Aspects of Toner Transport on a Traveling Wave Device

Michael D. Thompson, Yuri Gartstein and Jack T. LeStrange
Xerox Corporation, Wilson Center for Research & Technology
Webster, New York, USA

Abstract

Transport of powder xerographic toners on a traveling electrostatic wave device is studied and numerical simulations are discussed relative to experimental results. Simple single particle descriptions, which have been the basis of previous theoretical work in the field, are contrasted to simulations which include many-particle interactions. Many-particle results are shown to exhibit self-consistent behavior essentially independent of the initial particle conditions. The average macroscopic velocity of the flow results from the interplay of the driving field and the interactions in the system. This velocity can take any value between zero and the wave phase velocity. This average velocity in the intermediate regime is achieved through the scattering of particles between different velocity states.

Introduction

Xerographic development is dependent on the ability to transport charged powders in a controlled fashion and deliver them to a latent electrostatic image. For dry powders this is currently accomplished in a variety of ways such as two component conductive or insulative magnetic brush, single component methods using a donor roll with inductive charged toners or insulating toners with AC or DC jumping. All of these approaches try to control the electrostatics and toner transport characteristics in the development zone to produce defect free images in ever more demanding printing environments using smaller toners and closer, more precise spacings in the development zone.

Traveling electrostatic wave devices, which create running electrostatic waves along a solid boundary, have been discussed in the context of transport and handling of small charged particles without moving parts[1] and may provide a significant advance in printing technology when used for xerographic dry powder development.[2-5] Previous theoretical work has focused on single particle motion on such devices and analyses have shown that different modes of transport are possible. In realistic applications, transport flows consist of many particles. How the interaction of charged particles affects transport flow is a topic whose significance was realized[6,7] but studied only recently.[8] In this paper we use results of computer simulations to discuss this issue illustrating some qualitative generic features of many-particle flows driven with traveling waves and compare some of the results with experimental observations.

The single particle scenarios established in earlier studies can be summarized as follows. Basic transport modes induced by an idealized sinusoidal wave $V_0\sin(kx-\omega t)$ belong to two categories, synchronous and asynchronous. Here V_0 is the potential amplitude, k and ω are respectively the wavevector and the frequency of the wave, t is the time, and x the coordinate along the traveling direction. In the synchronous mode, particles follow the wave with the wave phase velocity $v_{ph} = \omega/k$, while in the asynchronous mode, particles move in the same direction but with a velocity usually much lower than v_{ph}. The curtain mode discovered by Masuda[1] is an asynchronous mode in which particles are repelled from the boundary producing the wave and confined to the grid by the force of gravity. The levitated particles execute cycloidal trajectories away from the boundary while slowly moving in the wave direction. The surfing and hopping modes introduced by Schmidlin [9] and Melcher *et al*[6] are synchronous modes. In these cases, particles slide or move in a hopping fashion along the boundary, being contained by the electrostatic field from the wave, in contrast to the curtain mode.

Frequently a particle would be able to move in either of these modes *depending on the initial conditions* (i.e. where and how the particle starts with respect to the wave).[5,9] In general, after some time has elapsed, a particle 'finds' the motion pattern appropriate under given conditions and then follows it in a (periodic) steady-state manner. In many-particle systems, the total electric field acting on individual particles consists of components from the traveling wave, other particles, *and* image charges induced in the substrate by *all* particles.

We have demonstrated that the resulting *self-consistent* behavior of the whole ensemble of particles is, to a large extent, independent of the initial particle conditions. The response of the particle ensemble to the traveling wave can be characterized by the distribution of the drift velocities v acquired by the particles. For a collection of non-interacting particles, depending on starting conditions, that could be a bimodal distribution with peaks at $v = v_{ph}$ and at v near zero. Synchronously moving particles would maintain a certain phase relationship with the wave. In the interacting system, however, both long-range Coulomb and short-range hard-core interactions between particles impede aggregation. When this 'repulsion' is strong enough and energy losses are substantial, only a portion of particles would be able to move in a synchronous mode. We will show that the self-consistent distribution of velocities in such a system has also an approximately bimodal character, with some particles moving with velocities close to v_{ph} and others lagging behind. The average velocity therefore has an intermediate value between 0 and v_{ph}. In contrast to the non-interacting case, however, this distribution is seen in the calculation only over short "observation" times. As we watch the particle velocity evolve over a number of driving wave periods (e.g. twenty) we see this distribution of velocities become singly peaked around the average velocity. That is, the interaction between particles causes not just a separation into two different groups, but rather leads to scattering of particles between different states.

Description of the Model

The simulations have been performed using a computer code (Pic3D[10]) that combines three-dimensional finite-element electrostatic field calculations with charged-particle dynamics. As appropriate for the traveling-wave environment, periodic boundary conditions along the wave propagation direction have been used both in the field calculations and for the particle dynamics. Figure 1 shows a snapshot of the simulation environment. Actual calculations involving 1000 particles have been done with numerical parameters suitable for xerographic toners. Toner nominal diameter for the calculations here was 7 microns with nominal charge at 10 μcoul/gm and, for the purposes of this discussion, size and charge of all particles were the same. We present here only results obtained for an idealized sinusoidal traveling wave as was used in many original single particle calculations.[4-7,9] (We have also studied the flow dynamics when the traveling wave is produced by a set of finite electrodes and particle parameters are distributions).

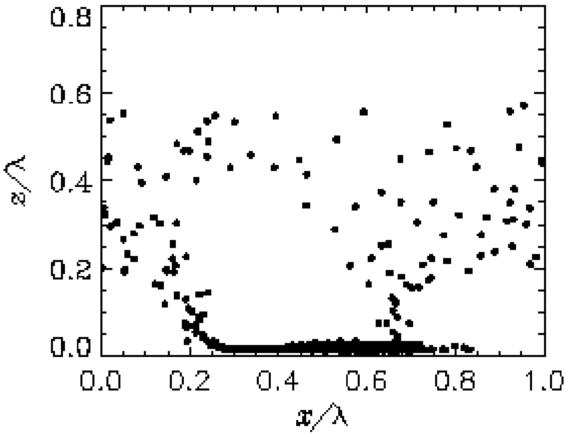

Figure 1. A snapshot of particles from the calculation projected onto the x-z plane. Wave propagation is along the x- axis ,the z-axis is perpendicular to the device surface. The particle diameters here are approximately .01 times the wavelength of the device.

Sources of energy loss included in the calculations are collisions and friction between particles and between particles and the solid boundary. Both are conventionally characterized by coefficients of friction and restitution which were taken in this paper as 0.5. The average surface density of particles in the present simulations was chosen to be close to a monolayer coverage. The relative strength of the collective electrostatic effect can be evaluated comparing the driving field E_0 to the field $E_l = \sigma/2\varepsilon_0$ that would be produced by a plane having the same uniform surface charge density σ as our layer of particles (ε_0 is the vacuum permeability). For the example in this paper, $E_l/E_0 \cong 0.85$, a moderately significant interaction strength.

Experimental Setup

Some simple experiments were performed looking at velocity of toner vs wave phase velocity as the frequency of the driving potential was varied. A schematic of the apparatus used to measure average toner velocities on the device is shown in figure 2. The grid is four phase with 100 μm electrodes and spaces on a polyimide substrate.

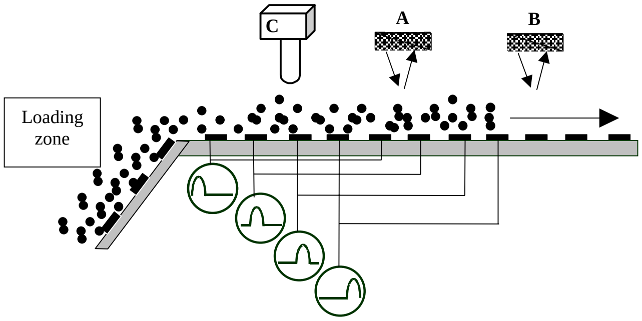

Figure 2. Apparatus used to measure toner velocities on traveling wave device. I R sensors A and B sense arrival times of toner cloud, high speed video camera C looks at short timescale events.

A toner layer was loaded at the leftmost end of the device and the leading edge of the traveling toner cloud was sensed via two infrared reflectivity sensors *A* and *B.* The differences in arrival times of the toner cloud for various conditions were recorded yielding the average speed. This value agreed with mass flow rate as directly measured, divided by the mass per unit area of toner on the grid. The high speed video camera C was used to get qualitative results of modes of toner motion and some approximate values for distribution of toner velocities. Different waveforms could be applied to the grid and different methods of loading are possible.

Results and Discussion

Numerical experiments have been done as previously described and the ensemble is looked at after the transients have died out and the system settles to some quasi-steady-state behavior. Figure 3 shows snapshots of the velocity distribution of our ensemble averaged over times of 1, 10 and 20 wavecycles. Essentially identical results have been obtained for particles started from very different initial conditions. This result is in sharp contrast to calculations with noninteracting systems where the same set of initial particle conditions has been found to lead to various responses ranging from all particles being transported asynchronously to all particles moving synchronously with the wave. Similar observations have also been made for other simulations, indicating that collective electrostatic effects, when strong enough, cause the system to behave in a certain self-consistent manner depending on the system parameters but practically independent of the initial particle conditions.

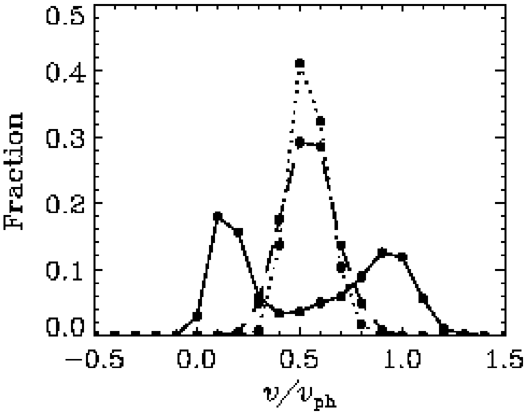

Figure 3. Distributions of particle velocities after various calculation times. The broad solid line distribution is after one wavecycle. The dashed line at 10 cycles and the dotted line at 20 cycles show the distribution coalesce into a singly peaked distribution centered on .5 vph.

Evidently, collective electrostatic fields have a much larger spatial scale than a single particle image force would have. (A single particle image force falls off as the inverse squared distance from the boundary while the field from a layer of image charges is practically distance-independent. See Figure 4 where a snapshot of the self consistent electric field is shown which includes the particle charges). Relatively distant particles can be attracted towards the boundary and then facilitate establishment of a periodic quasi-steady-state pattern. The behavior in Figure 3 can be rationalized if scattering of particles between different velocity states is assumed. Direct examination of individual particle trajectories justifies such an assumption. Figure 5 illustrates the history of one of the particles from the flow of Figure 3, other particles displaying similar patterns.

As seen in Figure 5(a), the particle moves for some time with the wave phase velocity, then for some time with a lower velocity, then again synchronously with the wave etc. Apparently, transitions between different states resemble random scattering events. The corresponding real-space trajectory in Figure 5(b) combines quasi-sliding and "hopping" portions and also exhibits a random behavior, in contrast to regular trajectories of the single particle motion.[4,6,7] It is important to realize that scattering events here can involve many particles through the long-range Coulomb forces as well as the driving force from the wave.

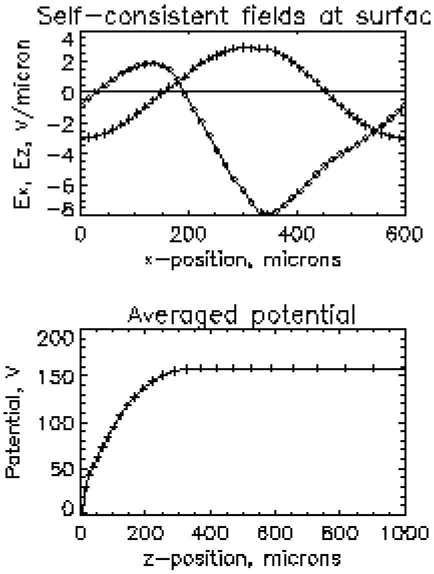

Figure 4. Snapshot of typical electric field and potential for the parameters of figure 1. Ex is denoted by the +

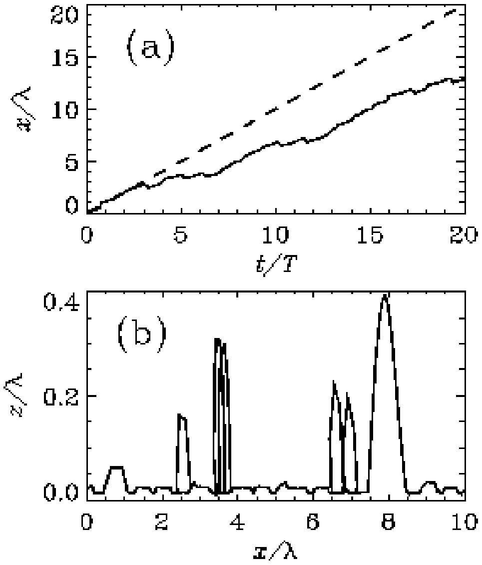

Figure 5. Trajectory of a particle from the numerical experiment in figure 1. Dashed line in (a) is trajectory of synchronous motion. The real space trajectory in (b) does not look smooth because of the relatively long time interval between positions.

Experimentally, we generally observe elements of the motion typical of various transport modes. Toner sticking, toner surface and toner-toner collisions (between toner particles stuck to the grid and incoming toner driven by the wave) are common. As an example of the foregoing discussion, we measure an average velocity for toner on a four phase traveling wave device as seen in figure 6. We see a relationship between toner speed and wave phase velocity for a square wave driving field with the average velocity of the ensemble staying around half of the phase velocity of the driving wave.

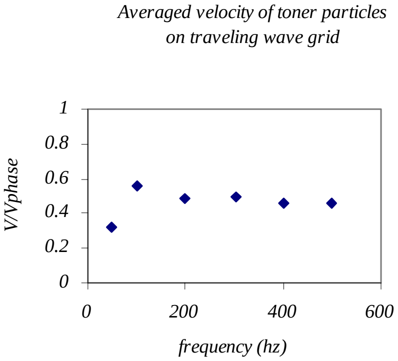

Figure 6 . Average velocity vs frequency for setup in figure 2 with low charged toner.

The average velocity is intermediate and clearly lower than would be observed in a pure “surfing” mode and indicates some type of asynchronous motion. If the velocity distribution of the particles in this flow contained significant numbers of particles moving near the phase velocity of the wave then we would expect a significant number to be in a very slow “curtain mode”, very susceptible to leaving the grid surface. In particular, if this were the case, we expect to see significant amounts of toner escape from the wave when the gravitational force is pointing away from the grid. We have observed stable motion for charged toner moving at less than the phase velocity in cases where the grid is upside down without losing significant amounts of toner, strongly suggesting that many body effects are at work. Studies of toner speed vs frequency in this configuration should provide insight into this issue.

Conclusion

Many–particle effects are an important consideration for particle motion on traveling wave devices. The presence of many charged particles in the wave tends to enhance the ability of the device to confine particles, an important point for applications. The scattering of particles and their correlation to each other lead to steady state flows relatively independent of the initial conditions.

References

1. S. Masuda, Electric Curtain for Confinement and Transport of Charged Aerosol Particles, *Proc. Electrostatic Society of Amer. Albany, NY*, pg. 27. (1971).
2. J. R. Melcher, E.P. Warren, R. H. Kotwal, *IEEE Transactions on Industry Applications*. **25,** 956 (1989).
3. Fred W. Schmidlin, A New Nonlevitated Mode of Traveling Wave Toner Transport, *Proc. IEEE Industry Applications Society Annual Meeting,* pg. 1607. (1988).
4. Fred W. Schmidlin, *Journal of Electrostatics* **34**, 225 (1995).
5. Fred W. Schmidlin, The Role of Traveling Wave Toner Transport in Powder Printing, *Proc. IS&T Eleventh International Congress on Advances in Non-Impact Printing Technologies*, pg. 515. (1995).
6. J. R. Melcher, E.P. Warren, R. H. Kotwal, *Particulate Science and Technology* **7,** 1 (1989) .
7. J. R. Melcher, E.P. Warren, R. H. Kotwal, *IEEE Transactions on Industry Applications* **25**, 949 (1989).
8. Y. Gartstein and J.G. Shaw, *Journal of Physics D: Applied Physics*, **32**, 2176 (1999).
9. Fred W. Schmidlin, *IEEE Transactions on Industry Applications,* **27**, 480 (1991).
10. J G Shaw and A T Retzlaff, *Proc. IS&T 12th Int. Congr. Adv. Non-Impact Print. Technol.,* pg. 283. (1996).

Biography

Michael D. Thompson is a member of the research staff at the Xerox Wilson Center for Research and Technology where he has worked in various areas of xerographic process physics since 1980. He did post doctoral research at Rensselaer Polytechnic Institute after receiving a PhD in Physics from the State University of New York at Albany in 1979. He holds patents in the areas of novel marking processes, MICR, and single and dual component xerographic development.