Comparison and Evaluation of Various Tribo-Charging Models for Two-Component Developer

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Abstract

Several models of tribo-charging of two-component developers have been proposed to explain the tribo-charging mechanism. Some of these models do not clearly explain all tribo-charging phenomena, e.g., the toner q/m is independent on toner concentration. Recently, we presented a new model to describe the tribo-electric charging characteristics of two-component developers. According to a new model, the dependence of tribo-electric charging characteristics on toner concentration is governed by the relative difference of charging site numbers between toners and carriers. Our model can clearly explain the tribo-charging phenomenon of two-component developers. We will compare and evaluate the various tribo-charging models for two-component developer with experimental results.

Introduction

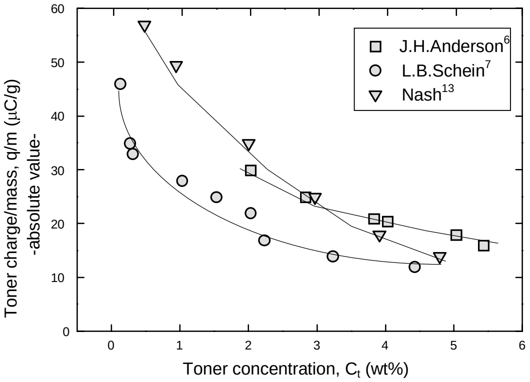
The toner tribo-charge due to the contact of toner and carrier, is one of the most important characteristics which decide image quality in electrophotography. The tribo-charging behavior has been a long standing challenge. However, the tribo-charging phenomenon can't do sufficient theoretical evaluation yet.

In this report, we will compare and evaluate with some proposed models of tribo-charging to define the physical meaning of the tribo-charging phenomenon of two-component developer from the experimental results of the toner concentration, C_t dependence of toner charge-to-mass ratio, q/m.

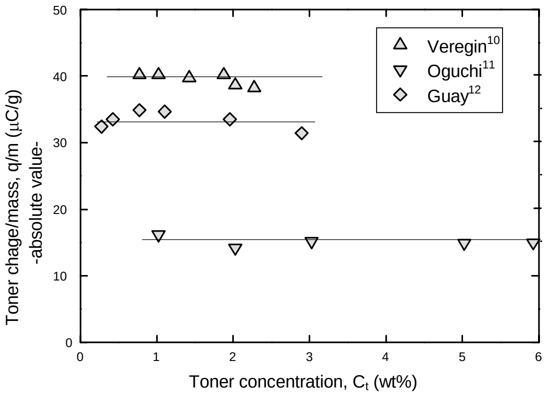
Experimental Results of Toner Tribo-Charging

First of all, the experimental results of tribo-charging of two-component developer which the toner q/m decreases with increasing toner concentration have been abundantly reported.[1-8,13] The typical experimental results of the toner concentration dependence of toner charge-to-mass ratio, q/m is shown in Fig.1-(a). However, as shown in Fig. 1-(b), the experimental results that toner charge-to-mass ratio, q/m don't depend on a toner concentration have been reported, too. It should be exist that the two phenomena of tribo-charging in the toner concentration dependence of toner charge-to-mass ratio, q/m.

As shown in Fig. 1-(a), the decrease of toner charge-to-mass ratio, q/m with toner concentration was discussed by many researchers and each had been explained by the proposed tribo-charging models. However, the experimental results that toner charge-to-mass ratio, q/m don't depend on a toner concentration don't discussed actively.



(a) Decreased q/m with increasing C_t



(b) Constant q/m with increasing C_t

Figure 1. Dependence of toner charge-to-mass ratio, q/m, on toner concentration, C_t. (a) Decreased q/m with increasing C_t (b) Constant q/m with increasing C_t

The results that the toner concentration dependence of toner charge-to-mass ratio, q/m was measured is shown in Fig. 2. The developers are made by combination of same minus toner and ferrite carrier and iron carrier, respectively. When ferrite carrier was used, as shown in Fig. 2, it doesn't have the toner concentration dependence of toner charge-to-mass ratio, q/m. On the other hand, when iron carrier is used, the tribo-charge characteristics that the toner charge-to-mass ratio, q/m decrease monotonously with increasing toner concentration is being shown in Fig. 2. It means that a tribo-charge characteristics is changed by the characteristics of carrier, even if same toner is used. Theoretical evaluation becomes necessary toward the physical meaning of the tribo-charging phenomenon for two-component developer that toner charge-to-mass ratio, q/m don't depend on a toner concentration. We will compare and evaluate the various tribo-charging models for two-component developer with experimental results.

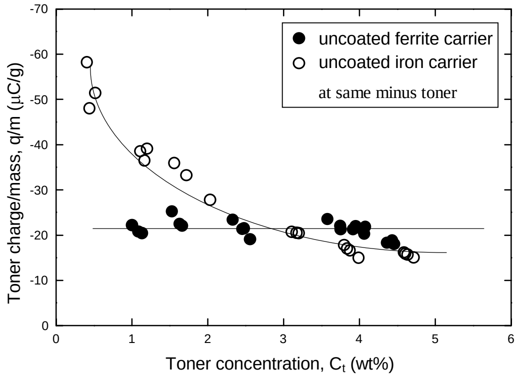


Figure 2. Dependence of toner charge-to-mass ratio, q/m, on toner concentration, C_t, by combination of same minus toner and uncoated ferrite carrier and uncoated iron carrier.

Comparison of Tribo-Charging Models

The reports due to three approach have been done as a way that the toner concentration dependence of toner charge-to-mass ratio, q/m is analyzed.

1) Electric field model: It is the model to suppose to become a certain saturation value which a balance of contact electric field is settled in property of the contact surface in the tribo-charge of toner and carrier. [3,4]

2) Surface state model: It is the model that tribo-charging of toner and carrier was explained by exchange charge until the their work functions are equilibrated. [5,6]

3) Kinetic model: It is the model to explain from being deciding the charged site number on developer surface. The charge exchange by a balance of the charge and discharge depends on the energy which exists in developer's surface. The energy is contributed to the relative difference of the number of sites which tribo-charging sites by donor and acceptor change with toner charge-to mass ratio, q/m by toner concentration.[1,2]

We compare and evaluate the these models for two-component developer with the experimental results as follows.

1. Electric Field Model (Gaussian Model)

Kondo3) proposed that the model which Gauss theorem was used as led by the supposition of having the mean electric field E_k of the contact part of toner and carrier is fixed. The saturation tribo-charge (q) of two-component developer was shown in the toner concentration C_t and a toner radius (r_t) and a carrier radius (r_c) in which electric field of the contact part is electric field by one toner add electric field by one carrier.

$$\frac{q}{m} = \frac{6\varepsilon_0 E_k}{\rho_t r_t + \rho_c r_c C_t} \qquad (1)$$

where ρ_t and ρ_c are specific gravity of toner and carrier, respectively, and ε_0 is dielectric constant in free space. When the number of the toner particles is n_t, a toner concentration C_t is shown with $C_t = n_t (\rho_t/\rho_c) (r_t/r_c)^3$.

On the other hand, Kurita 4) applied the Gauss theorem, too and changed the toner concentration of Kondo's model in the toner adhesion quantity per the carrier area, and simplified toner saturation tribo-charge as a function of the toner surface area ratio S_f. It can get a equation from concept as the total of the electric field which appears from the surface of the all toners particle equal to the total of the electric field which goes into the surface of all the particles of carrier. It could get the Eq. (2) that the toner saturation tribo-charge from a toner concentration or relations with the toner diameter to the relations with the surface area ratio. The coefficient of Eq. (2) becomes half of the Eq. (1). Because the toner tribo-charge is same to total q in system, whereas toner tribo-charge of Kondo`s model is same to half of total q in system.

$$\frac{q}{m} = \frac{3\varepsilon_0 E_k}{\rho_t r_t + \rho_c r_c C_t} \qquad (2)$$

Table 1 Classification of Proposed Tribo-Charge Model Equations

I	Kondo model3)	$\frac{q}{m} = \frac{6\varepsilon_0 E_k}{\rho_t r_t + \rho_c r_c C_t}$
	Kurita model4)	$\frac{q}{m} = \frac{3\varepsilon_0 E_k}{\rho_t r_t + \rho_c r_c C_t}$
II	L.H. Lee model5)	$\frac{q}{m} = \frac{3\Delta\phi e}{\frac{\rho_t r_t}{N_t} + \frac{\rho_c r_c C_t}{N_c}}$
	Anderson model6)	$\frac{q}{m} = \frac{-3\varepsilon_0\Delta\phi}{d\left[r_t\rho_t\left(\frac{\varepsilon_0}{N_t e^2 d}+1\right) + C_t r_c\rho_c\left(\frac{\varepsilon_0}{N_c e^2 d}+1\right)\right]}$

And, the model equation of Table 1-I classified with electric field model group which contact electric field E_k are fixed, indicates that the toner q/m decreases with increasing toner concentration. The relations of m/q and C_t become straight lines, and shows the toner concentration dependence of toner q/m proposed by many reports (Fig. 1-(a)). However, the experimental results like Fig. 1-(b) which doesn't have the toner concentration dependence of toner charge-to-mass ratio, q/m can't be explained with electric field model.

2. Surface State Model (Charge Exchange Model)

The concept of the surface state model is that charged state density by tribo-charging of the contact part by the difference in both work functions.

L.H.Lee[5] proposed the model that toner tribo-charge occur by the difference in the work function due to the electron transfer.

$$\frac{q}{m} = \frac{3\Delta\phi e}{\frac{\rho_t r_t}{N_t} + \frac{\rho_c r_c C_t}{N_c}} \tag{3}$$

where $\Delta\phi$ is a difference in the work function between toner and carrier, and e is electronic charge, and N_t and N_c are each surface states density (per unit area, unit energy) of toner and carrier, respectively. As for the difference from electric field model, toner q/m depends on a work function difference $\Delta\phi$ in the appearance of toner and carrier, and surface states density N. However, this model can't explain the experimental results as shown in Fig. 1-(b), either.

In Anderson model, two limits, i.e., low-density limit and high-density limit exist by the difference in the surface states density N and these are independent relationship. It is usually assumed that d represents the distance over which electron tunneling can occur. Therefore, it can be shown by Eq. (4).

$$\frac{q}{m} = \frac{-3\varepsilon_0 \Delta\phi}{d\left[r_t\rho_t\left(\frac{\varepsilon_0}{N_t e^2 d}+1\right) + C_t r_c \rho_c\left(\frac{\varepsilon_0}{N_c e^2 d}+1\right)\right]} \tag{4}$$

At high-density limit ($\varepsilon_0/(N_t e^2 d) \ll 1$ and $\varepsilon_0/(N_c e^2 d) \ll 1$), Eq. (4) is changed to Eq. (5). Eq. (5) corresponds to electric field model.

$$\frac{q}{m} = \frac{-3\varepsilon_o \Delta\phi}{\{d\left(r_t\rho_t + r_c\rho_c C_t\right)\}} \tag{5}$$

However, at low-density limit ($\varepsilon_0/(N_t e^2 d) \gg 1$ and $\varepsilon_0/(N_c e^2 d) \gg 1$), Eq. (4) is changed to Eq. (6).

$$\frac{q}{m} = \frac{-3\Delta\phi e^2}{\frac{\rho_t r_t}{N_t} + \frac{\rho_c r_c C_t}{N_c}} \tag{6}$$

From Eq. (3) and Eq. (4), it only explains that toner q/m decreases with increasing toner concentration such as the results of Fig. 1-(a). In other words, Eq. (3) and Eq. (4) are made a reciprocal equation like $m/q \propto C_t$, and the equation shows the linear relationship between toner q/m and toner concentration. However, the case of the toner concentration independence of toner q/m (Fig. 1-(b)) can't be explained.

L. H. Lee and Anderson didn't discuss that the relative difference of N_t and N_c. At the low-density limit case, we tried Anderson model expansion in consideration of the relative difference of the surface states density, N_t and N_c.

When the surface condition is $N_c \gg N_t$, Eq. (6) becomes Eq. (7).

$$\frac{q}{m} = \frac{-3\Delta\phi e^2 N_t}{\rho_t r_t} - e^2\Delta\phi \frac{n_t}{m_t} \tag{7}$$

It is expressed that toner charge-to-mass ratio, q/m don't show a toner concentration dependence. The results in Fig. 1-(b) can be explained by Eq. (7).

When the surface condition is $N_c \ll N_t$, Eq. (6) becomes Eq. (8). This equation can be explained that the toner concentration dependence of toner q/m proposed by many reports such as the results of Fig. 1-(a). Therefore, the derived Eq. (7) and Eq. (8) from the charge exchange model group in consideration of the relative difference of N_t and N_c could explain completely the experimental results on Fig. 1 and Fig 2. It is strongly suggested that each tribo-charging sites number of toner and carrier are related in the toner concentration dependence of toner charge-to-mass ratio, q/m.

$$\frac{q}{m} = \frac{-3\Delta\phi e^2 N_c}{f\ddot{I}_t r_t \frac{N_c}{N_t} + f\ddot{I}_c r_c C_t} \bullet - e^2\Delta\phi \frac{n_c}{m_c}\frac{1}{C_t} \tag{8}$$

3. Kinetic Model (Dynamic Model)

A time dependence of sites number that tribo-charge is possible was taken into consideration by the charge exchange which depended on the surface of toner and carrier, and it was tried to look for the toner concentration dependence of toner charge-to-mass ratio, q/m. Because tribo-charge is done by stirring, tribo-charging of toner and carrier is dynamic process. The tribo-charge depends on a balance of the charge and discharge, and the toner and carrier charged sites go to equilibrium by exchanging their charges each other. At a certain toner concentration, let N_t and N_c denote the maximum number of charging sites of toner and carrier in total system, respectively, and let n^+ and n^- denote the number of tribo-charged sites of toner and carrier, respectively and $n^+=n^-$. Based on this model, it can be shown by Eq. (9). Eq. (10) is given by Eq. (9) after an equilibrium condition.

$$\frac{dn^+}{dt} = \alpha\left(N_c - n^-\right)\left(N_t - n^+\right) - \beta n^+ \tag{9}$$

$$n^+ = \frac{2N_c N_t}{\left(N_c + N_t + \sqrt{\left(N_c - N_t\right)^2}\right)} \tag{10}$$

where α is related charging constant and β is related discharge constant. Supposing that it is in proportion to the number of effective surface charged sites between toner and carrier under an equilibrium condition, as for the toner charge-to-mass, q/m of the total system becomes Eq. (11).

$$\frac{q}{m} \propto \frac{en^+}{m} = \frac{2N_cN_te}{m\cdot\left(N_c+N_t+\sqrt{\left(N_c-N_t\right)^2}\right)} \tag{11}$$

It is shown that tribo-charge is controlled by the difference in the number of charging sites that tribo-charge of toner and carrier is possible, and relationship between toner charge-to-mass ratio, q/m and toner concentration can get it by the relative difference of Nt and N_c.

When the surface condition of the developer is $N_c < N_t$, Eq. (11) becomes Eq. (12).

$$\frac{q}{m} \propto \frac{en_c}{m_c}\cdot\frac{1}{\mathrm{C}_t} \tag{12}$$

where, m_c is mass of one carrier particle and n_c is number of tribo-charged sites on one carrier particle. From the Eq. (12), the toner charge-to-mass ratio, q/m decreases as toner concentration increases such as shown in Fig. 1-(a).

On the other hand, when the surface condition of the developer is $N_c > N_t$, Eq. (11) becomes Eq. (13).

$$\frac{q}{m} \propto \frac{en_t}{m_t} = \text{constant} \tag{13}$$

where, m_t is mass of one toner particle and n_t is number of tribo-charging sites on one toner particle. It doesn't have the toner concentration dependence of toner charge-to-mass ratio, q/m so that Eq. (13) may show it with Fig. 1-(b), and constant value is shown.

Therefore, when Eq. (8) from the electronic exchange model compares with Eq. (12) and, in the same way, Eq. (7) compares with Eq. (13), because a difference is only the way of taking N_t, N_c or n_t, n_c, after all, it is explained that Eq. (11) by the dynamic model gives it the same results of Anderson model. However, the difference between dynamic model and Anderson model is that the surface condition of $N_c>N_t$, $N_c = N_t$, $N_c<N_t$ are taken into consideration in the dynamic model in Eq. (11) though the surface condition of $N_c>>N_t$ and $N_c<<N_t$ are taken into consideration in Anderson model. All of the experimental results (Fig. 1 and Fig. 2) are could be clearly explained.

Concept of Tribo-Charging Model for Two-Component Developer

With two-component developer, if a charge exchange is done with a certain toner concentration between toner and carrier and a toner particle sticks on carrier and it is a balance, because it is $Q = n_cq_c = n_tq_t = q$, where Q is carrier tribo-charge and q is toner tribo-charge in total system. q_c is carrier tribo-charge and q_t is toner tribo-charge of one particle. It can be shown Eq. (14).

$$q_c = (n_t / n_c)\bullet q_t = k\bullet q_t \tag{14}$$

where $k = (n_t / n_t)$ becomes a k individual toner sticks to one carrier particle. Eq. (14) shows the toner concentration dependence of toner charge. The charge exchange in closed system (limited surface area) should be thought that the k individual toner in the limited surface area sticks to one carrier in the limited surface area. When q_c of Eq. (14) is fixed, the decrease of q/m means that q_t decreases with increasing k. However, as the q_t is constant case (fixed value), q_c increase with increasing k, in other words, toner concentration dependence of toner, q/m may not be shown. Then, we should discuss toner concentration dependence of toner charge-to-mass ratio, q/m from the concept of the relative difference of the effective charging sites number N_t of toner side and N_c of the carrier side in the closed system, based on Eq. (14). The physical meaning of results of Fig.1 and Fig. 2 could be clearly explain.

Conclusions

Our tribo-charge model was compared with some models for tribo-charging proposed about the tribo-charging mechanism of two-component developer. It is understood that many tribo-charge models and experimental results can be explained with our tribo-charging model. Our model can explain for the tribo-charging phenomenon which doesn't depend on the toner concentration of toner charge-to-mass ratio, q/m, too. The charging sites are donor and acceptor which depends on the energy which exists in the surface of the toner and carrier. The dependence of triboelectric charging characteristics on toner concentration is governed by the relative difference of number of charging sites in which energy included. The relative difference of toner and carrier effective charging sites is very useful concept for the analysis of microscopic behavior of two component systems.

A tribo-charging phenomenon can be explained with our model for two-component developer in closed system (limited surface area). Therefore, it is important that the tribo-charging characteristics of two-component developer can be evaluated by measuring the toner concentration dependence of toner charge-to-mass ratio, q/m.

References

1. T. Kishimoto and Y. Takahashi, *Electrophotography*, vol. **34**, No. 3, p. 190 (1995)
2. Y. Takahashi and W. S. Lee, Proceedings of NIP12: International Conference on Digital Printing Technologies, p.526 (1996)
3. A. Kondo, The Society of Electrophotography of Japan, The 43rd Research and Symposium Meeting, p. 26 (1979)
4. T. Kurita, *Electrophotography*, vol. **26**, No. 2, p. 126 (1987)
5. L. H. Lee, *Photogr. Sci. Eng*, vol. **22**, No. 4, p. 228 (1978)
6. J. H. Anderson, *J. Imaging Sci. Technol.*, vol. **38** , No. 4, p. 378 (1994)
7. L. B. Schein, *Electrophotography and Development Physics*, 2nd Ed. Springer-Verlag (1992)
8. E. J. Gutman and G. C. Hartmann, *J. Imaging Sci. Technol.*, vol. **39**, No. 4, p. 285 (1995)
9. T. Yamazaki et al., *Electrophotography*, vol. **31**, No. 2, 113 (1992)
10. R. P. N. Veregin et al., Proceedings of NIP12: International Conference on Digital Printing Technologies, p. 501 (1996)
11. T. Oguchi et al., *Electrophotography*, vol. **16**, No. 2, p. 126 (1977)

12. J. M. Guay and J. W. Robinson, Proceedings of NIP12: International Conference on Digital Printing Technologies, p.549 (1996)
13. R. J. Nash and R. N. Muller, Proceedings of NIP13: International Conference on Digital Printing Technologies, p.112 (1997)

Biography

Won-Sup Lee received his B.S. and M.S. in Chemical Engineering from the Seoul National University at Seoul/Korea in 1985 and 1987, respectively, and he is Ph.D. course student in Electo-Photo-Optics of the Tokai University at Hiratsuka/Japan at present. He joined LG Chemical Research Institute in 1987 working on polymer compounding. His current interests are in toner triboelectrification and toner materials.

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