Traveling Wave Transport of Particles and Particle Size Classification

Hiroyuki Kawamoto▲ and Naoto Hasegawa
Department of Mechanical Engineering, Waseda University, Shinjuku, Tokyo, JAPAN

Experimental research was carried out on transport of particles and particle size classification in a traveling electrostatic field. Particle conveyors which consisted of parallel electrodes were constructed and a four phase traveling electrostatic wave was applied to the electrodes to transport particles on the conveyor. The following points were clarified by the experiment: (1) Particles were transported almost linearly with time. Transport rate was also linear with applied voltage but a threshold existed due to adhesion force. (2) The direction of particle transport did not always coincide with that of the traveling wave but it was in part changed depending on the frequency of the traveling wave, the particle diameter, and the electric field. Motion of particles at low frequency was nearly synchronized with the traveling wave but at medium frequency it was opposite to and slower than the wave. Particles were vibrated but not transported at high field frequency. (3) Particles were efficiently transported under conditions of high electrostatic field with a rectangular waveform. (4) Particles essentially moved along the electric flux line, but electrostatic interaction and particle-particle and particle-conveyor collisions made trajectories complex. (5) Particles were classified according to size under application of voltages of appropriate frequency.

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Introduction

The idea of transporting particles with electrostatic traveling waves was first conceived by Masuda.[1] Since then many investigations have been performed on this technology,[2–12] because utilization of a traveling wave conveyor for particle transport has the advantage that transport can be controlled through electrical parameters instead of mechanical means.[2-4] However, because very few experimental data were reported and the mechanism of the transport is not clear so far, we are conducting a basic research on this technology to utilize it for the transport of toner and carrier particles. As the first step of the investigation, we have conducted a systematic experiment to establish its utility for practical applications and for establishment of a realistic numerical model. In the course of the basic investigation, we discovered that particles were classified with size utilizing this technique, as is also presented in this report.

Experimental

A conveyor and a power supply used for experiments are shown in Fig. 1. The conveyor consists of parallel copper electrodes etched by photolithography on a plastic substrate, 120 mm in width and 250 mm in length, as shown in Fig. 2. The surface of the conveyor is covered with an insulating film made of acetate rayon (3M, 810-18D) to prevent electrical breakdown between electrodes. Four kinds of conveyor were prepared: 0.5 mm width and 1.0 mm pitch (w/p = 0.5/1.0); 0.5 mm width and 1.5 mm pitch (w/p = 0.5/1.5); 1.0 mm width and 1.5 mm pitch (w/p = 1.0/1.5); and 1.0 mm width and 2.0 mm pitch (w/p = 1.0/2.0).

Traveling wave propagation is achieved utilizing four amplifiers (Matsusada Precision Inc, Tokyo, HOPS-1B3) and five function generators (IWATSU, Tokyo, SG-4105), one of which is used to control phase differences of the other four generators. Not only rectangular, as shown in Fig. 1, but also sinusoidal and triangular waves are generated by the function generators to examine the effect of waveform.

Five kinds of spherical carrier particles made by the polymerization method (Toda Kogyo) were used for experiments. Specifications of particles are listed in Table I and photographs are shown in Fig. 3.[13]

Fundamental Characteristics

Transport Rate

Initially, a transport rate was measured by the following steps. First, a cloud of particles (0.5 g) was introduced at a position of 40 mm from the left end of the conveyor, and a rectangular wave of 1.0 Hz was applied to the electrodes. Then the weight of particles which overflowed from the right end of the conveyor was measured by an electronic balance every five seconds. Some examples of experimental results are shown in Fig. 4. The ordinate, a relative weight of transported particles,

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▲ IS&T Fellow

kawa@waseda.jp

TABLE I. Specification of Carrier Particles Used for Experiment

item	unit	ACM318	ACM235	ACM255	ACM288	ACM2107
averaged diameter	μm	18.30	29.70	47.40	72.60	106.30
standard deviation	μm	4.80	5.30	11.80	23.30	13.10
density		3.55	3.50	3.52	3.62	3.50
resistivity (@10 V)	Ωcm	3 ± 10^7	1 ± 10^9	2 ± 10^7	3 ± 10^9	8 ± 10^7

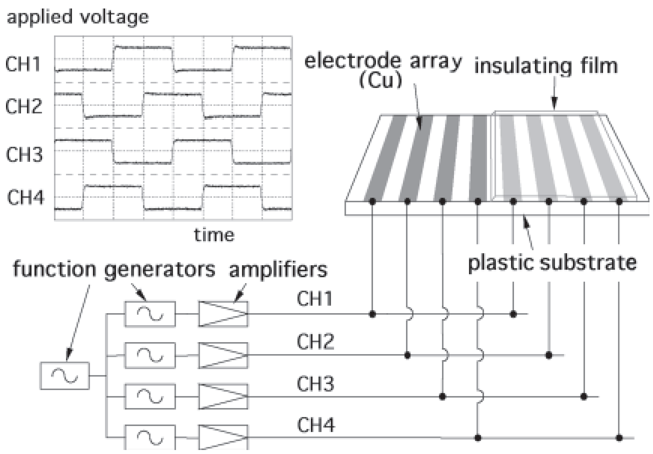


Figure 1. Particle conveyor and power supply.

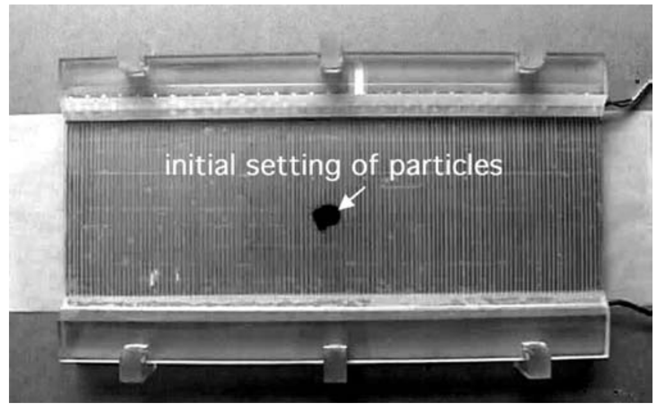


Figure 2. Photograph of particle conveyor.

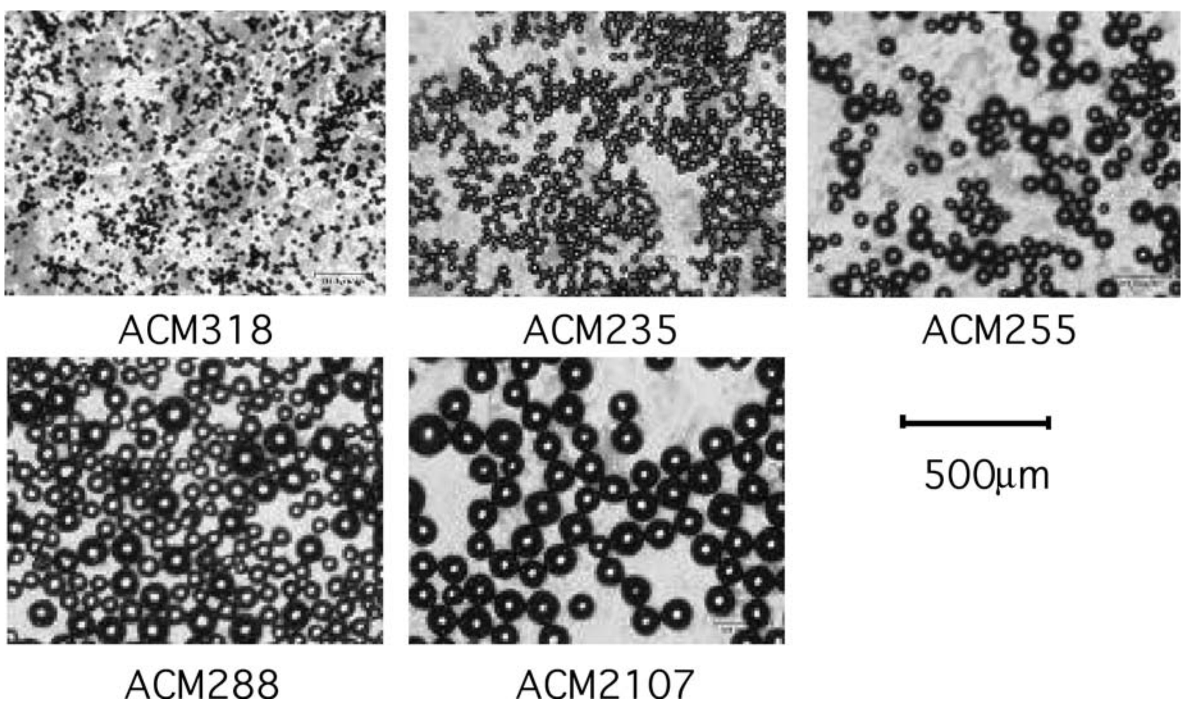


Figure 3. Photograph of carrier particles used for experiment.

is the accumulated weight which overflowed from the edge of the conveyor relative to the initially applied weight. Because some particles adhered to the insulating film on the conveyor and were not transported, the final integral value was less than unity. It is recognized that particles were transported almost linearly with time.

Figure 5 shows applied voltage versus a relative transport rate, measured as time differential of the relative weight of transported particles. The transport rate linearly increased with the applied voltage but a threshold voltage existed. The threshold may be determined by adhesion and the static friction forces between particles and the insulating film.

Transport Direction

At low frequency operation, particles were transported in the direction common to that of the traveling

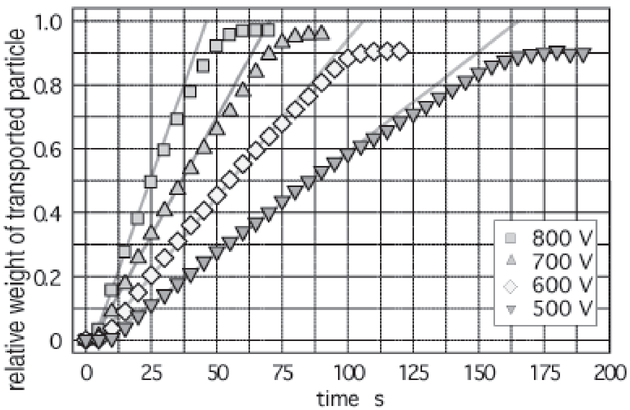


Figure 4. Relative weight of transported particles with time. (ACM 2107, 1 Hz, rectangular wave, w/p = 1.0/2.0)

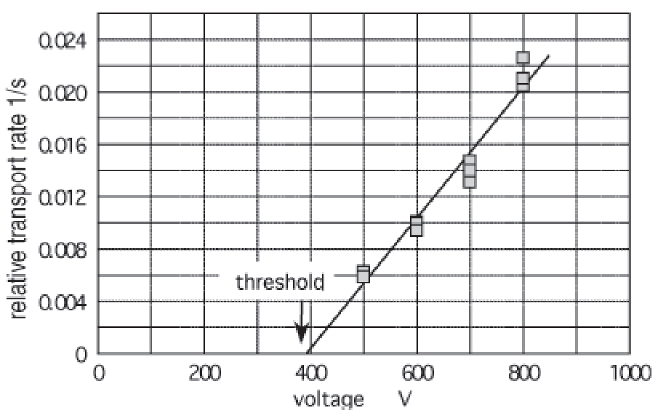
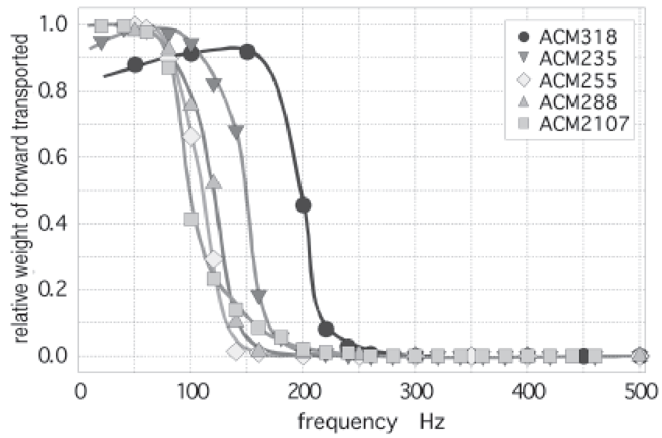
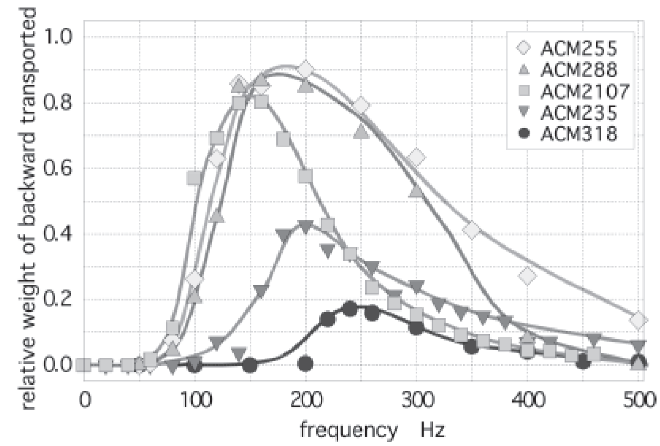


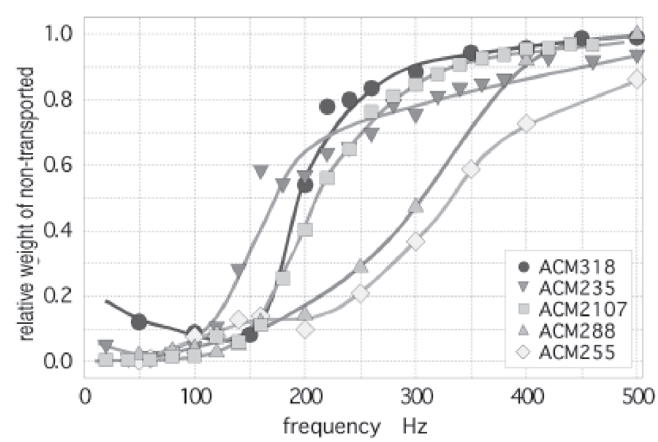
Figure 5. Applied voltage vs. relative transport rate. (ACM2107, 1 Hz, rectangular wave, w/p = 1.0/2.0)



(a) forward



(b) backward



(c) non-transported

Figure 6. Relative weight of forward, backward, and non-transported particles with respect to frequency of traveling wave. (800 V, rectangular wave, w/p = 1.0/2.0)

wave, and the motion was nearly synchronized with the wave speed. However, at high frequency some particles were delayed relative to the wave and some moved in the opposite direction. To examine characteristics associated with the direction of the particle transport, we implemented the following experiments. First, an 0.5 g cloud of particles was introduced at the center of the conveyor and a ±800 V rectangular wave was applied to electrodes (w/p = 1.0/2.0). Then we measured the weight of particles transported forward and backward, as well as those non-transported in 30 seconds, where ‘forward’ is the same direction as that of the traveling wave and ‘backward’ is the opposite direction. The measured relative weights of forward, backward, and non-transported particles at each frequency is summarized in Fig. 6. There are three modes with respect to the transport direction.

(I) *Forward Transport Mode*: Particles were transported forward when the frequency was low, less than 100 – 200 Hz, as shown in Fig. 6. Particle speed was almost synchronized with the wave speed and almost all particles were transported in the forward direction. Small particles were apt to be transported forward even at high frequency. Details on particle motion are described below.

(II) *Backward Transport Mode*: Particles were transported backwards at medium frequency, 100 – 300 Hz, as shown in Fig. 6. Not all particles were transported backwards; some particles stayed on the conveyor. Details on the particle motion in this region are also described below.

(III) *Non-Transported Mode*: Particles were not transported at high frequency, more than 300 Hz, as shown in Fig. 6, but vibrated on the conveyor and only diffused around the initial point of introduction. Very large particles, e.g., ACM2107, were

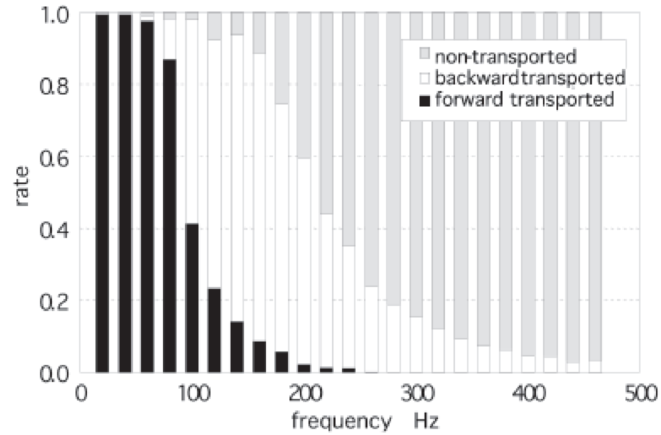


Figure 7. Rates of forward, backward, and non-transported particles with respect to frequency of traveling wave. (ACM2107, 800 V, rectangular wave, w/p = 1.0/2.0)

generally not transported. The non-transport of very small particles, ACM318 and ACM235, was significant, because relative adhesion force to the film on the conveyor was large for small particles and they stayed on the conveyor even at relatively low frequency.

Figure 7 illustrates relative rates of three modes of one kind of particle, 1. Summation of the three rates is unity. It is clearly recognized that particles were transported forward at low frequency, but some particles moved backward and some were not transported at medium frequency, and almost all particles were not transported at high frequency.

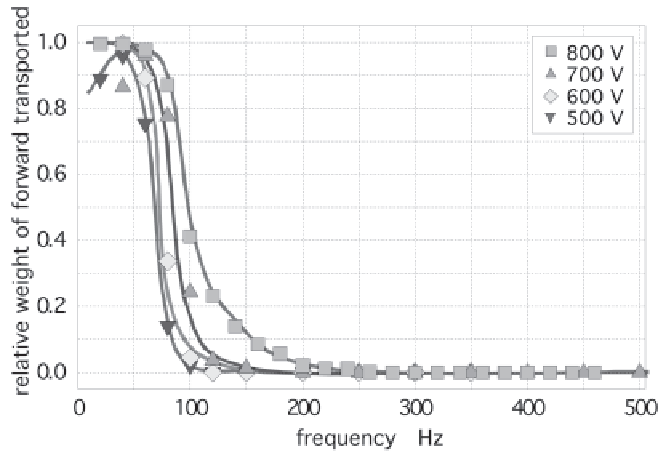
Similar experiments were conducted with the parameter of applied voltage. The result is shown in Fig. 8. Because the Coulomb force to particles was large in the high electrostatic field, particle motion was synchronized with the electrostatic wave and transported forward even at high frequency. Therefore, high voltage operation is preferable for efficient transport, although it is restricted by the insulation breakdown between electrodes. Threshold voltage of our conveyor (w/p = 1.0/2.0) was 800 V.

Figure 9 shows the effect of waveform. Three kinds of waveform, rectangular, sinusoidal, and triangular, were tested with a common peak voltage (not rms), because maximum voltage is determined by its peak value due to electrical breakdown. It is obvious that the rectangular wave is most effective. This implies that the transport of bulk particles is not determined by the peak but rather the rms field strength, because it takes a finite time to hop, synchronized with the wave.

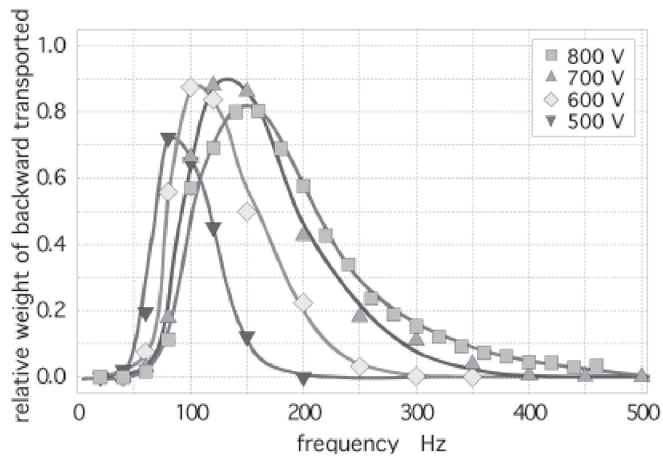
Lastly, effect of the electrode dimensions was investigated. The result is shown in Fig. 10. The applied voltage was decreased to 600 V, which was the limit against insulation breakdown for conveyors with short spacing, w/p = 1.0/1.5 and w/p = 0.5/1.0. Because the particle diameter was very small compared to the electrode dimensions and the electrostatic field is maximum when $p = 2w$, a thin electrode with the common space length and width was preferable.

Particle Trajectories

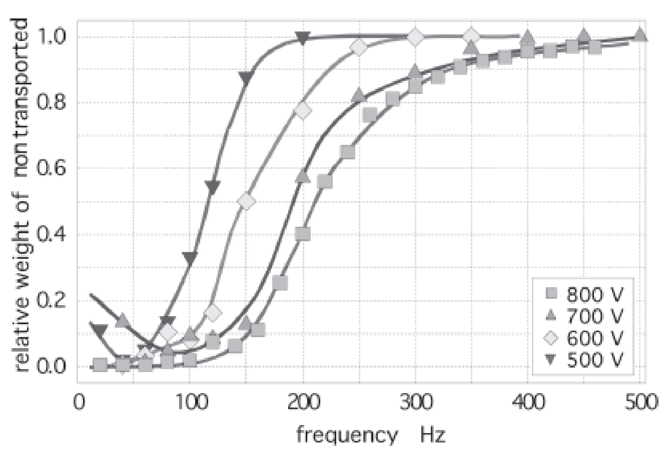
Particle trajectories during transport were measured by a high speed microscope camera ((Red Lake MASD, San Diego, CA, Motion-Meter 1140-0003). Figure 11



(a) forward



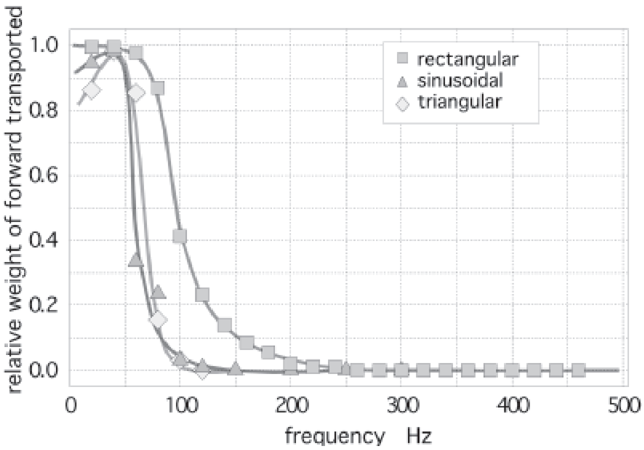
(b) backward



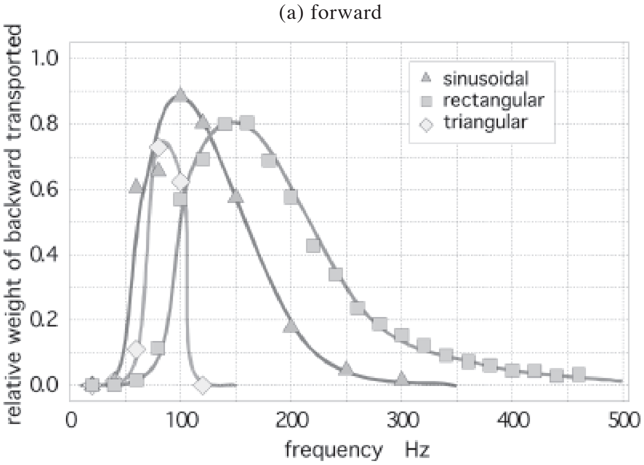
(c) non-transported

Figure 8. Relative weights of forward, backward, and non-transported particles with respect to frequency of traveling wave. (ACM2107, rectangular wave, w/p = 1.0/2.0)

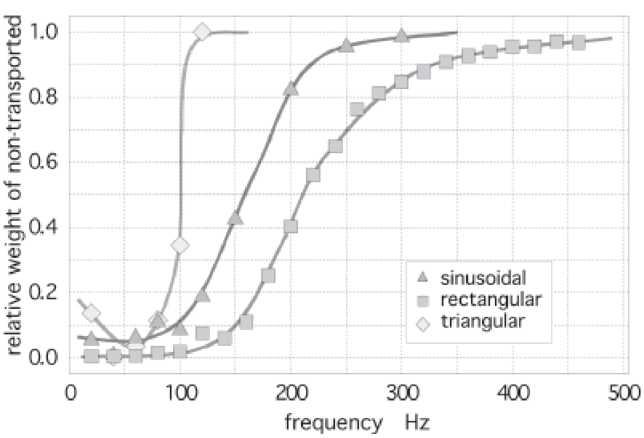
shows horizontal trajectories of randomly selected particles observed from the upper side of the conveyor. The origin of time is not the start of operation but several seconds after the transport became steady. It is clearly recognized that (1) at low frequency, particles were transported in the forward direction almost synchronized with the speed of the traveling wave, but at very low frequency, some particles moved ahead to the wave,



(a) forward

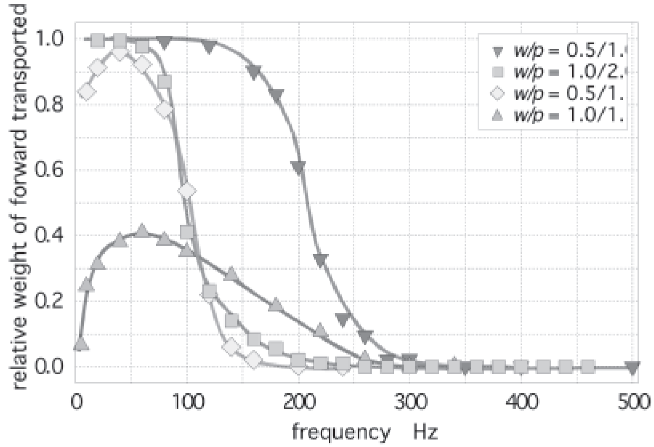


(b) backward

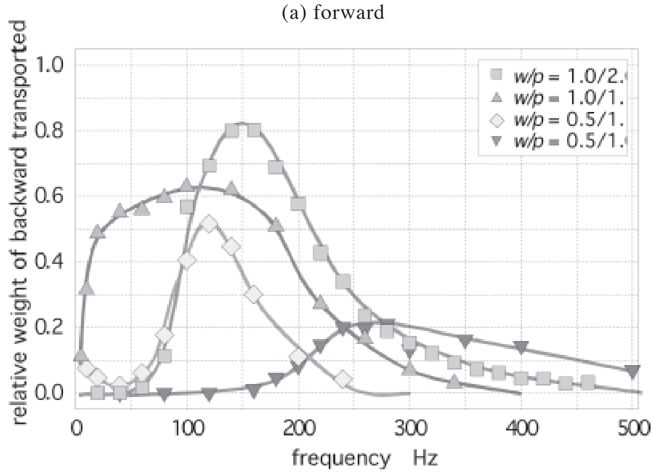


(c) non-transported

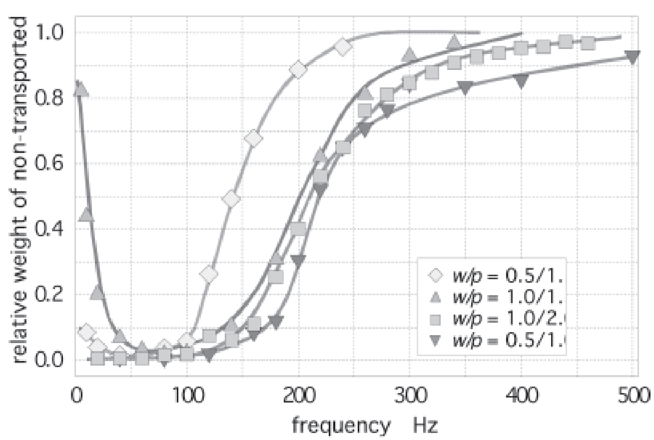
Figure 9. Relative weights of forward, backward, and non-transported particles with respect to frequency of traveling wave. (ACM2107, 800 V, w/p = 1.0/2.0)



(a) forward



(b) backward



(c) non-transported

Figure 10. Relative weights of forward, backward, and non-transported particles with respect to frequency of traveling wave. (ACM2107, 600 V, rectangular wave)

(2) that some particles were delayed with respect to the wave and some were transported backward at medium frequencies, and (3) that at high frequencies, almost all of particles moved very slow backward.

Vertical trajectories were also observed from the side of the conveyor. Particles seemed to move essentially along the electric flux line as shown in Fig. 12, that is, a so-called "hopping mode"[6] was predominant. However, mechanical and electrostatic particle-particle and particle-conveyor collisions make trajectories complex. Although some typical modes of motion of particles, such as surfing mode, curtain mode, and hopping mode have been presented, based mainly on a theoretical single-particle model,[6] the actual motion is not simple. For

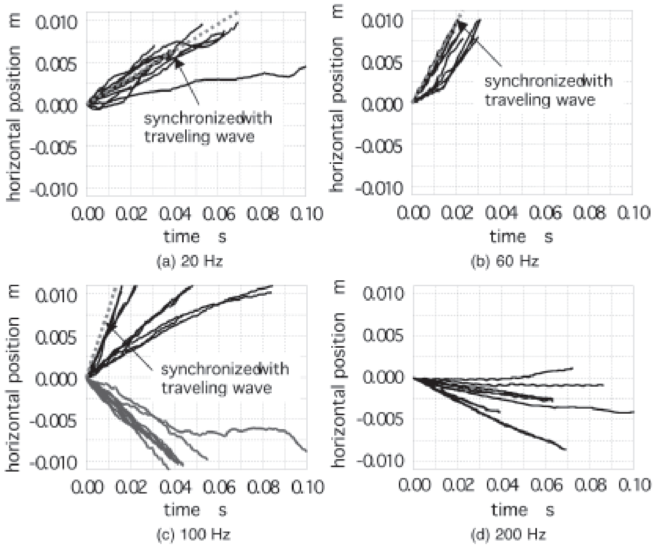


Figure 11. Horizontal trajectories of particles. (ACM2107, 800 V, rectangular, w/p = 1.0/2.0)

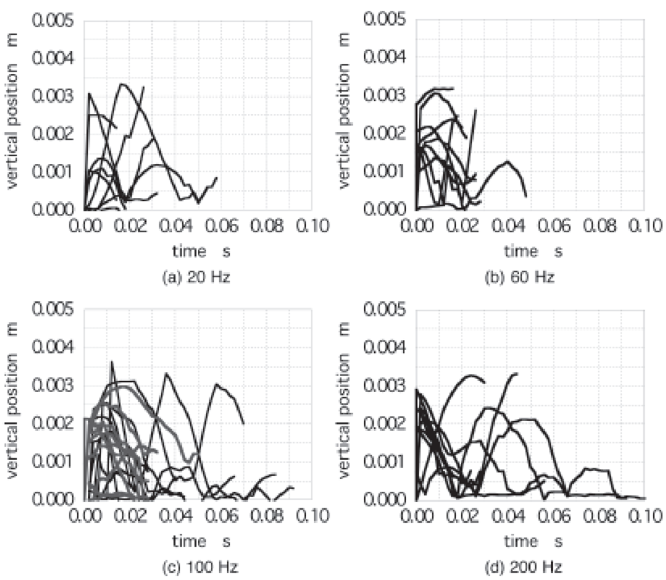


Figure 12. Vertical trajectories of particles. (ACM2107, 800 V, rectangular, w/p = 1.0/2.0)

example, motion of particles is not identical, rather, we observed a complex combination of modes. Single particle models cannot simulate this experimental result. Although simplified models are useful for intrinsic understanding of the full system, an additional advanced model is necessary to understand the system more accurately and to simulate performance for practical uses. Present experimental results will be utilized to establish a more realistic multi-particle model.

Particle Classification

An interesting finding of the experiment was that the transition frequency from forward to the backward transport region depended on the particle size, i.e., although small particles were transported to the forward direction even at relatively high frequencies, large particles delayed and moved backwards even at lower frequencies. This feature suggested that particles could be classified size by application of according to traveling wave of an appropriate frequency. Figure 13 shows the measured relative weight of forward transported small particle ACM235 and the large particle ACM2107. The results indicated that the relative weight of forward transported particles depended not only on the wave frequency but also on the particle diameter, that is, at an appropriate frequency small particles may be transported forward but large particles may be transported backward. To confirm this hypothesis we prepared a mixture of mixed particles of ACM235 and ACM2107, in equal number. Under conditions of the optimum frequency, 140 Hz in this case, significant classification was realized as shown in Fig. 14. We can also confirm the classification by the photograph shown in Fig. 15. Figure 16 shows additional evidence of particle classification, with particle ACM288 whose diameter was distributed over a wide range (refer to Table I).

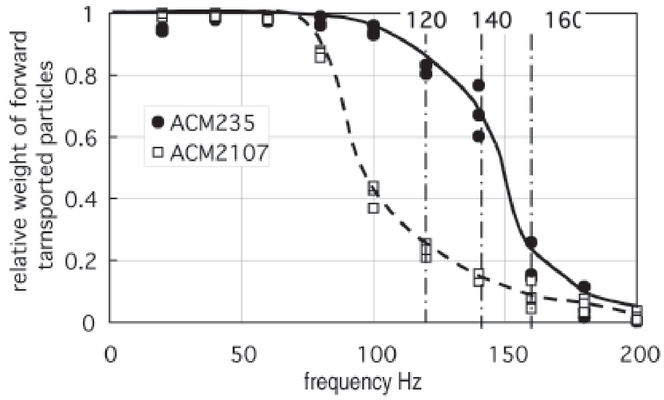


Figure 13. Relative weight of forward transported particles with respect to frequency of traveling wave. (800 V, rectangular wave, w/p = 1.0/2.0)

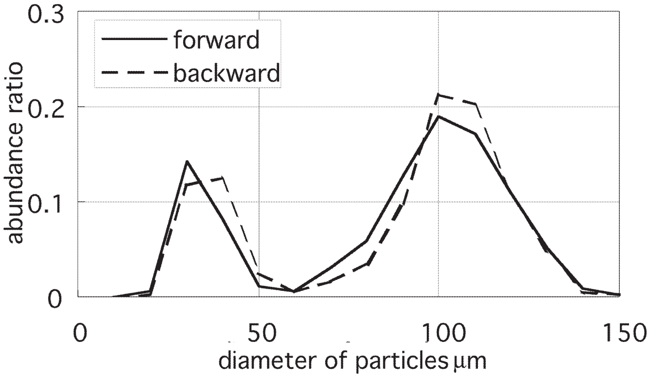
Concluding Remarks

Basic research was carried out on transport of particles and particle size classification in a traveling periodic electrostatic field. The following points were inferred from the investigation.

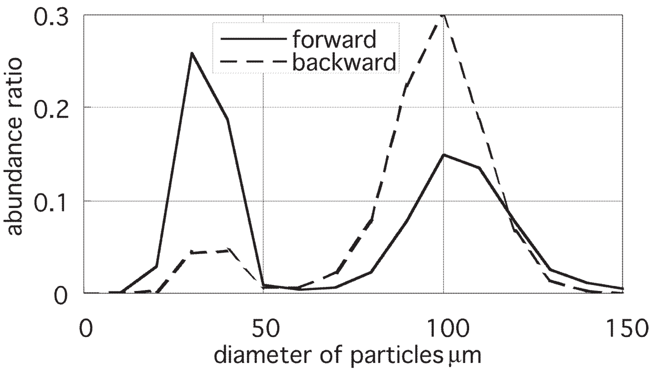
(1) Particles were transported almost linearly with time. A transport rate was also linear with applied voltage, but a threshold existed due to adhesion force. Effective transport was achieved under application of effective high electrostatic field.

(2) The transport directions were categorized as relatively forward, backward, and non-transported. At low frequencies, particles were transported in the direction of the traveling wave propagation (forward direction) but at relatively high frequencies the number of particles transported backward increased. Motion of forward moving particles was nearly synchronized with the traveling wave, but motion of backward moving particles was slower than the wave. Particles were not transported but only vibrated at higher frequencies, herein a limitation for transport existed.

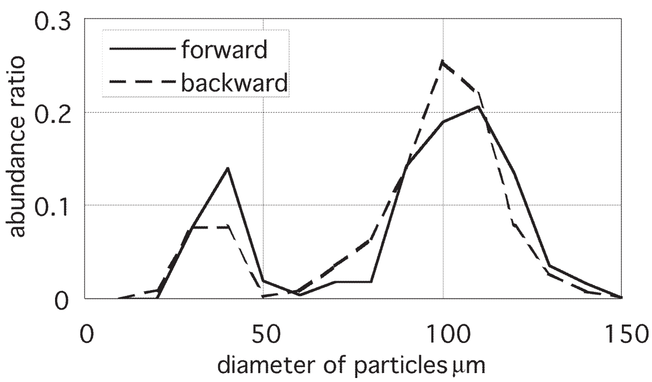
(3) Particles moved essentially through the electric flux line but electrostatic interactions and particle-par-



(a) 120 Hz



(b) 140 Hz



(c) 160 Hz

Figure 14. Distributions of particle diameter in forward and backward transported particles. (ACM235 + ACM2107 mixed particles, 800 V, rectangular wave, w/p = 1.0/2.0)

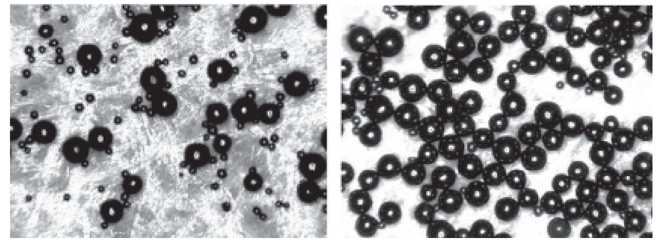


Figure 15. Photographs of forward and backward transported particles. (ACM235+ACM2107 mixed particles, 800 V, 140 Hz, rectangular wave, w/p = 1.0/2.0)

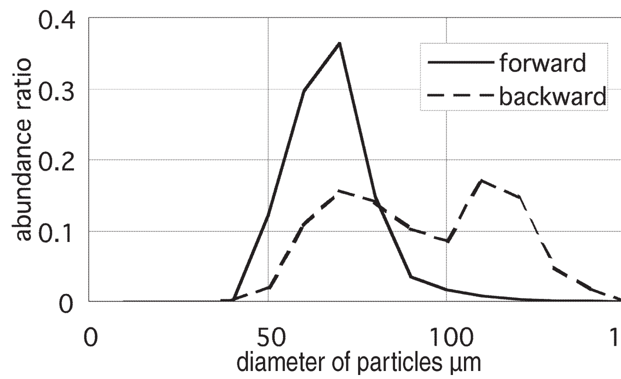


Figure 16. Distributions of particle diameter in forward and backward transported particles. (ACM288, 800 V, 140 Hz, rectangular wave, w/p = 1.0/2.0)

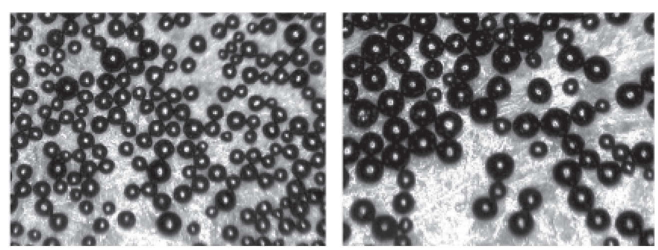


Figure 17. Photographs of forward and backward transported particles. (ACM 288, 800 V, 140 Hz, rectangular waver, w/p = 1.0/2.0)

ticle and particle-conveyor collisions make trajectories complex. The motion of particles are not identical but a complex contribution of some modes at any frequency.

(4) Utilizing the difference of the critical frequency with respect to the particle size, we demonstrated particle classification with size.

A multi-particle numerical model is being constructed based on the present experimental observation and will be reported in a separate article.

Acknowledgment

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