conveyance velocity in direct proportion to the electric field's low frequency and the electrode gap. A multi-channel, PC-controlled, high voltage supply is conjoined to the panel, where every sixth electrode belongs to the same phase state: *a*, *b*, *c*, *d*, *e*, or *f*.

The conveyance principle is incorporated in the structure of the *electric panel*, as shown in Fig. 1.

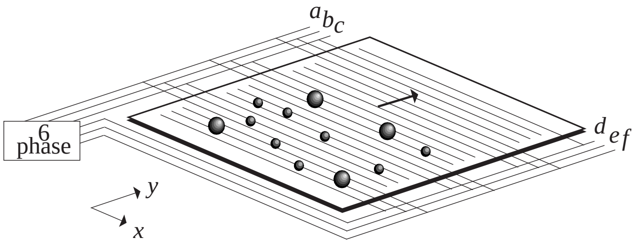

Fig. 1. Simplified perspective of the *electric panel* device.

The supply sequence of the voltage source to the electrode attachments is given in Table I. Considering balanced square profile voltages, the sequence is written with [+], [0], and [-] for a three- and a six-phase supply representing the 3 voltage states. The six-phase case requires all of the 6 attachments, whereas in the three-phase case, *a* and *d*, *b* and *e*, *c* and *f* are connected together to the supply. Particle transportation occurs with the variation of the sequence, i.e. the particle synchronously moves with one phase. As a consequence, within one six-phase period, the particle is conveyed along a distance double that of one three-phase period. The three-phase sequence of Table I will be named as square #1 later in this paper.

TABLE I

6 ELECTRODE ATTACHMENTS A, B, C, D, E, AND F AND THEIR SUPPLY FROM A MULTI-PHASE VOLTAGE SOURCE

Sequence ↓

a	*b*	*c*	*d*	*e*	*f*
+	-	0	+	-	0
+	0	-	+	0	-
0	+	-	0	+	-
-	+	0	-	+	0
-	0	+	-	0	+
0	-	+	0	-	+

Supply sequence of three-phase square profile voltages

a	*b*	*c*	*d*	*e*	*f*
+	+	0	-	-	0
0	+	+	0	-	-
-	0	+	+	0	-
-	-	0	+	+	0
0	-	-	0	+	+
+	0	-	-	0	+

Supply sequence of six-phase square profile voltages

Two types of balanced high voltage profiles are utilized: sine and square waves, each having a different effect on the particle conveyance dynamics.

Three structurally novel devices were developed: the ***electric panel***, the ***electric tube*** and the ***electric dots***. Each incorporates the same principle for particle handling, but serves a different purpose.

III. ELECTRIC PANEL DEVICES

A. Structures

As shown in Fig. 2, the device is composed of parallel electrodes encased in epoxy resin, an insulating thin cover-film, a supporting panel, and electrode-attachments to the power supply.

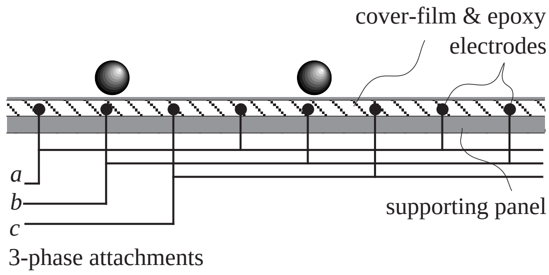

Fig. 2. Basic structure of the *electric panel* with three-phase electrode attachments.

The parallel electrodes have an average center-to-center pitch length of 400 µm, a diameter of 50 µm and are situated parallel to the surface at a distance of 25 µm to 75 µm. The *electric panel* represents the most compliant device. Due to the simple electrode design, the *panel* can be fabricated with various features as outlined in Fig. 3 and Fig. 4:

Fig. 3 shows the perspective of a modified *electric panel*. The two electrode-attachments *a* and *b*, which correspond to their phases *a* and *b*, are inversed in one half-plane. By this *phase inversion technique*, particles can be gathered in the area of the central electrode, or dispersed to the two peripheral electrodes when applying a reversed voltage profile sequence. By changing the attachments of electrodes *a* and *b* to a non-inversed configuration, the particles can be conveyed in one dimension across the entire surface.

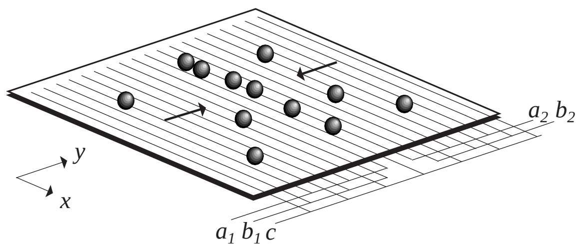

Fig. 3. *Electric panel* for bi-directional particle transportation in *y*-direction and grouping along central or peripheral lines.

An approach to achieving two-dimensional particle handling is shown in Fig. 4. A second electrode layer perpendicular to the first can be added. Alternatively, a mesh interweaving the two layers can be employed as shown in Fig. 5. In order to endure the high voltage differences at the nodal points, individual mesh-electrodes must be covered with a sufficient insulation such as polyamide-imide. By applying the *phase inversion technique* now in both directions, particles can be selectively accumulated into 9 different locations and along 6 different lines as well as conveyed two-dimensionally over the entire surface.

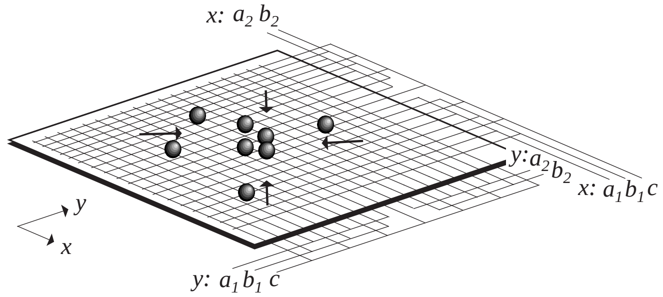

Fig. 4. *Electric panel* for *x-y* particle handling and grouping in central and peripheral areas.

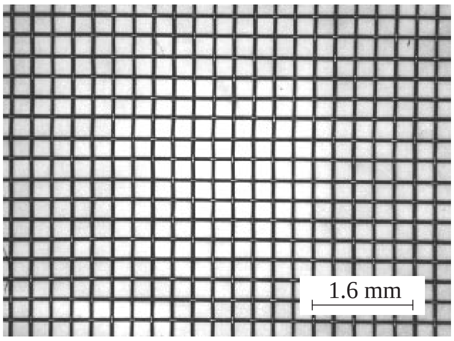

Fig. 5. Mesh incorporated in the *x-y- electric panel* consisting of insulated wires in each direction.

B. Particles

Particles involved in the experiments were in the 5 µm to 400 µm diameter range, held diverse moisture contents, and had different shapes and size distributions. Representative samples utilized in the experiments are shown in Fig. 6.

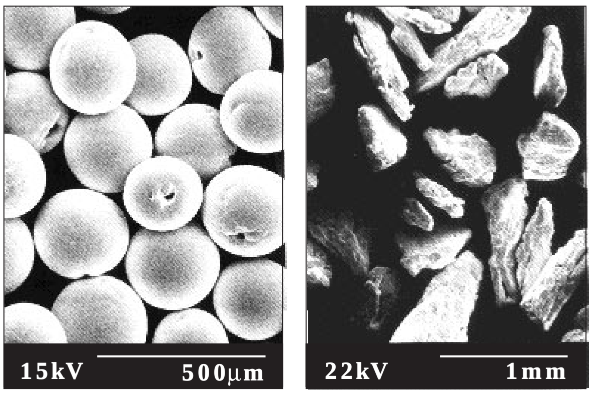

Fig. 6. A Scanning Electron Microscope image of representative *Al*- and *Fe*-particles.

Aluminum, various metals, glass, and plastic spherical particles were the most promising in a series of conveyance tests conducted on the *electric panel*. A selection of 70 different types of substances have been examined, and about half of the tested particle substances showed an acceptable frequency dependent transportation behavior. The applied sine profile three-phase voltage was approximately 1 kV_{ptp} and the frequency varied from 1 Hz to 50 Hz. Raising the frequency higher than the 100 to 200 Hz range caused the particle movement to cease with this configuration.

It has been observed that spherical particles smaller in diameter than the pitch-length were suitable for conveyance in most of the experiments. However, in cases where the particle shape has sharp edges, it is believed that the charge distribution is most concentrated at the edge, thus disturbing and distorting the conveyance process. A study of the charge distribution on the particle surface and its impact on particle conveyance dynamics remains for future research. For the following experiments, we focused on the usage of spherical and metallic particles, even though glass and plastic spheres showed good performances as well.

C. Experimental Environment

The dynamic forces of the electric field acting on particles have been tested by the *electric panel* in various environments such as air, vacuum, and dielectric liquids. In atmospheric conditions, several problems must be taken into account and solved due to the ever present humidity. This leads to increased adhesive forces, causing particles to stick to the surface. Furthermore, the generated electric forces decreased considerably in a vacuum environment; the cause has to be investigated more closely. Good results, which are presented later in this paper, could be obtained for particles being handled in dielectric liquids.

D. Conveyance Characteristic & Improvements

Some experimental results in particle handling reveal improvements in conveyance smoothing on the *electric panel*. For normal particle transportation, a simple set of parallel electrodes is sufficient, but the produced conveyance shows a high sidewise fluctuating behavior. The cause of this disturbance is believed to lie in the unequal gaps between the electrodes and inaccuracies originating from the fabrication process which result in a non-uniform field. A further explanation can be found by considering the presence of a non-uniform charge distribution on the particle surface which imposes a torque on the particle itself. In the low frequency range, the voltage profile also has an impact on the transportation performance, as verified experimentally.

The goal to smoothen and improve particle conveyance dynamics on the *electric panel* can be solved by a simple method: A series of parallel electrodes is incorporated below and perpendicular to the already existing layer or simply, a mesh with insulated wires is embodied into the device. The newly added layer is then supplied by a *constant* voltage.

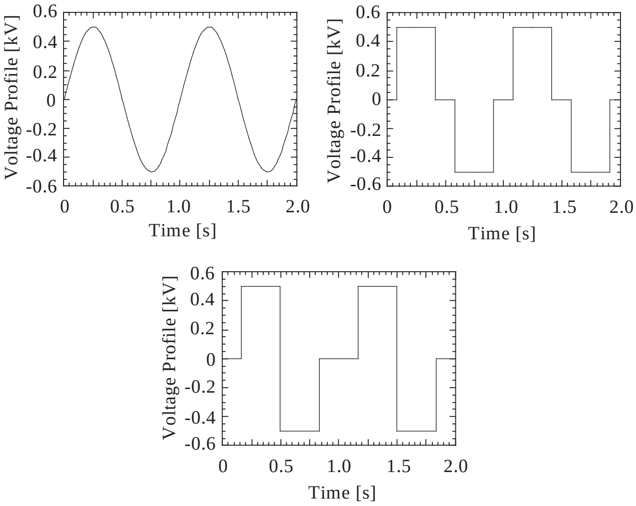

Fig. 7. *Fe*-particle conveyance behavior test employs 3 different voltage wave-profiles: sine, square #1 and square #2; here, one of the three engaged phases is shown.

The ac supplied layer works as the particle conveyor, whereas the dc supplied layer constrains the particles to track on the activated electrode. Therefore, this method is referred to as *tracked particle conveyance.*

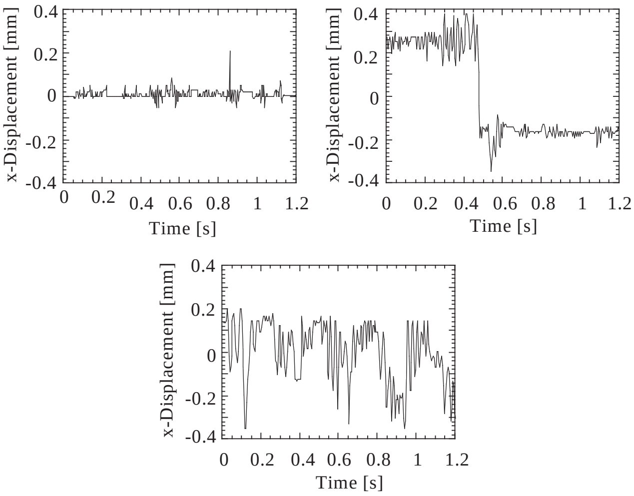

Fig. 8. Tracked particle conveyance monitored in *x* -direction for each of the three voltage profiles with 1 kV_{ptp} at 2.5 Hz.

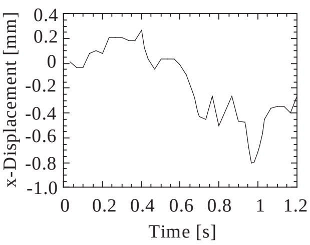

Fig. 9. Untracked and high fluctuating particle conveyance monitored in *x* -direction for sine profile with 1 kV_{ptp} at 2.5 Hz.

Under the condition of three-phase supply, three different voltage wave profiles as shown in Fig. 7, with a voltage of 1 kV_{ptp} and frequency of 2.5 Hz, were applied to the *electric panel* to study its influence on particle conveyance. *Fe*-particles of 250 μm diameter were monitored by a high speed camera at a recording-frequency of 4.5 kHz over a time span of 1.2 s and a distance of 5 mm. The resulting conveyor characteristics in the *y*-direction are shown in Fig. 8 for tracked and in Fig. 9 for normal, untracked particle conveyance. The high fluctuation of the normal conveyance is clearly visible in Fig. 9. Among the tracked conveyance characteristics in Fig. 8, the particles driven by a sine profile show a smooth and low-fluctuating behavior. For the square profiles, which result in high particle acceleration between the gaps, the tracking method maintains the sidewise fluctuation within a well defined range which is dictated by the pitch of the tracking electrodes. It should be noted that the profile of square #1 with an additional step produces a visibly smoother conveyance than that of square #2.

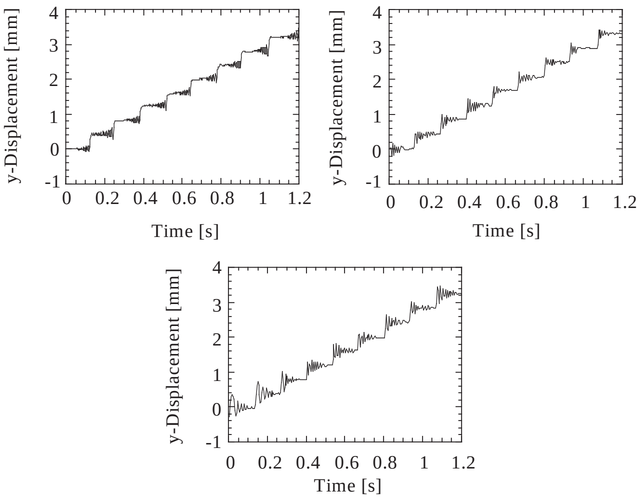

Fig. 10. Tracked and stepwise particle conveyance monitored in *y*-direction for each of the three profiles with 1 kV_{ptp} at 2.5 Hz.

The stepwise transportation from electrode to electrode is clearly shown in Fig. 10 for the three voltage profiles. On comparing the monitored stepwise conveyance of the sine and the two square profiles, it is clear that the reversed oscillation response is the outcome of different accelerations. It will be interesting to employ custom wave-profiles incorporating only the favorable elements of the produced transportation characteristics for future experiments.

Good results could be obtained for a *Fe*-particle being handled in dielectric liquid. The conveyance behavior shows an increased damping, compared to the previous atmospheric condition. Fig. 11 and Fig. 12 present the traces of a 250 μm in diameter *Fe*-particle, which was monitored by a high speed camera at a recording-frequency of 4.5 kHz over a time span of 1 s and a distance of 5 mm. A six-phase square profile with

1.4 kV_{ptp} at 2 Hz was applied. The traced particle conveyance over the surface is shown in Fig. 11 for tracked conveyance, and as a function of time in *x*- and *y*-components in Fig. 12.

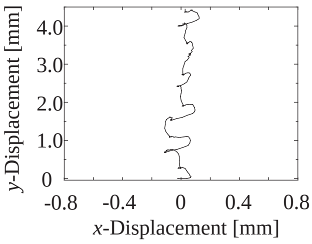

Fig. 11. Tracked particle conveyance monitored in dielectric liquid.

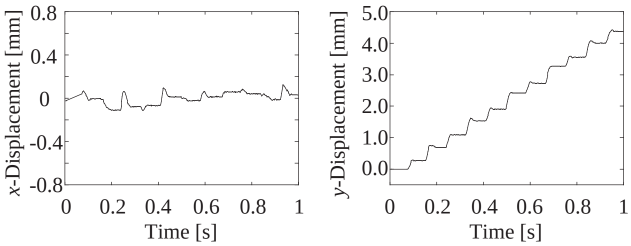

Fig. 12. Tracked particle conveyance monitored as a function of time in *x*- and *y*-direction.

E. Particle Handling

Fig. 13 shows the results of using the *electric panel* for particle accumulation. The *phase inversion technique* allows a group of particles to be gathered at the upper right corner, arranged in the center of the upper line and finally separated into the left and right corner. This technique also yields an assembly of particles along a desired line in central or peripheral areas.

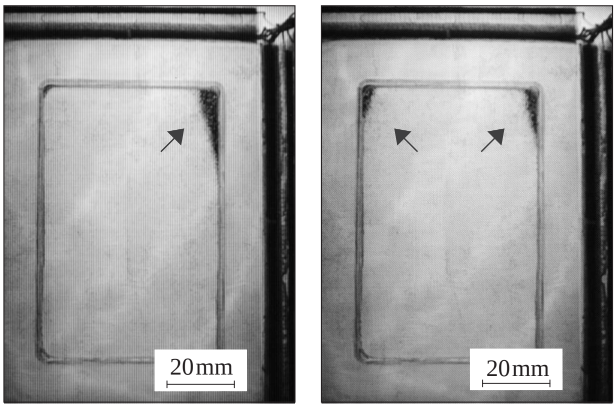

Fig. 13. *Electric panel* with incorporated *phase inversion technique* allowing two-dimensional particle handling and accumulation.

Furthermore, it has been observed that a three-phase voltage supplied to the electrodes shows less force generation on the particles than a six-phase voltage. An increase in phases strengthens and also improves the particle conveyance characteristics necessary for fine manipulation. However, the additional phases make the whole device more complicated to fabricate.

The total area for the activated electrodes is larger for a six-phase supply than a three-phase supply. This phenomena can be observed directly in Fig. 14. Groups of particles are concentrated in the active areas and conveyed in the *x*-*y*-direction forming a gap of the same width as the active area. The particles appear grouped in a checker board pattern.

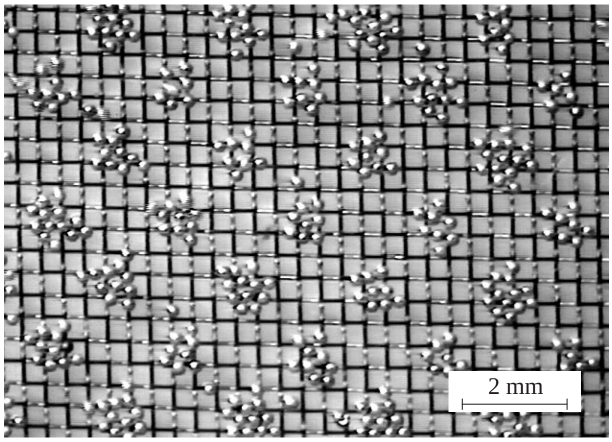

Fig. 14. Groupwise conveyance of *Fe*-particles in *x*-*y* direction for a six-phase voltage supply.

One further advantage of the *electric panel* is that particles can be packed in a single layer and evenly arranged at any surface location. This interesting occurrence has currently only been examined and observed with larger sized particles in the diameter range of over 100 µm. The actual limitations and its causes must be examined more closely.

IV. Additional Devices

A. Electric Tube Device

Fig. 15 depicts a tube shaped device, which is named the *electric tube*.

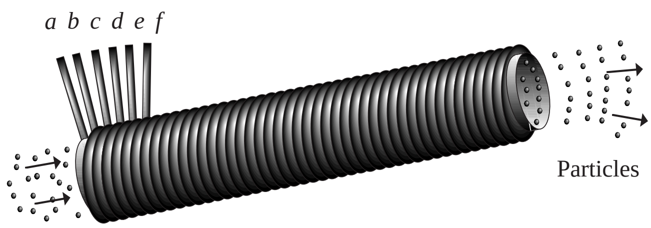

Fig. 15. Perspective of the *electric tube* device.

It embodies the same principle as the *electric panel*, but is made of a single layer of spooled electrodes with a defined and constant gap-width and a typical electrode center-to-center pitch length of 256 µm. The inner diameter is 5 mm.

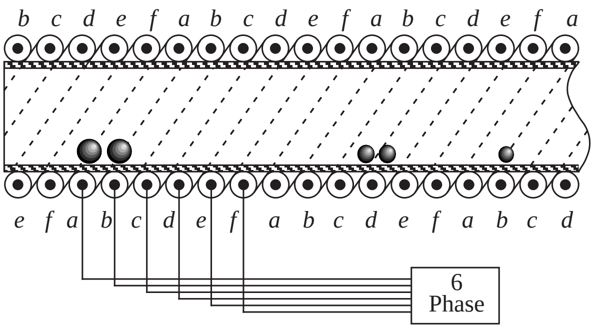

Fig. 16. Cross-section of the *electric tube* illustrating its numerous attachments for a six-phase voltage supply.

This *electric tube* is meant for particle mass transportation taking an inherent advantage of utilizing multiple electrode attachments, such as in Table I. Particles can be transported due to their particular physical properties, whenever a multi-channel, PC-controlled, power-supply is used and a voltage phase sequence to activate desired electrode combinations is sent to the device.

Preparatory results have been obtained for particle transportation under direct influence of gravitational forces in an *electric tube* which has been positioned vertically. The goal is to use a long *tube* in order to transport particles from one location to another.

B. Electric Dots Device

Fig. 17 illustrates the concept of the *electric dots* device.

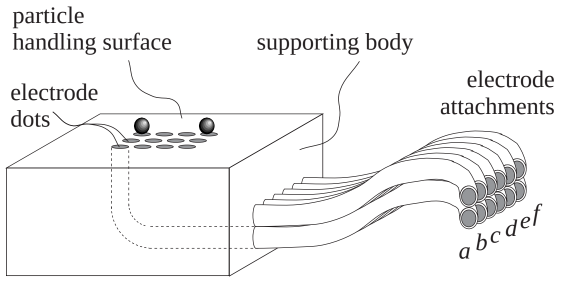

Fig. 17. Perspective of the *electric dots* device.

The manipulation electrodes appear as a matrix of dots in the handling surface. The device incorporates a bundle of insulated conductive wires, embedded in a supporting body. The surface has been ground in a plane normal to the wires to form the handling surface which is subsequently covered by a thin film. The particles are manipulated on the film-surface along the dot electrodes. The dots have a center-to-center pitch length of 400 μm and a diameter of 50 μm.

Particles are handled precisely from dot to dot, as shown in Fig. 18 for a *Fe*-particle. By increasing the applied voltage amplitude, the conveyed particles form groups on the dots. The main drawback is the existence of electrostatics on the non-activated, surrounding surface which also attracts the particles. In a more refined version of the *electric dots* device, two thin aluminum film-strips have been attached to the surrounding surface in order to eliminate the electrostatic disturbance. The surface of the latest device is shown in Fig. 19. The outer two rows of electrode dots are kept on dc and the inner two rows on ac level in the following particle manipulation experiment.

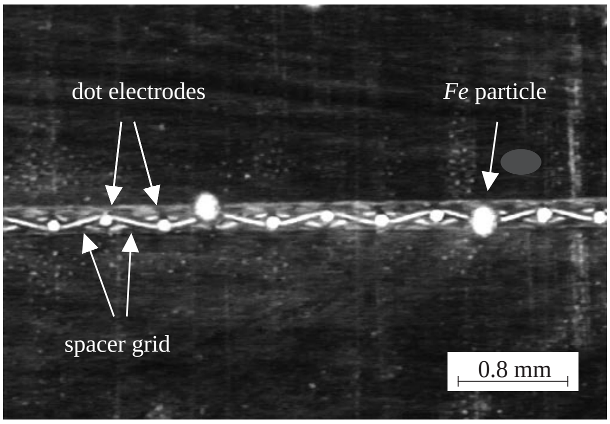

Fig. 18. Conveyance of two *Fe*-particles along a row of electrode dots.

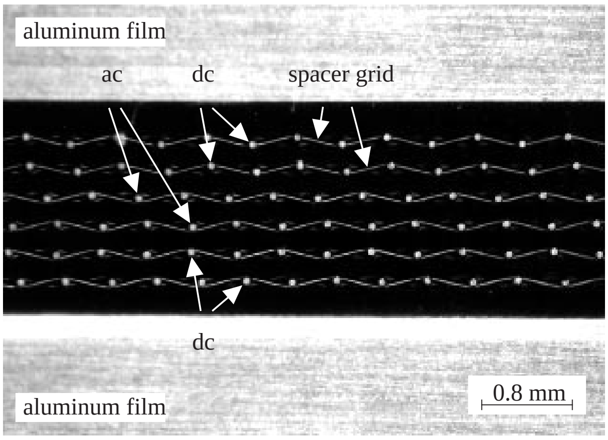

Fig. 19. Surface of the *electric dots* device showing 6 rows of electrode dots and the spacer-grid. The surrounding is covered by a thin aluminum film.

Fig. 20-23 present the traces of a 250 μm diameter *Fe*-particle, which was monitored by a high speed camera at a recording-frequency of 2.25 kHz for three-phase and at 4.5 kHz for six-phase supply over a time span of 1 s and a distance of 4 mm. The square profile voltages were supplied with 1 kV_{ptp} and at a frequency of 2 Hz. The direct particle conveyance along the 2 inner rows of electrode dots is shown in Fig. 20 and in Fig. 22. The graphs of Fig. 21 and Fig. 23 depict the particle motion time-dependent in *x*- and *y*-components. The oscillation response strength of the three-phase case is less than that of the six-phase case which is visible from the different oscillation pattern. The particle is conveyed more forcefully by six-phase than by three-phase voltages.

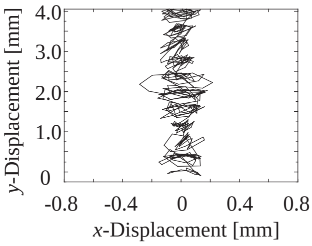

Fig. 20. Trace of particle conveyance along two rows of electrode dots. Three-phase voltages with 1 kVptp and at 2 Hz were supplied.

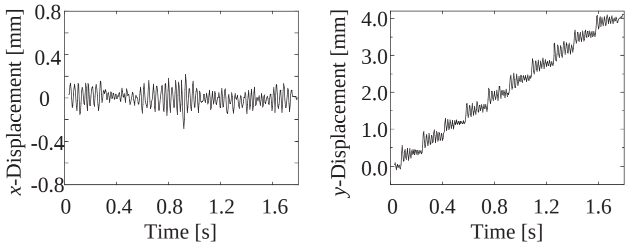

Fig. 21. Particle conveyance monitored as a function of time in *x*- and *y*-direction for the three-phase case.

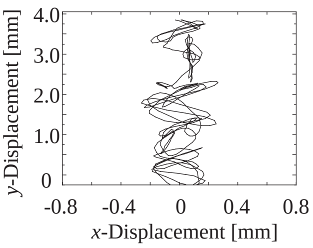

Fig. 22. Trace of particle conveyance along two rows of electrode dots. Six-phase voltages with 1 kVptp and at 2 Hz were supplied.

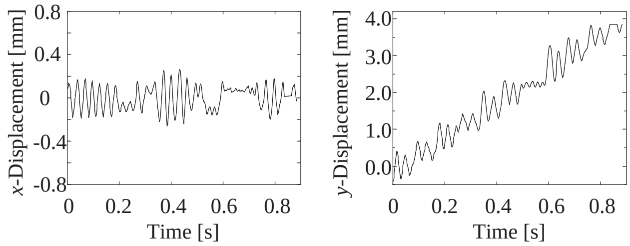

Fig. 23. Particle conveyance monitored as a function of time in *x*- and *y*-direction for the six-phase case.

V. Conclusion & Future Prospects

Three devices for particle handling by an ac electric field have been proposed and experimentally validated. The *electric panel* enables two-dimensional tracked manipulation which includes particle spot- and line-accumulation, conveyance in particle groups and sorting. Experimental results show the difference between untracked and tracked transportation and also the influence of the applied three-phase sine and square voltage profiles. Furthermore, a *Fe*-particle driven by six-phase has been traced in dielectric liquid, as an example of non-atmospheric environment.

The advantages and drawbacks of three- and six-phase voltages have been discussed. By its guiding shape, the *electric tube* serves as a particle sorting and mass transportation system. The *electric dots* device targets single particles to be conveyed along a row of electrode dots. The particle-manipulation on the *electric-dots*-device-surface has been trailed for both, three- and six-phase square profile voltages.

Since no moving machine parts are involved, the forces of the electric field can reduce overall energy consumption.

The devices developed can also serve as a parts feeder and manipulator for MEMS. The compact size and simple design of the devices will allow further down-scaling.

Future experiments using more sophisticated devices will be based on the developed handling principle to perform improved particle sorting, e.g. devices as the *electric panel* and *tube* will include linearly increased gap lengths to sort particles in groups of different sizes, size distributions, charges and moisture contents under additional influence of gravitational and centrifugal forces.

Future plans include refining the device structures, and conveyance improvements by using uniquely designed voltage profiles. Furthermore, experiments in a wider range of environments, with special emphasis on vacuum and solutions, will be conducted.

Acknowledgment

We wish to acknowledge the appreciated and valuable collaboration of our colleagues S. Yashiro and A. Fujita for their engagement in the mesh-electrodes and *electric tubes*, S. Egawa and T. Niino for their expertise on voltage supply systems, J. Jin and S.J. Woo for prolific discussions, and W. Yang for his contributory involvement in this project. We would like to extend our gratitude to the *Kanagawa Prefecture* of Japan for the support and contributions which led to the direct realization of this project.

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