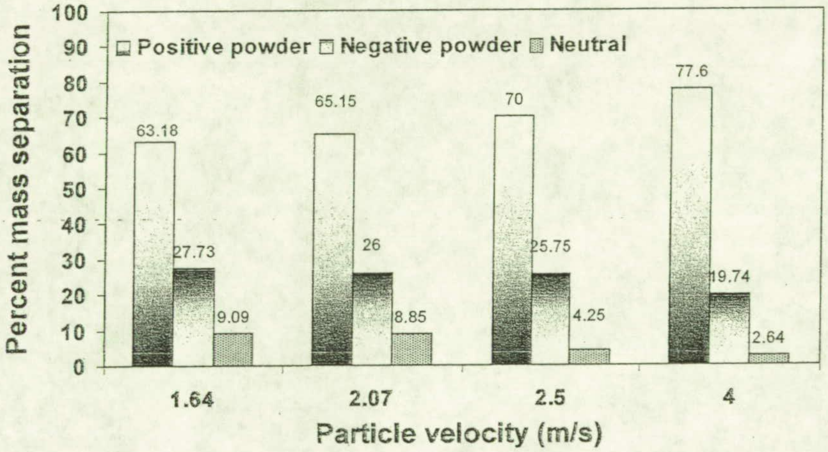

Fig. 5. The charge separation data for the acrylic powder tribocharged in the stainless steel static mixer at a flow rate of 70 g/min.

As expected based on their tribocharging properties, chargers made of different materials charged the powder differently. Most of the chargers except the one made of aluminum charged the acrylic powder positively, while the epoxy powder charged negatively against aluminum, copper, and stainless steel and positively against polycarbonate.

The powder Q/M values measured at 70 g/min and around 2 m/s are plotted in Fig. 6. It was observed that the same powder charges oppositely in contact to different charger materials.

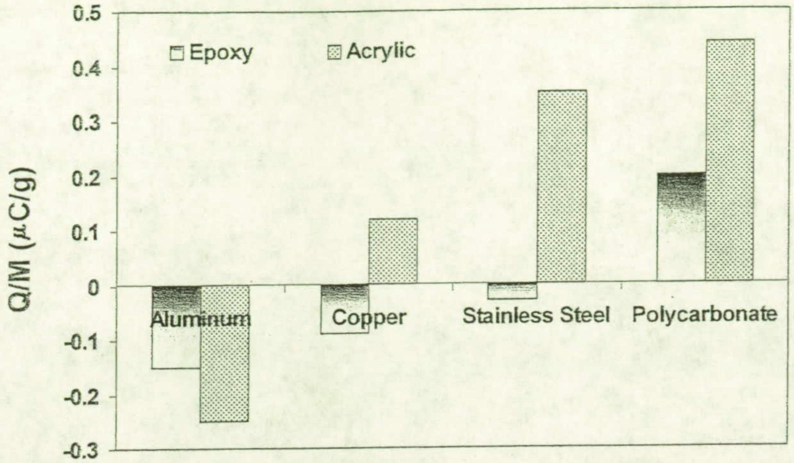

Fig. 6. Q/M values for the acrylic and epoxy powders charged in static mixers made of different materials

To reduce the velocity of the particles, a special finger nozzle (Fig. 1) which splits the main powder flow into ten secondary streams, was employed. The nozzle was made of PTFE, and was attached at the end of the chargers. Besides splitting the airflow, the PTFE charger also induced a slightly positive charge to the powder particles. Therefore in order for the powder cloud to have a net Q/M close to zero it is required for the powder to acquire a negative charge inside the static charger to compensate for the positive charge gained in the nozzle and during fluidization and transportation. Depending on the type of powder, the velocity and the charger material has to be very carefully selected so that the net charge of the cloud to be close to zero.

For the acrylic powder, the aluminum charger and a velocity of 2.05 m/s provided a negative net charge. If the velocity was lower, the powder particles did not have enough momentum to reach the target and very little powder was collected on the copper tubes. The average powder Q/M when charged inside the aluminum charger with the finger nozzle attached, was – 0.05 μC, very close to zero.

A direct correlation is obtained between the work function difference of the chargers' material and the reported value for the acrylic powder and the measured Q/M of the powder (Fig.7). It means the higher the work function difference between the two materials in contact, the higher the charge transfer and the Q/M acquired by the powder. Obviously this is in good agreement with the fact that two similar materials will not get charged while in contact. These data can show that a high charging is expected when the polymer powders are passed through metal chargers, given the large difference between their work functions [7].

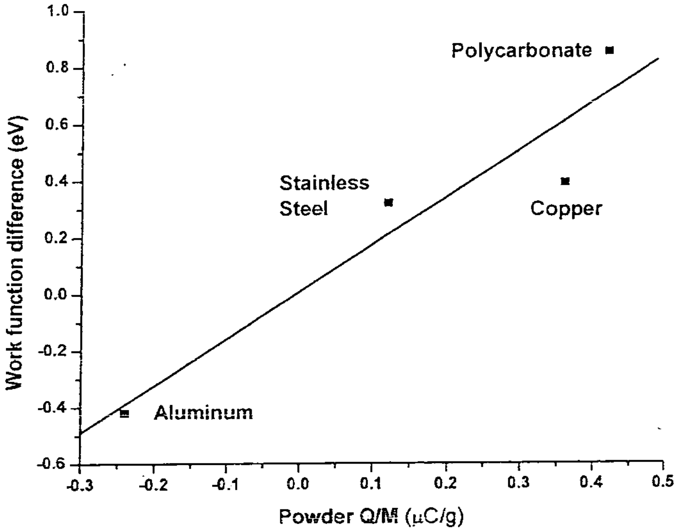

Fig. 7. Variation of the net Q/M of the acrylic powder as a function of the difference in work function of the charger material and of the powder.

V. CONCLUSION

The results showed that both acrylic and epoxy powders acquired bipolar charges, and the net Q/M varied with the velocity of the particles through the chargers. The rate of increase of the powder Q/M was greatest for velocities ranging from 2 to 2.5 m/s. As the velocity was further increased, the Q/M reached plateau values. The velocity of the powder inside the chargers was found to influence the charging characteristics of the both the acrylic and epoxy powders. As the velocity increased from 1 to 4 m/s, the ratio of powder that acquired negative charge increased from 63 to 78 %.

Direct correlations between the difference in work function of the polymer powders used for electrostatic coatings and the chargers, polarity and amount of charge were observed. In conclusion, for powder coating applications, the right material for the polymer powders and velocity inside the chargers need to be optimized.

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