Assessment of New Forces Acting on Metal Particles by Electric Curtains Conveyor

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Abstract - A traveling wave conveyor (TWC) is generally employed for moving high-resistivity micronized particles. In this study, a planar TWC was used to analyze the attraction force applied on metal pieces. A three-phase conveyor comprising parallel electrodes that obtained power from high-voltage amplifiers (2 kV, 20 mA) controlled by digital function generators was used for analyzing the attraction force on 15 × 15 mm^2 square metal pieces made of copper, bronze, and steel. The TWC was fixed on a mechanical device that allowed its manual inclination from 0° (horizontal; initial condition) to 180°. The intensity of the force was then estimated by measuring the drop angle at which the metal piece detached from the surface of the conveyor. The obtained results revealed the existence of an attraction force that depends on the frequency, amplitude, and waveform of the applied voltage. This force is maximum at high voltages and frequencies and for a square waveform.

Keywords – Metal Particles Electric, micronized particles, Curtains traveling, wave conveyor.

I. INTRODUCTION

Traveling wave conveyors (TWCs) are typically used to produce movement of micronized insulating materials through the interaction between polarized particles and a phase-shifted electric field. A TWC comprises parallel electrodes with two, three, or four phase-shifted AC potentials [1-3].

When a neutral particle is subjected to a nonuniform electric field E, an electric dipole moment P is induced in the particle. Thus, the particle is subjected to a nonzero resultant force, which is known as the dielectrophoretic force [4]. The TWC, also known as the "electric curtain," has been employed in several applications, such as dust mitigation [5][6].

The electric curtain technique was used by Masudafor the confinement and transport of an aerosol cloud[7]. The technique was also used by Masuda for transporting blood cells in a liquid[8]. Later, the electric curtain technique was used in a charged toner conveyor device used to spread xerographic toner onto a thin film [9][10]. Other applications of the electric curtain technology include bubble containment[11], containment of radioactive dust generated by sputtering within a fusion reactor[12], liquid droplet transport [13][14], particle size classification [15], and particle separation and sorting [16-18]. Moreover, various authors have used electric curtain technology for space applications [19-21].

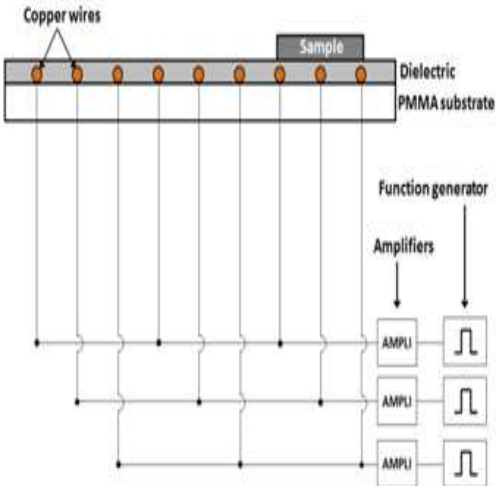
The objective of this study was to experimentally investigate a phenomenon completely different from that generally observed in a TWC, namely the displacement of insulating particles due to the Coulomb and the dielectrophoretic force. In this novel phenomenon, an attractive force is exerted on metal pieces by the conveyors. The attractive force causes the pieces to be "glued" to the surface of the conveyors. An analysis was conducted to study the influence of several factors, such as the amplitude, frequency, and waveform of the applied voltage, on the intensity of the attractive force [22-23].

II. MATERIAL AND METHODS

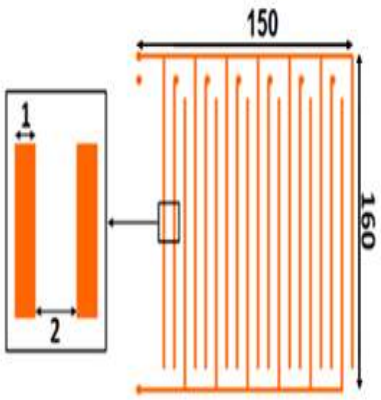
The experimental setup used in this study comprised a three-phase TWC and a mechanical system that varied the inclination angle of the conveyor from 0° to 180°. The TWC was fabricated using a poly(methyl methacrylate) (PMMA; plexiglas®) plate with dimensions of 30 × 15 cm2. Identical parallel copper wire electrodes with a diameter of 1 mm, length of 15 cm, and separated by an interval of 2 mm were

fixed on the plate (Fig. 1). The plate was then covered with an insulating acrylic varnish layer to prevent breakdown between the electrodes.

The electrodes belonging to the same electrical phase were connected together, as displayed in Figure 1.



(a)



(b)

Fig. 1. Three-phase conveyor : a) Schematic description b) Dimensions in mm.

Square-shaped alternating voltages with a phase shift of 120° were supplied to the three phases by using voltage amplifiers (TREK, Model 2220) that could deliver a variable voltage of up to 2 kV and current of 20 mA. The amplifiers were controlled by two function generators (Siglent SDG 1025).

An experimental device using a TWC with variable inclination was developed to analyze the intensity of the attraction force applied to the metal pieces. To measure the value of the drop angle (α) at which the metal samples are detached from the surface of the conveyor, the TWC was fixed on a mechanical device that allowed manual inclination from 0° (initial conditions; horizontal plan) to 180° (Fig. 2).

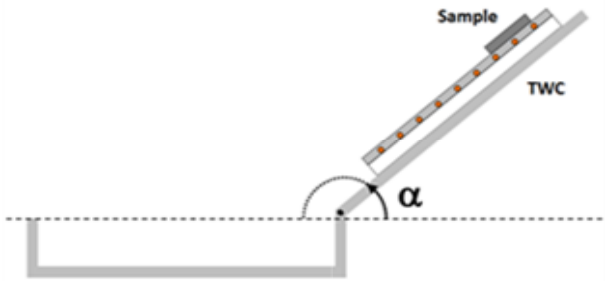


Fig. 2. Inclination system of the travelling wave.

The metal samples used in this study were square-shaped pieces with an area of 15 × 15 mm^2. The samples were prepared using three types of metals, namely copper, bronze, and steel. The mass of copper, bronze, and steel used was 1.4, 1.6, and 1.3 g, respectively (Fig. 3).

Fig. 3. Metal pieces.

For each experiment, three identical pieces of the same metal were placed in a defined area on the conveyor surface at the horizontal plan (α = 0°). After being switched on, the TWC was then slowly inclined until the pieces detached one after the other from the surface of the conveyor and the value of α was 180°. The mean value of the drop angles of the three identical samples was considered for plotting. Furthermore, the experiments were conducted under two humidity conditions (35% and 75% RH) to detect a possible effect that could influence the adhesion of the metal pieces on the TWC.

Moreover, when the TWC is fixed on a vibrating plate as shown in Figure 4, although the intense mechanical vibrations, the metal particles remain strongly pinned to the conveyor surface due to the attraction force. On the other hand, when the TWC is not vibrating, at the opposite of

micronized particles which are transported by the Coulomb and the dielectrophoretic forces, no movement of metal/plastic particles was observed in our experiments due to the higher mass of the mm-size particles.

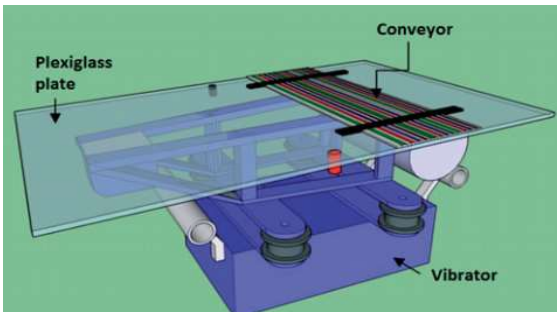


Fig. 4. TWC fixed on a vibrating plate.

III. RESULTS AND DISCUSSION

The TWC produced an attraction force that acted on the metal pieces. The attraction force caused the metal pieces to "attach" to the surface of the conveyor. (Fig. 5).

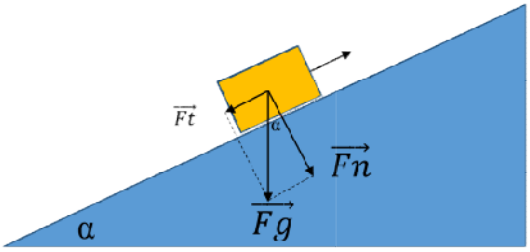


Fig. 5. Forces applied on the metal piece.

The friction force for a normal inclined plan is :

$$Ff = \mu \cdot Fn = \mu \cdot Fg \cdot \cos\alpha \quad (1)$$

Before sliding

$$Ff = Ft = Fg \cdot \sin\alpha_0 \quad (2)$$

From (1) and (2) the friction coefficient can be defined as:

$$\mu = \tan\alpha_0 \quad (3)$$

The preliminary experiments carried out with voltage V=0 have shown that the copper piece starts sliding at α_0=30°.

Friction force with extra attraction force becomes:

$$Ff = \mu \cdot (Fa + Fn) = \mu \cdot (Fa + Fg \cdot \cos\alpha) \quad (4)$$

Before sliding the friction force is :

$$Ff = Ft = Fg \cdot \sin\alpha \quad (5)$$

From (4) and (5), the attraction force can be defined as follows:

$$\mu \cdot (Fa + Fg \cdot \cos\alpha) = Fg \cdot \sin\alpha \quad (6)$$

$$Fa = \frac{Fg \cdot \sin\alpha - \mu \cdot Fg \cdot \cos\alpha}{\mu} \quad (7)$$

$$Fa = \frac{Fg\,(\sin\alpha - \mu\cos\alpha)}{\mu} \quad (8)$$

$$Fa = \frac{Fg\,(\sin\alpha - \tan\alpha_0 \cdot \cos\ )}{\tan\alpha_0} \quad (9)$$

At the vertical position for α=180°, we obtain F_a=F_g

$$Fg = m \cdot g \quad (10)$$

Where :

Fg=mg: gravitational force

m: mass of the piece

g: gravitational acceleration

F_f: friction force

F_n: normal component to the plan of the gravitational force

F_t: tangential component to the plan of the gravitational force

Fa: attraction force

μ : friction coefficient

α_0: angle of the plan at the equilibrium just before sliding (no attraction force)

α angle of the plan at the equilibrium just before sliding (with attraction force)

The metal pieces were pinned to the conveyor surface by a magnetic-like force expressed by the following equation [18-20]:

$$F = \int I.d\vec{l} \wedge \vec{B} \quad (11)$$

where I is the eddy current induced by induction B. Here, Bis produced by the time-variable electric field according to the Maxwell–Ampere equation.

$$\overrightarrow{Rot}\vec{H} = \vec{J} + \varepsilon\frac{d\vec{E}}{dt} \quad (12)$$

where, ε, $\vec{H}$, and $\vec{J}$ represent the permittivity of air, magnetic field, and current density, respectively.

Because the TWC comprised electrodes isolated from each other, the conducting current was almost zero. Therefore, a magnetic field was produced by the variation in the electric field,

which is expressed by the term $(\varepsilon \frac{d\vec{E}}{dt})$. The variation in the high voltage (up to 2 kV) generated a sufficiently high magnetic field to produce an eddy current in the metal pieces followed by a magnetic attraction force.

In addition to the electromagnetic force, an electrostatic force is also applied on the metal particles. As shown in Figure 6, when the metal piece is in contact with the electrodes, an induction electric charge with opposite polarity to the applied voltage is induced on it.

Therefore, an attraction electrostatic force is generated that causes the attachment of the metal pieces. Whatever is the polarity of the adjacent electrodes, an electrostatic attraction force is created on the metal pieces.

Moreover, a small polarization charge is also produced on the plastic particle. However, this charge is much smaller and thus not sufficient to cause the plastic particles to be attached to the conveyor surface.

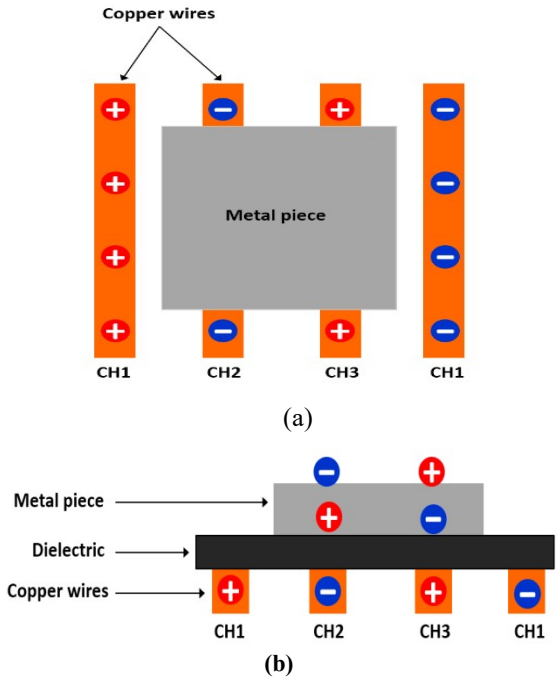


Fig. 6. Schematic description of the induction charge and the attraction force applied on the metal pieces : a) Top view; b) side view

The results plotted in Figure 7 represent the variation in the drop angle as a function of the applied voltage for the three samples. The results reveal that the force is considerably influenced by the value of the applied voltage. The higher the voltage, the higher is the electric field and thus stronger is the attraction force.

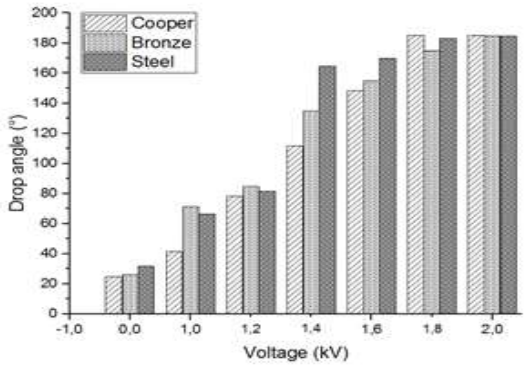


Fig. 7. Variation of the drop angle as a function of the applied voltage for the three pieces.

Compared with the copper and bronze samples (mass of 1.4 and 1.6 g, respectively), the steel sample "adhered"better to the surface of the TWC because of its smallermass (1.3 g). The difference between the drop angle values was due to the difference between the mass values of the three metal samples.

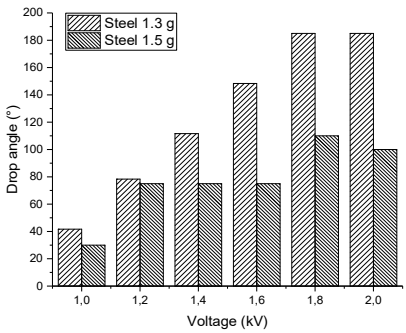


Fig. 8. Variation of the drop angle according to the applied voltage for two steel pieces of the same surface and different masses.

However, we observed no effect related to the ferromagnetic nature of the steel sample, as illustrated in Figure 8. Thus, the drop angle of two steel pieces with the same surface area but different masses is different. The lighter the piece, the higher is the drop angle.

Figure 9 depicts the variation α due to the signal frequency. The drop angle of the three samples increased with frequency because the term $(\varepsilon \frac{d\vec{E}}{dt})$ depends on both the electric field

intensity and variation rate $(\frac{d\vec{E}}{dt})$ caused by frequency increase.

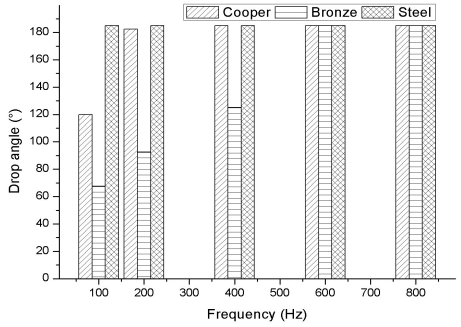


Fig. 9. Variation of the drop angle as a function of the frequency for the 3 metal pieces (V = 2 kV).

Conversely, the relative ambient humidity had a significant influence on the attraction force applied by the TWC. A significant increase in the moisture leads to poor mechanical contact between the metal pieces and conveyor due to the wet layer on the TWC.

Because the time variation in the electric field is related to the shape of the voltage waveform, an experimental study was performed for comparing square, sinusoidal, and triangular signals. As expected, the sinusoidal and triangular waveforms did not generate a significant force because these waveforms had a smaller voltage variation rate than square waveforms did (Fig. 10).

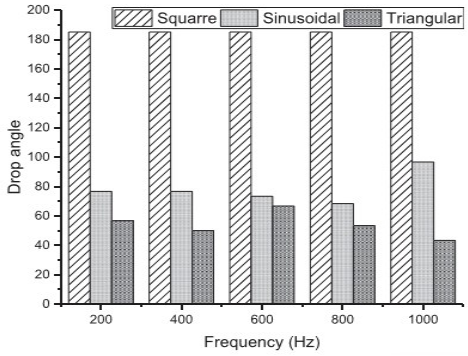
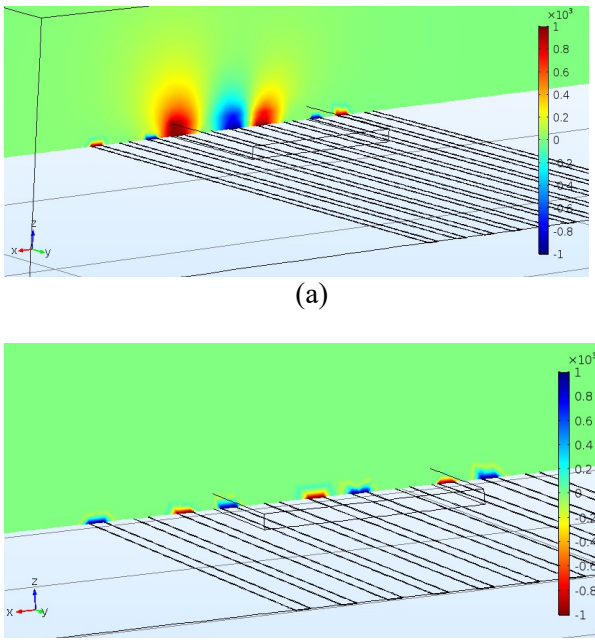


Fig. 10. Variation of the drop angle according to the frequency for square,sinusoidal and triangular waveforms signal

Moreover, when the TWC is fixed on a vibrating plate as shown in Figure 4, although the intense mechanical vibrations, the metal particles remain strongly pinned to the conveyor surface due to the attraction force. On the other hand, when the TWC is not vibrating, at the opposite of micronized particles which are transported by the Coulomb and the dielectrophoretic forces, no movement of metal/plastic particles was observed in our experiments due to the higher mass of the mm-size particles.

Furthermore, numerical analysis were carried out with COMSOL software 5.3 , using copper and PVC (PolyVinyl Chloride) pieces (Figure 11).

The obtained results have shown that the electric potential at the extremity of the metal piece is greater, while this tendency is not observed in the case of the PVC piece.



(a)

(b)

Fig. 11. Potential distribution on the TWC in the presence of the piece : a) Metal piece; b) PVC piece.

IV. CONCLUSION

A commonly known force acting on actuators is the dielectrophoretic force applied only on insulated micronized particles. In this study, the effect of the applied voltage and other parameters on the novel attraction force acting on centimeter-sized metal pieces was analyzed. The following conclusions were obtained in this study:

(1) The amplitude, frequency, and waveform of a signal have a significant effect on the attraction force.

(2) The force is strong when the applied voltage has high amplitude and frequency values and a square shape.

(3) The attraction force can be used for several applications, such as the separation of nonferrous or plastic particles.

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