Triboelectric Phenomena in Suction-Type Dilute-Phase Pneumatic Transportation Systems for Granular Plastics

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***Abstract*—The triboelectric phenomena related to particle-to-particle and particle-to-wall impacts are known to affect the efficiency of suction-type dilute-phase transport systems. The aim of this study is to evaluate the effects of two factors: the granular material feed rate and the aspirating air flow-rate. The study was conducted with mm-size ABS and HIPS particles, two granular materials originating from genuine information technology wastes. The tribo-charging processes in PVC and Al pipes were modeled using the response surface method of experimental design. An induction type sensor, connected to an electrometer has been employed for the measurement of the charge imparted to a well-defined section of the duct, which is equal to the charge transferred to the particles passing through that section of the pneumatic transport system. The measured data were processed by a virtual instrument developed in LabVIEW and then analyzed using a commercial software (MODDE 5.0, Umetrics, Sweden). Under the specific conditions of the experiments described in this paper, the charge/mass ratio of the processed particles was found to increase with the aspirating air speed, but was less affected by the granular material feed rate. It was concluded that the appropriate design of the transport system might provide an effective pre-charging of the granular mixtures of insulating materials that are processed in standard triboelectrostatic separators.**

***Index Terms*—Electric charge, electrostatic measurements, pneumatic transport systems, triboelectricity.**

I. INTRODUCTION

THE suction-type dilute-phase pneumatic transport systems are typically used for the transportation of powders, but also of granular materials, such as seeds, drugs or chopped industrial wastes [1]. Several triboelectric phenomena occur in the ducts through which such materials are conveyed [2-5].

Electric charge is exchanged at each particle-to-particle or particle-to-wall contact. The magnitude and the polarity of the charge acquired by the particle can vary widely, depending on the chemical composition of the conveyed materials and on the nature of the pipes [6-8]. In some cases, the oppositely charged particles can agglomerate or adhere to the walls of the ducts, altering the characteristics of the material flow.

On the other hand, in function of the nature of the materials they are made of, the ducts can preserve the acquired charge for longer or shorter periods of time. Thus, an insulating pipe rapidly saturates (i.e., it attains a limit beyond which it cannot exchange charge with the moving particles), while a conductive hose connected to the ground is able to continuously donate or accept electrons [8]. The consequences of charge build-up on insulating ducts are less predictable, though various solutions exist for preventing the electrostatic hazards related to this situation [9].

The design of pneumatic transportation systems should take into account these triboelectric phenomena. The empirically established triboelectric series [9, 10] indicate the direction of charge migration between the materials in contact. The magnitude of the exchanged charge can be roughly estimated from the maximum charge-to-mass ratio attainable for tribo-charged solid particles: 4.5 μC/g [3, 8]. Though useful, this kind of knowledge is not enough for appropriately modeling and analyzing the charging and discharging phenomena involving particles moving through pipes.

Therefore, in a previous paper [11], the authors measured the charge accumulated on powders conveyed through an insulating duct by collecting the particles in a Faraday pail located at the exit of the pneumatic transport system [3, 12]. In a more recent publication [13], the authors made a step further in the understanding of the triboelectrostatic phenomena that might affect the efficiency of suction-type dilute-phase pneumatic transport systems. They employed an electrostatic induction type sensor for measuring the charge build-up on a PVC pipe when processing mm-size ABS-PS particles, a granular material originating from information technology (IT) wastes. The tribo-charging process was modelled using the response surface method of experimental design [14, 15]. In was found that: (i) the magnitude of the tribocharging effect depends mainly on the hourly quantities of processed materials; (ii) adjusting the air flow-rate is a convenient way to reduce this effect.

Manuscript received May 1st, 2009. This work was supported in part by the Poitou-Charentes Regional Council, Poitiers, France, and the ERASMUS Program of the European Union.

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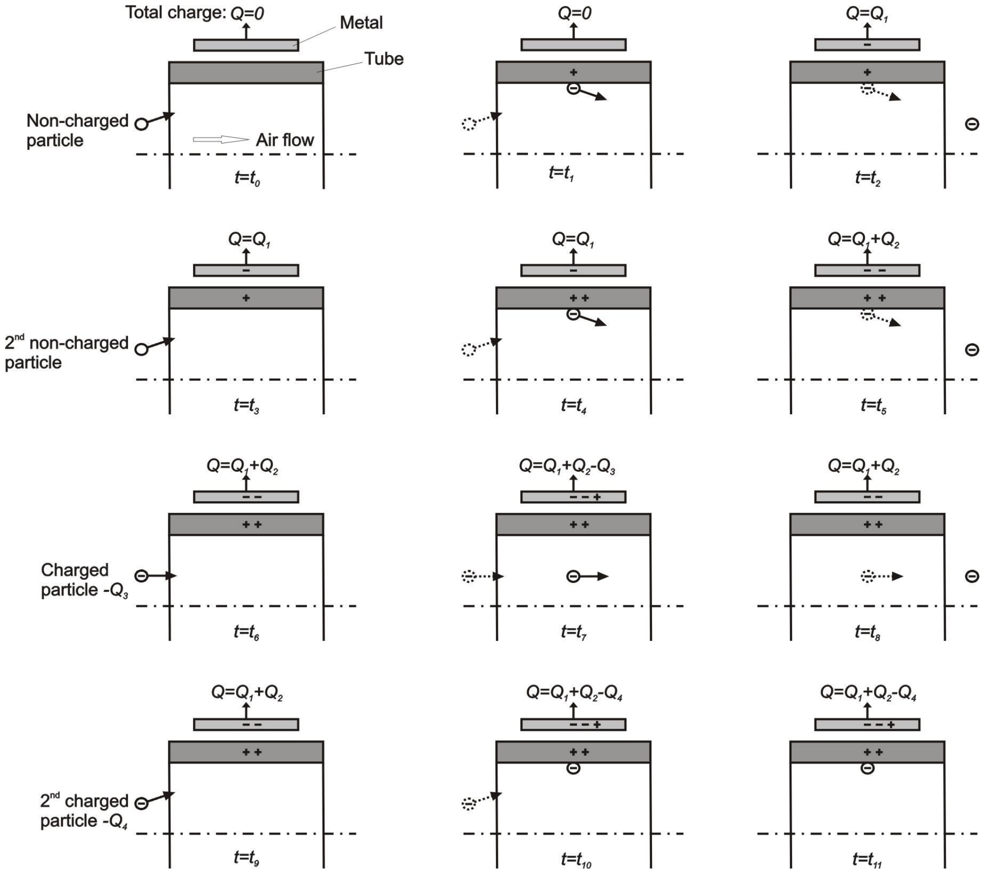


Fig. 1. Principle of the electrostatic induction method employed for the measurement of the tribo-charges generated by the particles conveyed in an insulating duct.

The aim of the present paper is to compare the effects of the granular material feed rate and the aspirating air speed on the charge accumulated on conducting and insulating pipes. The experiments were carried out with ABS and HIPS particles in sizes between 1 and 2 mm, originating from IT wastes, using 1.5 meter long PVC and Al pipes. They simulated the operating conditions of intermittent suction-type dilute phase pneumatic transport systems to be employed for feeding a class of tribo-electrostatic separators designed for the recycling of granular plastics.

II. THEORETICAL ASPECTS

The measurement of the charge that builds-up on the insulating pipes composing a pneumatic transport system can be performed using the electrostatic induction phenomena [4, 12, 16, 17]. In the experiments described in the next sections of this paper, a short metallic cylinder coaxial with a well-defined zone of the pipe and separated from it by a good insulator was employed as charge probe connected to an electrometer.

As schematically represented in Fig. 1, the net charge of the respective zone of the pipe induces a charge of opposite polarity in that metallic cylinder. A non-charged particle that enters the zone of the insulating pipe "viewed" by the cylindrical probe at the instant $t = t_0$ (Fig. 1) and collides the pipe wall at $t = t_1$ will get a negative charge $Q_p = -Q_1$. The charge Q_t of the tube being equal and of opposite sign to the charge acquired by the particle, $Q_t = Q_1$ and the total charge "viewed" by the probe is zero. As soon as the charged particle exits this zone, entrained by the air-flow (time $t = t_2$), the electrometer connected to the probe will measure a charge $Q_i = Q_1$ equal to that of the pipe wall.

After the passage of a second particle, which exchanges a charge Q_2 with the duct wall, the electrometer will indicate a charge $Q_1 + Q_2$ (time $t = t_5$). At the passage of a charged particle $Q = -Q_3$, the instrument will first indicate a total charge $Q_i = Q_1 + Q_2 - Q_3$ (time $t = t_7$). If that particle passes through the zone "viewed" by the induction probe without touching the pipe wall, the instrument will show the value $Q_i = Q_1 + Q_2$, at $t = t_8$. If another charged particle $Q = -Q_4$ gets closer to the pipe wall which carries a charge of opposite sign, it is attracted and stick to it. In that case, at $t = t_{11}$, the instrument indicates $Q_i = Q_1 + Q_2 - Q_4$.

More generally, the charge Q_i measured by the electrometer after the suction of a given quantity of material during a well-defined period of time t_m is equal to the sum of charges acquired by the zone of the pipe "viewed" by the probe, plus the charge of the particles that stick to the wall.

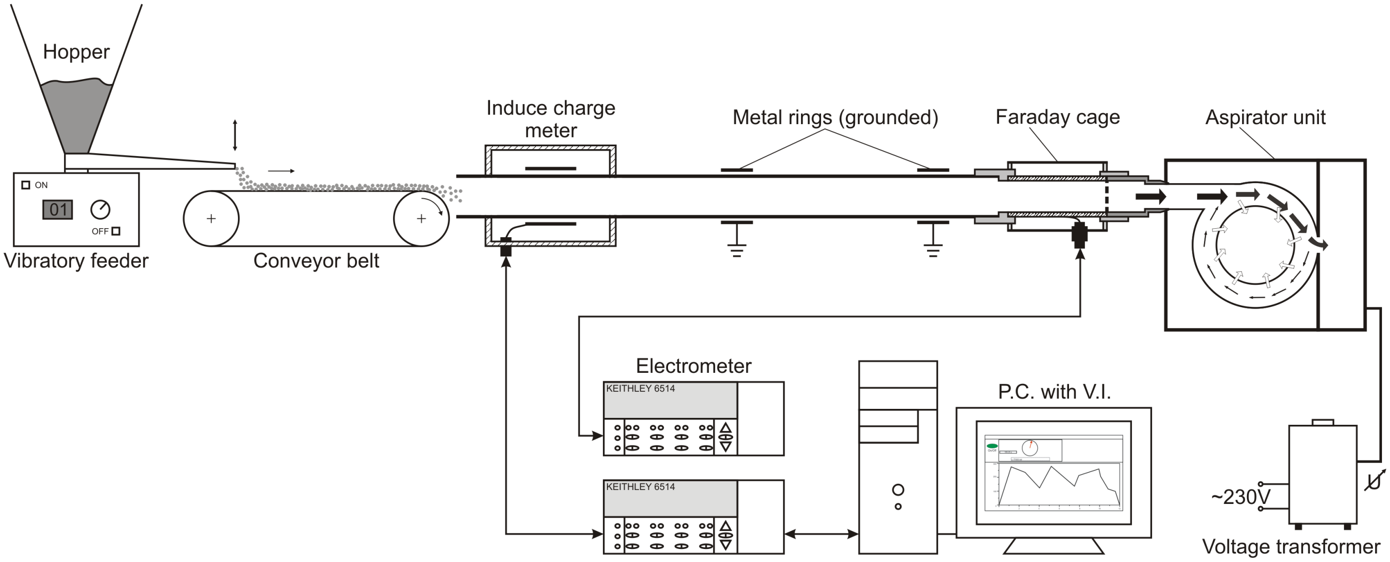


Fig. 2. Schematic representation of the electrostatic induction probe for the study of tribocharging phenomena in suction-type dilute phase pneumatic transport systems.

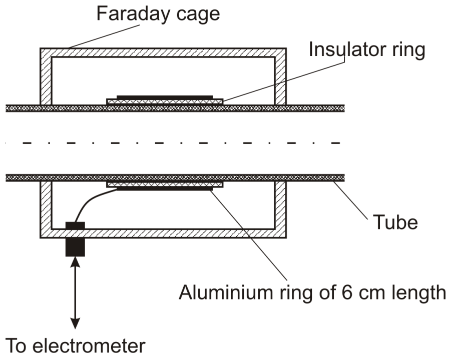


Fig. 3. Schematic representation of the electrostatic induction probe.

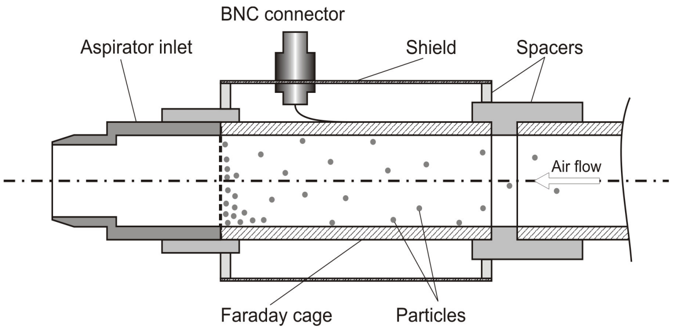


Fig. 4. Design of the modified Faraday cage used to measure the charge acquired by the particles in the tube.

III. MATERIALS AND METHOD

The granular material that served in the experiments originated from IT wastes processed by an industrial scrap recycler, APR2, Bonnières-sur-Seine, France. It consisted in less than 3 mm in size ABS and HIPS particles, obtained by crushing out-of-use computer housings and other information technology (IT) equipment.

The experiments were performed on the laboratory installation represented in Fig. 2, consisting in a straight pipe (length: 1.5 m; inner diameter: 40 mm) and an aspirator unit (a modified commercial cyclone-type bag-free vacuum cleaner, model R07165, Rowenta, France). At a rated air-flow ϕ_{max} = 33 dm^3/s, the average air speed in the pipe was 25 m/s. Two materials were tested for the suction pipe: PVC and aluminum.

The tribocharging processes in the pipe were monitored by using three electrostatic induction probes, located close to the inlet, in a median position and close to the outlet of the pipe (Fig. 3), and fabricated by wrapping the pipe with a 0.5 mm thick Teflon tape, and then with a 0.5 mm thick adhesive Aluminum tape, which was connected to an electrometer via a BNC cable. Each probe was shielded by a grounded metallic cylinder, coaxial with the pipe.

The electrometer (model 6415, Keithley Instruments) connected to the probe was operated as a Coulomb-meter, and controlled by a custom-designed virtual instrument (VI), which was developed in a LabVIEW environment (National Instruments) [18].

The VI records the charge detected every three seconds by the electrostatic induction probe. The total charge measured by the electrostatic induction probe q_p was calculated as the sum of the values recorded during the 12-second aspiration process, for a given quantity m of granular material.

The charge q acquired by the granular particles is measured with a modified Faraday cage (Fig. 4) placed between the end of the tube and the inlet of the aspirator unit. The main feature of this pail is the metal woven grid that is used to retain the particles inside the cage. This was the sole solution found even that the method of measurement is somehow intrusive, because of the pneumatic charge that is built by the retained particles. The Faraday cage is connected to a second electrometer (model 6415, Keithley Instruments), operated as a stand-alone Coulomb-meter. The values were read over the same period of 12 s, concomitantly with the electrostatic induction probe measurements.

The granular material was fed at the inlet of the pipe by a conveyor belt at various feed rates m, ranging between m_{min} = 50 g/min and m_{max} = 100 g/min. The aspiration of 100 g/min was possible for any air-flow ϕ higher than ϕ_{min} = 21 dm^3/s.

Before each new experiment, the pipe was discharged by connecting it to ground in several points during a time long-enough for the surface potential, checked with an electrostatic voltmeter probe, to decay at less than 10% of its initial value.

When the objective is the optimisation of a process, experimental design methodology [14, 15] recommends the adoption of quadratic model:

$$y = f(x_i) = a_0 + a_1 x_1 + a_2 x_2 + a_{11} x_1^2 + a_{22} x_2^2 + a_{12} x_1 x_2 \quad (1)$$

where y is the response of the process and x_i is the normalized centred value for each factor u_i:

$$x_i = (u_i - u_{ic}) / \Delta u_i = u_i^* \quad (2)$$

with

$$u_{ic} = (u_{i\max} + u_{i\min})/2 \quad \Delta u_i = (u_{i\max} - u_{i\min})/2 \quad (3)$$

For the factors considered in the present study, i.e. the material feed rate m and air flow-rate ϕ, the quadratic model of the response q, i.e. the charge acquired by the particles, will take the following form:

$$q = a_0 + a_1 m^* + a_2 \phi^* + a_{12} m^* \phi^* + a_{11} n^{*2} + a_{22} \phi^{*2} \quad (4)$$

In order to obtain such a quadratic model, the composite design (Table I) was employed for the present study, as recommended in [14, 15]. The results of charge measurements were then analysed with an experimental design software: MODDE 5.0 (Umetrics, Sweden) [19]. The program calculates the coefficients of the mathematical model, evaluates their statistical significance, draws the response contours and identifies the best adjustments of the input variables for optimizing the process. Moreover, the program calculates two statistical criteria: the goodness of fit: R^2, and the goodness of prediction: Q^2. This latter is a measure of how well the model will predict the responses for new experimental condition. A good mathematical model must have criteria R^2 and Q^2 with the numerical value close to the unit.

IV. RESULTS

Represented in Fig 5 is a typical example of $q_p(t)$ curves recorded by the electrometer connected to the electrostatic induction probe located at the inlet (zone A) and in the center (zone B) of the transport pipe.

The results of the Faraday cage measurements of the first 11-run composite experimental design carried out with HIPS particles in aluminium tube are given in Table I. With these data, the mathematical models of the responses q and q/m obtained with MODDE 5.0 were:

$$q[nC] = -358.79 - 66.74m^* - 38.01\phi^* - 3.18m^*\phi^* + 3.01m^{*2} + 13.73\phi^{*2} \quad (5)$$

$$q/m[nC/g] = -23.91 + 3.66m^* - 2.7\phi^* + 0.67m^*\phi^* - 0.98m^{*2} + 0.86\phi^{*2} \quad (6)$$

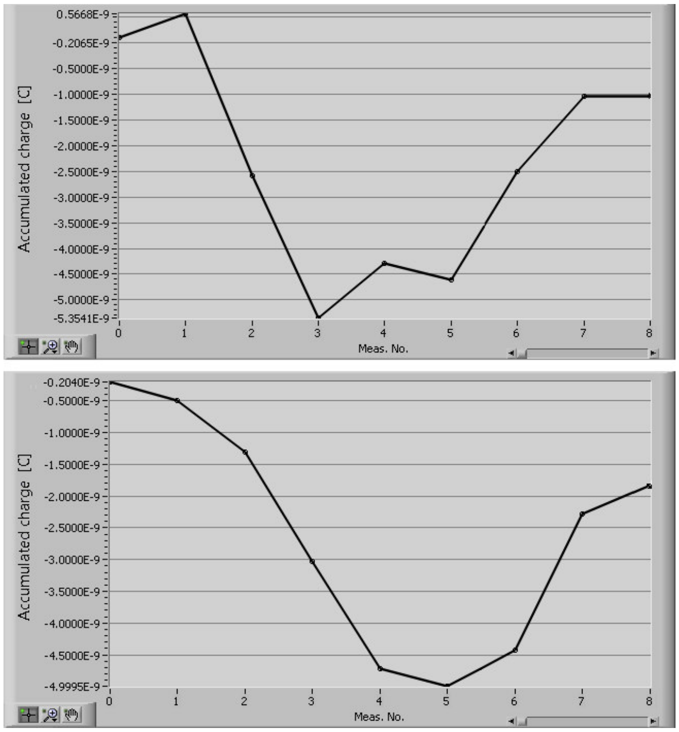
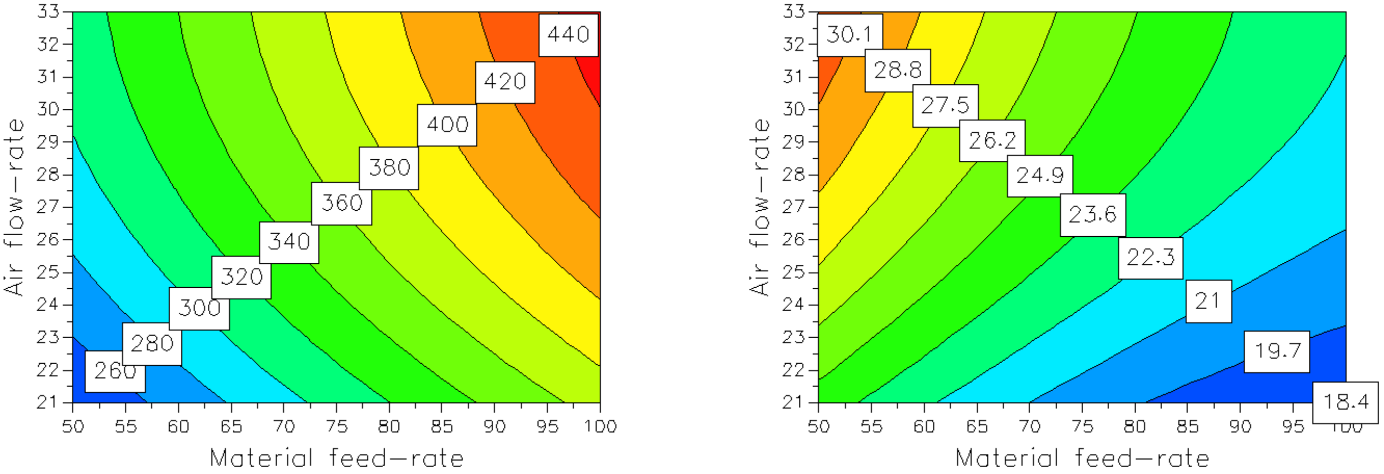


Fig. 5. Charge q_p vs time t as displayed by the VI when using two electrostatic induction probes placed in points A and B of the pipe.

TABLE I. FARADAY-CAGE-MEASURED CHARGE q AND COMPUTED CHARGE PER MASS q/m OF HIPS PARTICLES IN THE ALUMINUM PIPE, FOR THE 11 RUNS OF THE COMPOSITE EXPERIMENTAL DESIGN.

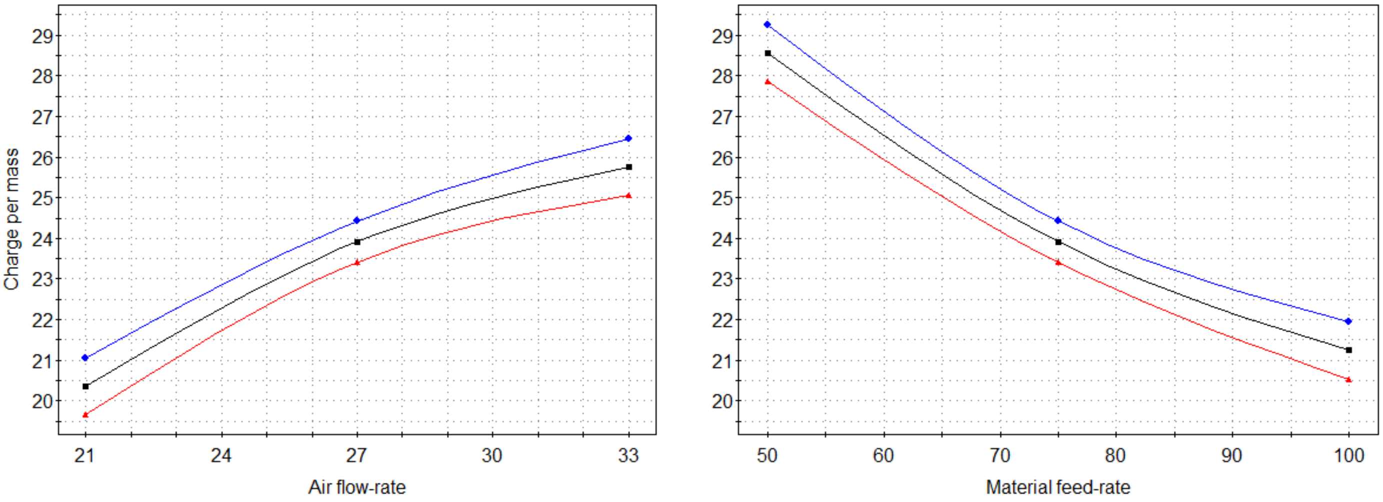
Run No. [-]	ϕ [dm^3/s]	m [g/min]	q [nC]	q/m [nC/g]
1	21	50	-245.7	-24.57
2	33	50	-312.6	-31.26
3	21	100	-369.74	-18.487
4	33	100	-449.37	-22.468
5	21	75	-299.64	-19.976
6	33	75	-381.2	-25.51
7	27	50	-281.3	-28.13
8	27	100	-420.98	-21.049
9	27	75	-359.6	-23.97
10	27	75	-361.24	-24.08
11	27	75	-364.8	-24.32

Both models fit well the experimental data (R^2 = 0.994), and enable a highly-accurate prediction of q and q/m values (Q^2 = 0.959 and 0.963, respectively) in any other operating conditions (Fig. 6, a and b). All the coefficients in the model (6) are statistically significant. As it can be seen in Fig. 7a, too, the absolute value of $|q/m|$ increases with the air flow-rate ϕ within the limits of the investigated experimental domain. On the contrary, the increase of the material feed-rate m causes a significant decrease of $|q/m|$, as shown in Fig. 7b. It is likely that at higher feed-rates part of the particles have less or no charge at the exit of the pipe, as their probability to impact the pipe walls diminishes.



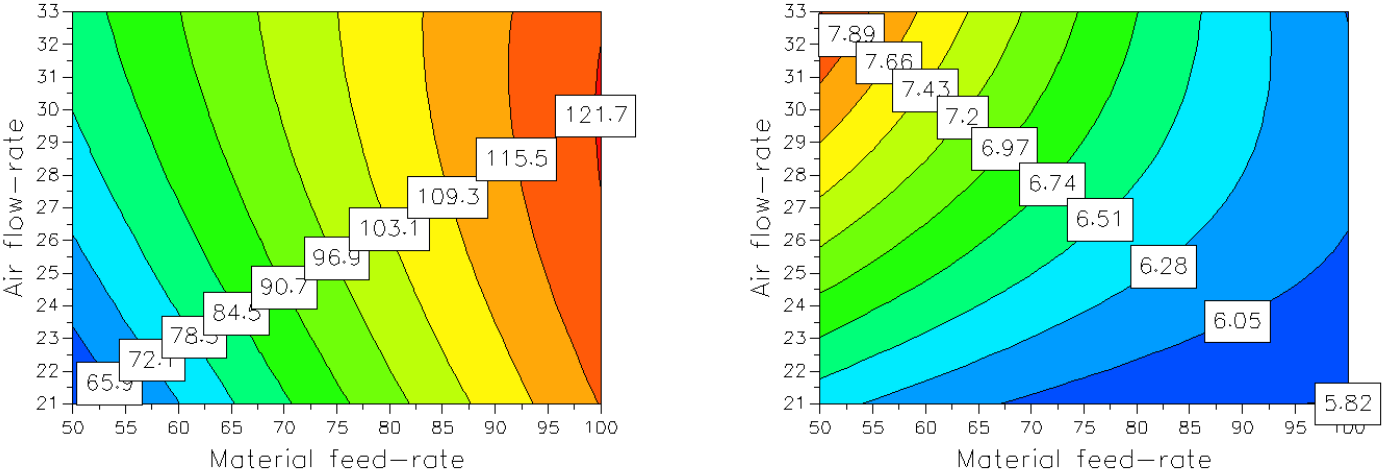
(a) (b)

Fig. 6. MODDE 5.0 predicted equal-│q│ [nC] contours (a) and equal-│q/m│ [nC/g] contours (b) in the case of HIPS particles conveyed through the Aluminum pipe; the material feed-rate m and the air flow-rate ϕ are expressed respectively in [g/min] and [dm^3/s].



(a) (b)

Fig. 7. MODDE 5.0 predicted │q/m│ [nC/g] of HIPS particles conveyed through the Aluminum pipe as function of the air flow rate ϕ [dm^3/s] (a) and the material feed rate m [g/min] (b).



(a) (b)

Fig. 9. MODDE 5.0 predicted equal- q_p [nC] contours (a) and equal- q_p/m [nC/g] contours (b), based on electrostatic induction probe measurements for the Aluminum pipe in the case of HIPS particles; the material feed-rate m and the air flow-rate ϕ are expressed respectively in [g/min] and [dm^3/s].

TABLE II. ELECTROSTATIC-INDUCTION-PROBE-MEASURED CHARGE q_p AND COMPUTED CHARGE PER MASS q_p/m, IN THE CASE OF HIPS PARTICLES IN THE AL PIPE, FOR THE 11 RUNS OF THE COMPOSITE EXPERIMENTAL DESIGN

Run No. [-]	ϕ dm^3/s	m [g/min]	q_P [nC]	q_P/m [nC/g]
1	21	50	74.21	7.421
2	33	50	82.27	8.22
3	21	100	114.12	5.706
4	33	100	120.34	6.017
5	21	75	90.9	6.06
6	33	75	103.27	6.884
7	27	50	72.97	7.297
8	27	100	124	6.2
9	27	75	96.02	6.4013
10	27	75	98.7	6.58
11	27	75	100.81	6.72

These findings are well correlated with the electrostatic probe measurements (Table II). The induced charge q_p as well as the ratio between q_p and the mass m of the particles that generate it are modeled by the following quadratic polynomials (Fig. 9):

$$q_p[nC] = 99.13 + 23.91m^* + 6.85\phi^* - 4.08m^*\phi^* - 1.57m^{*2} - 2.97\phi^{*2} \tag{7}$$

$$q_p / m \ [nC] = 6.58 - 0.65m^* + 0.49\phi^* - 0.38m^*\phi^* + 0.14m^{*2} - 0.13\phi^{*2} \tag{8}$$

The highest q_p/m is obtained for an air flow ϕ = 33 dm^3/s, and a feed rate m = 50 g/min: q_p/m = 8.22 nC/g. This value is roughly 1/3 of that recorded in the Faraday cage, i.e. q/m = 28.08 nC/g. This observation can be explained as follows: the charge generated in the aluminum pipe should be of opposite sign but equal in absolute value with that of the particles accumulated in the Faraday cage; due to the conductive nature of the pipe, this charge is shared quasi-equally between the three electrostatic induction probes that monitor the tribocharging phenomena in the device.

The HIPS particles charge less in the PVC pipes (Table III). The mathematical models are similar to those obtained for the Aluminum pipe:

$$q\ [nC] = -320.88 - 58.06m^* - 35.18\phi^* - 9.93m^*\phi^* + 7.11\phi^{*2} \tag{9}$$

$$q / m\ [nC / g] = -21.48 + 3.51m^* - 2.37\phi^* - 0.93m^{*2} + 0.39\phi^{*2} \tag{10}$$

It is interesting to note that the first three coefficients of models (9) and (10) are roughly 9/10 of their counterparts in models (5) and (6), obtained for the Aluminum pipe, which means that the tribocharging mechanisms are similar in the two situations. Consequently, the best charging conditions are similar: ϕ = 33 dm^3/s, m = 50 g/min (Fig. 10)

TABLE III. FARADAY-CAGE-MEASURED CHARGE q AND COMPUTED CHARGE PER MASS q/m OF HIPS PARTICLES IN THE PVC PIPE, FOR THE 11 RUNS OF THE COMPOSITE EXPERIMENTAL DESIGN

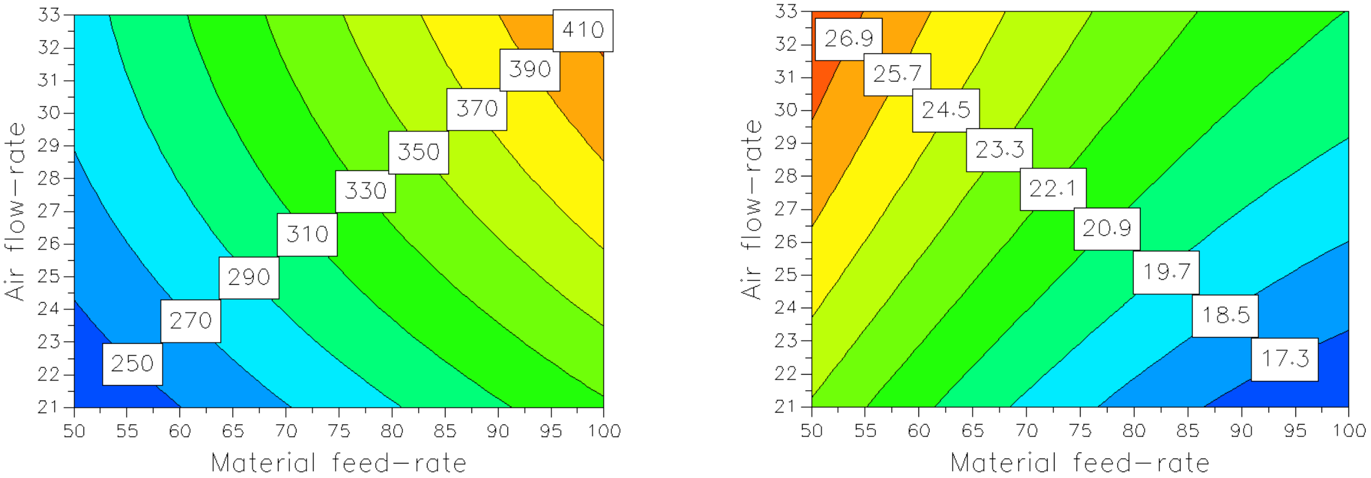
Run No. [-]	ϕ dm^3/s	m [g/min]	q [nC]	q/m [nC/g]
1	21	50	-232,74	23,274
2	33	50	-280,89	28,089
3	21	100	-327,8	16,39
4	33	100	-415,67	20,7835
5	21	75	-275,21	18,3473
6	33	75	-350,29	23,3527
7	27	50	-256,09	25,609
8	27	100	-374,64	18,732
9	27	75	-316,81	21,1207
10	27	75	-325,61	21,7073
11	27	75	-331,23	22,082

TABLE IV. ELECTROSTATIC-INDUCTION-PROBE-MEASURED CHARGE q_p AND COMPUTED CHARGE PER MASS q_p/m, IN THE CASE OF HIPS PARTICLES IN THE PVC PIPE, FOR THE 11 RUNS OF THE COMPOSITE EXPERIMENTAL DESIGN

Run No. [-]	ϕ dm^3/s	m [g/min]	q_P [nC]	q_P/m [nC/g]
1	21	50	2,752	0,2752
2	33	50	-2,311	-0,2311
3	21	100	5,587	0,27935
4	33	100	8,361	0,41805
5	21	75	3,601	0,240067
6	33	75	-0,163	-0,0108667
7	27	50	3,078	0,3078
8	27	100	3,177	0,15885
9	27	75	4,946	0,329733
10	27	75	4,245	0,283
11	27	75	5,888	0,392533

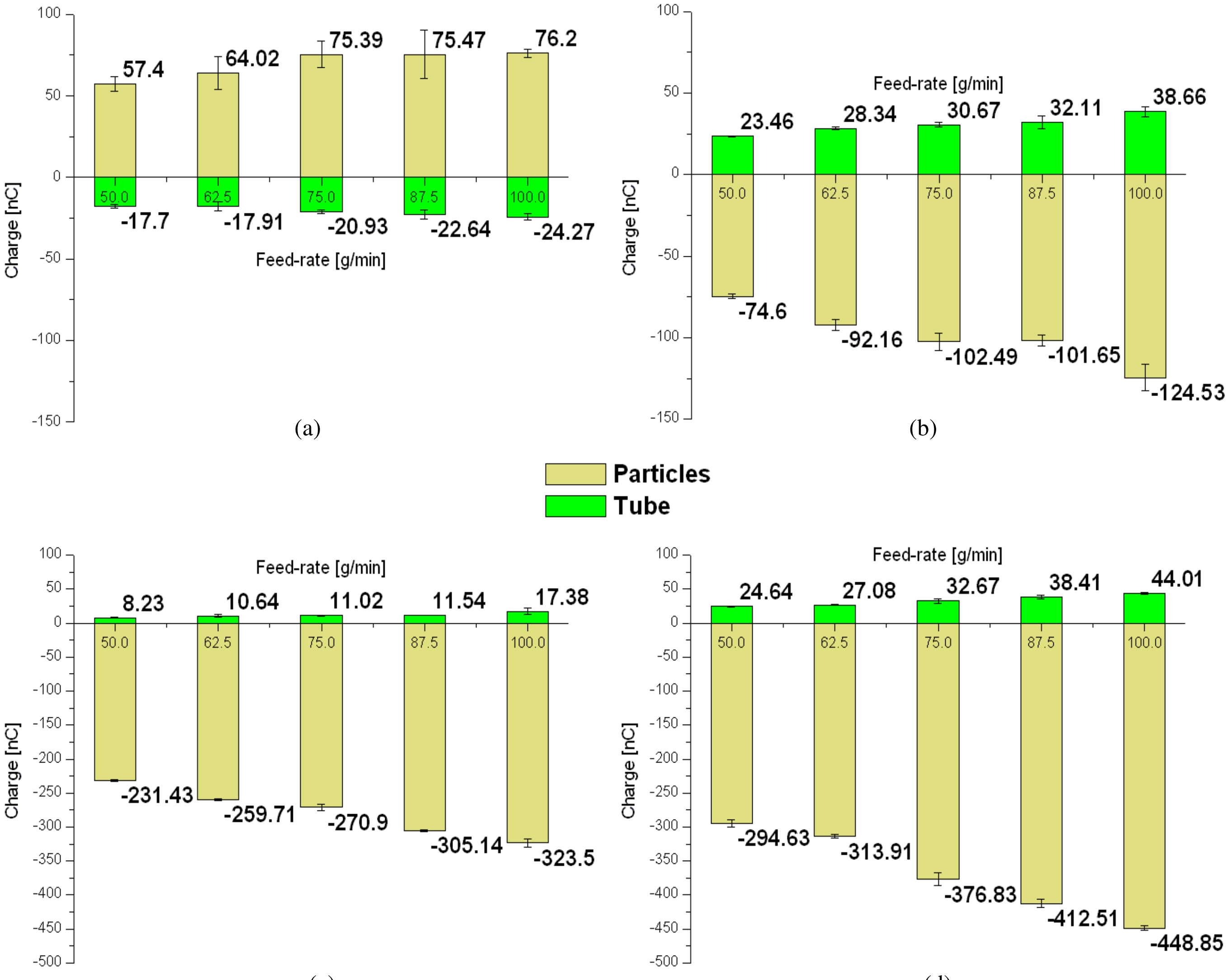
The values measured by the electrostatic induction probe are much lower in the case of the PVC pipe (Table IV). The maximum q_p = 8.361 nC represents only 1/50 of the total charge measured in the Faraday cage at that experiment. This observation can be explained by the fact that in the case of the insulating PVC pipe, the electrostatic induction probe "sees" only the charges generated in the 60 mm pipe zone covered by its sensing element (the aluminum ring), which represents 1/25 of the total pipe length (1.5 m). A second reason for the lower-than-expected values of q_p is related to the occurrence of gliding discharges along the inner pipe walls, due to the non-uniformity of the charge generated by triboelectric effect.

As higher air-flow rates were found to favor higher charge/mass ratios, a set of experiments were carried out at the maximum value of ϕ provided by the aspirator unit, i.e. 33 dm^3/s, for both types of pipes and for two granular materials: ABS and HIPS. The values of q and q_p at various feed rates m are given in Fig. 11. ABS acquires less charge, in absolute values, than HIPS in both aluminum and PVC pipes. The sign of their charge is the same in aluminum pipes, but different in the case of PVC pipes. This means that PVC pipes could be employed as tribocharging devices in conjunction with an electrostatic separator for sorting ABS and HIPS.



(a) (b)

Fig. 10. MODDE 5.0 predicted equal-charge *q* [nC] contours (a) and equal charge per mass q/m [nC/g] contours (b) in the case of HIPS particles conveyed through the PVC pipe; the material feed-rate *m* and the air flow-rate ϕ are expressed respectively in [g/min] and [dm^3/s].



(a) (b)

(c) (d)

Fig. 11. Charge q vs feed-rate m for ABS particles and PVC tube (a); ABS particles and Al tube (b);
HIPS particles and PVC tube (c); HIPS particles and Al tube (d).

The experiments were performed at very low mixture ratios (mass of the powder/mass of the air < 0.1), in a rather short pipe (1.5 m), during a short period of time (12 s). Though the tribocharging cannot be neglected, the measured charge/mass ratios are at least one order of magnitude lower than what is obtained in vibratory feeders or fluidized bed reactors [20, 21].

V. CONCLUSION

The charging of particulates in the suction-type pneumatic devices that have been the object of the present study is very poor. The behavioral model of the process derived in the present work points out that increasing the air flow-rate and decreasing the feed rate may increase the charge/mass ratio for ABS and HIPS granules. Reducing the diameter of the pipes, modifying their lengths and shape may increase the number of particle-wall impacts and improve the charging conditions of granular materials, in view of electrostatic separation.

ACKNOWLEDGMENT

Three of the authors (CD, MB and RC) benefited of ERASMUS Student Mobility scholarships financed by the European Union. The authors are grateful to Prof. G Touchard, Dr. T. Paillat, and Dr. N. Zouzou for fruitful discussions, as well as to M. Gauthier, for his technical help. The contributions of B. Bordier, M. Deckeur, et J. Rivet with the experimental set-up are acknowledge with thanks.

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