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# Dielectrophoretic Gold Particle Separation

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**Abstract:** We present a novel process for gold particle separation from aqueous setup with a high separation efficiency and without any environmental risk. Dielectrophoresis (DEP), as the main mechanism of this separation process, is applied for the first time to separate gold even continuously from a raw mineral mixture. Electrothermal and high-pass-filter effects, occurring in DEP with water as liquid phase, were investigated and considered during the design of the separation process. The experimental results demonstrate that even ultra thin gold particles can be separated from a raw mineral mixture with an efficiency of up to 88% at an electric field of 32 kV/m and 200 kHz in continuous operation with specific fluid flow of about 400 $m^3$/(m h).

**Keywords:** Dielectrophoresis, electric field flow fractionation, gold leaf, non-uniform electric field, pearl chain, thermal effect

## INTRODUCTION

In nature, gold occurs as a pure free metal, typically associated with oxides of other metals. In gold mining, techniques like manual panning or continuous sluicing are used to produce mineral concentrates. For separating gold particles from such mixtures, typically cyanidation or amalgamation is applied, however both methods pose a considerable operational and environmental danger (1). As a non-chemical method,

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magnetism has been suggested in the recovery of gold particle from ores; however, the separation efficiency is low (1). Another non-chemical method was reported for the separation of colloidal gold particles from gold laden material in water by using an oppositely charged collecting material to capture colloidal gold particles from gold laden material (2). Although this method is environmentally friendly, it appears not to be suitable in mining due to the small size of the particles. This is also true for a dielectrophoretic method (DEP), which has been proved by Kumar et al., who reported a bridging effect of 20 nm gold nanoparticles between two electrodes by DEP (3).

In this work, we focus on a non-chemical separation of gold particles of μm- scale that is based on the movement of pure gold particles in aqueous medium by DEP.



## Dielectrophoresis

Dielectrophoresis, which has been employed in trapping particles mainly in biological industries (4–8), is defined by Pohl to describe the translational motion of neutral matter caused by polarization effects in a nonuniform electric field (6). The dipole moment induced in the particle can be represented by two equal and opposite charges at the particle boundary; however, when they are not uniformly distributed over the particle surface a macroscopic dipole will be created (7). When the dipole is positioned in a nonuniform electric field, the local field strength on each side of the particle will be different, causing a net force referred to as the dielectrophoretic force. Therefore, a suspended particle in a liquid medium will be induced to move either towards a stronger electric field region (positive DEP) or towards a weaker electric field region (negative DEP), depending upon the different polarizations of the particle and the liquid medium.

When a spherical particle (radius $a$) suspended in a medium, whose relative dielectric constant (permittivity) is $\varepsilon_M$, the dielectrophoretic force can be given as (4),

$$F_{DEP} = 4\pi a^3 \varepsilon_0 \varepsilon_M re[K](E \cdot \nabla)E \tag{1}$$

where $\varepsilon_0$ is the permittivity of free space with the value of $8.854^{*}10^{-12}$ F $m^{-1}$, $re[K]$ is the real part of Clausius-Mossotti factor $K$, a parameter defining the effective dielectric polarizability of the particle, and $E$ is the electric field intensity. The Clausius-Mossotti factor is a function of frequency of the electric field, depending upon the particle and medium's

dielectric properties and is expressed as,

$$re[K] = re\left(\frac{\tilde{\varepsilon}_P - \tilde{\varepsilon}_M}{\tilde{\varepsilon}_P + 2\tilde{\varepsilon}_M}\right) \tag{1a}$$

$$\tilde{\varepsilon} = \varepsilon - \frac{i\sigma}{\omega} \tag{1b}$$

where $\tilde{\varepsilon}$ is the complex permittivity of the particle ($\tilde{\varepsilon}_P$) and the medium ($\tilde{\varepsilon}_M$), $\sigma$ the conductivity, $\omega$ the angular frequency of the applied electric field ($\omega = 2\pi f$) in which $f$ is frequency, $i = \sqrt{-1}$. $\nabla|E|^2$, the (geometric) gradient of the square of the field intensity, is defined by Pohl and generally applied in DEP to calculate $(E \cdot \nabla)E = |E|\nabla|E| \approx \frac{1}{2}\nabla|E|^2$ with the assumption that the materials are linear isotropic dielectrics (6).

The motion of a particle suspended in an aqueous medium is often simply assumed to be a steady state by balancing the dielectrophoretic force and drag force. Thus, the velocity of particle v is obtained by,

$$v_{DEP} = \frac{2a^2\varepsilon_0\varepsilon_M re[K](E \cdot \nabla)E}{3\eta_M} \tag{2}$$

where $\eta_M$ is dynamic viscosity of medium.

The DEP gold-separation is a unique case because gold is chemically inert and exists as a free and pure metal in nature. Gold, which is characterized by an infinitely huge permittivity (6), will consequently always move towards a stronger electric field when suspended in any liquid, depicting a positive DEP. Therefore, the principal concept is to move and trap gold particles at the stronger electric field regions, which concurrently repel other particles in the mixture away from gold particles.

Nevertheless, due to the high electric field strength necessarily applied in a DEP system, a side-effect, which often occurs in a DEP system and is termed to be an electrothermal effect, presents a temperature gradient caused by the energy dissipation of internal friction on the medium (9). Joule-heating from the temperature gradient in the DEP system will drive the medium to flow. The driven fluid flow influences the particle's motion. Especially when the order of magnitude of the system's characteristic length is above 1 mm, the buoyancy due to joule heating always dominates the fluid flow (9). The gravitational body force on a fluid generated by a temperature field, which is directed from a higher electric field region to a lower electric field region, is due to the local density change caused by the temperature difference. The temperature difference can be given as (9)

$$\Delta T = \frac{U^2 l}{R\rho_M C_P V u} \tag{3}$$

where, $\Delta T$ is the temperature difference, $U$ is the applied voltage, $l$ is the characteristic length, $\rho_M$ is the density of the medium, $C_P$ is the specific heat capacity, $V$ is the volume of the medium, and $u$ represents the fluid flow speed.

In addition, a constraint in the application of DEP is caused by a high-pass-filter effect. The insulated electrodes applied in a DEP system together with the medium could be represented as a high-pass-filter circuit. Such a high-pass-filter circuit will require much higher voltage to satisfy the high electric field requirement for DEP system in a low frequency region. Therefore, the high-pass-filter effect not only limits the DEP application in a low frequency region, but increases the energy requirement in a DEP system.

Therefore, in order to increase the separation efficiency by preventing the disadvantage from the side effect and constraint caused by electrothermal and high-pass-filter effect respectively, a continuous separation process with a specific electrode configuration for high frequency electric field application is designed and examined in this work and compared with the batch operation. The separation phenomena and efficiency are recorded and discussed to optimize and demonstrate the feasibility of gold separation using dielectrophoresis.



## EXPERIMENTAL SETUP AND PROCEDURES

### Electrode Configuration Design

With insulated electrodes configuration, the setup could be modeled to be a high-pass filter circuit with two serially connected capacitors (the two insulated electrodes $C_{E1}$ and $C_{E2}$) in series with a resistor $R_M$ paralleled by a capacitor (the medium and insulation material $C_M$), as shown in Fig. 1.

The frequency-dependent voltage fraction of voltage across the medium $U_M$ to voltage applied $U_0$ is simulated as shown in Fig. 2, from which, it is deducted that at low frequency the electric field in the medium tends to zero, meaning that the dielectrophoretic force on particles will tend to zero and no movement will occur. When both electrodes are insulated, the critical frequency, $f_{cr}$, for the electric field to be able to develop across the medium is about 300 kHz. But, when one bare electrode and one insulated electrode are used in the setup, the critical frequency $f_{cr}$ is comparatively reduced to approximately 150 kHz, at which the voltage

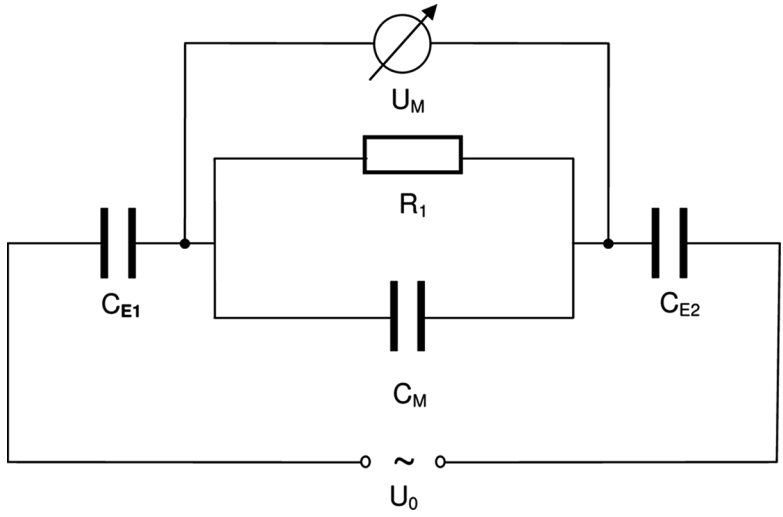


*Figure 1.* Electrical analogy of the setup including two electrodes E1 and E2 as well as medium M.

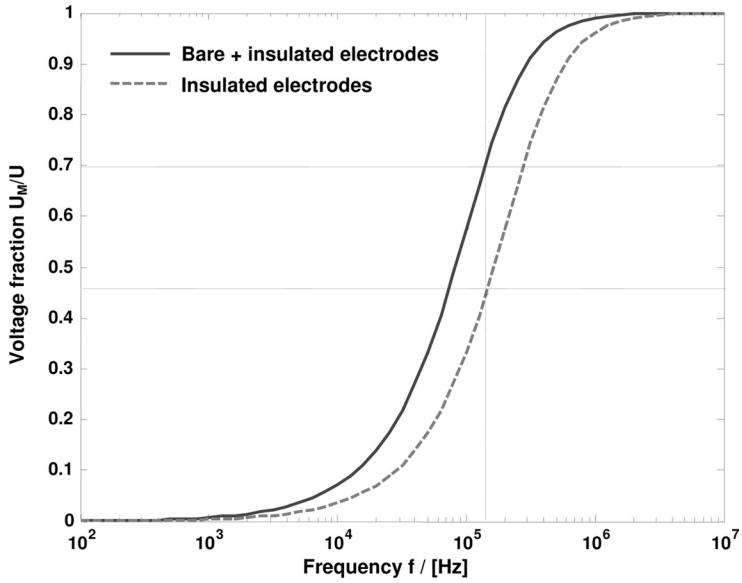


*Figure 2.* Frequency dependency of voltage fraction of voltage across medium $U_M$ to output voltage $U_0$.

fraction of the insulated electrodes is less than 0.5. This implies that the insulated electrodes could decrease the danger of electrical shock and provide electrode fouling protection. However, the energy cost from a much higher frequency and output voltage requirements will also be proportionally higher. With one bare electrode together with one insulted electrode, the energy cost can be effectively decreased and some advantages of the insulated electrodes setup can be reserved. Therefore, the electrode configuration is designed with an insulated wire together with a bare plate to form a cylindrical electric field across the medium. The inhomogeneous electric field around the wire presents much higher electric field strength compared with the electric field near the plate when the voltage of output from the power supply is 200 $V_{rms}$ at 200 kHz.

## Experimental Setup and Procedures

The experimental setup, shown in Fig. 3, was composed of a PC (1), a camera (2) (SONY MODEL XCD-X710), a lens (3) (RODENSTOCK, TELECENTRIC LENS with 114 mm focal length), a power amplifier (4) (FM1290, FM ELEKTRONIK BERLIN), a function generator (5) (VOLTCRAFT® 7202), the separation chamber (acrylic glass, channel length 200 mm) (6) with two opposite electrodes installed, one bare stainless

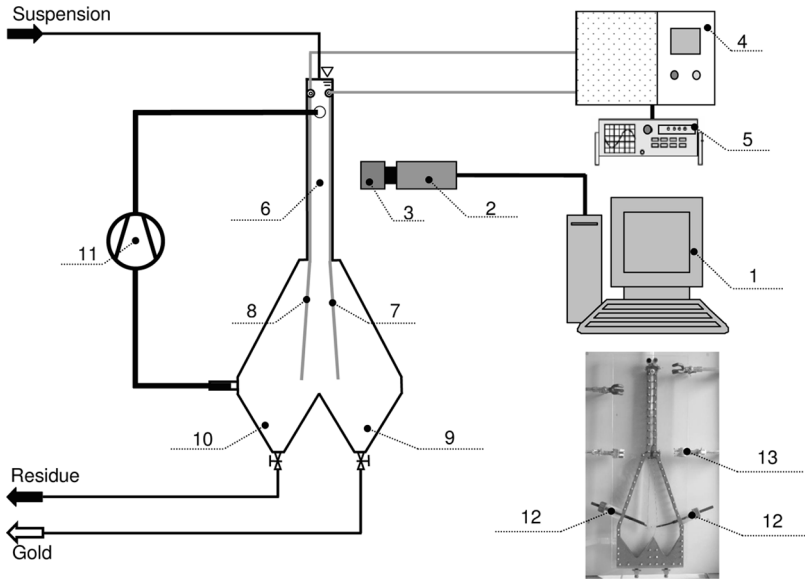


*Figure 3.* Experimental setup.

steel plate (thickness 0.5 mm) (7) and an insulated wire (diameter 0.5 mm) (8) with a 6 mm distance between, as well as two collectors for collecting gold particles (9) and residual particles (10). Both ends of the two electrodes were connected and fixed with adjustments for electrodes distance (12). The whole experimental setup was fastened with fixations (13).

The power amplifier (4) and the function generator (5) together provided alternating effective voltage approximately from 0 to 280 V, and frequency from 0 to $10^6$ Hz. The particles mixture investigated was a sample from the sand classification. It mainly consists of gold, zircon, and quartz of unknown fractions (Fig. 4). The gold particles are ultrathin plates of about $227.3 \pm 39.7$ μm diameter and $30.3 \pm 3.5$ μm thickness, i.e. an aspect rate of a 7:1. In each experiment a certain mass ($0.02 \pm 0.005$ g) was introduced into the separation chamber with a volume of 4.2 mL (6), which was completely filled with demineralized water (i.e. a solid to liquid ratio of $4.8 \pm 1.2$ g/L). Only in "batch operation mode with recirculation" this water was continuously cycled by a pump (DC15/5 HARTON) (11). Using the lens (3) and camera (2), the motion of the introduced particles' was simultaneously projected on the monitor and recorded into the computer (1). The treatment time, which is constrained by the particle's settling time, can be estimated to be 10 seconds. Particles settled in the collectors were collected and dried. The gold particles gathered from the samples were counted. The numbers from the counted gold particles samples in both collectors were recorded and compared.

As shown in Fig. 3 this experimental setup allows a continuous feeding of particles ("continuous operation mode") applying two independent mass flows. One is the recirculated flow of operating liquid, the other is the particle suspension feed flow. However, only discontinuous feeding of particles suspension is reported here.

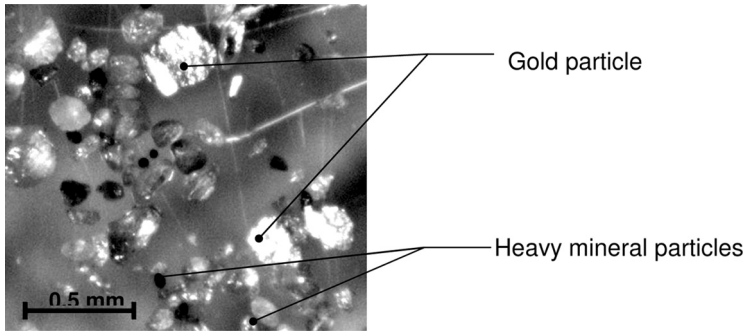


***Figure 4.*** Particle mixture, with gold particles (bright plate), and heavy mineral particles (zircon and quartz).

## RESULTS AND DISCUSSION

Theoretically, in the case of the mineral mixture composed of gold, zircon, and quartz particles suspended in distilled water, the simulation of the real part of the Clausius-Mossotti factors as a function of frequency from Eq. (1a) is shown in Fig. 5. From Fig. 5, the real part of the Clausius-Mossotti factor for gold particle in distilled water is always positive and independent of frequency (the magnitude is 1) due to the much higher conductivity and relative dielectric constant of gold compared to distilled water; instead, those of zircon and quartz particles in distilled water are negative (−0.4 for zircon and −0.45 for quartz) and dependent on the frequency (when frequency is over 10 kHz). Therefore, the gold particles alone will move towards the stronger electric field (positive DEP), rather the zircon and quartz particles will move towards weaker electric field regions (negative DEP), although the movement speed will be different between these two particles as the frequency is larger than 10 kHz, thereby the gold particles are separated from the mixture. In a designed dielectrophoretic gold separator, according to Eq. (2), the gold particle's motion velocity will be increased with the increment of the electric field.



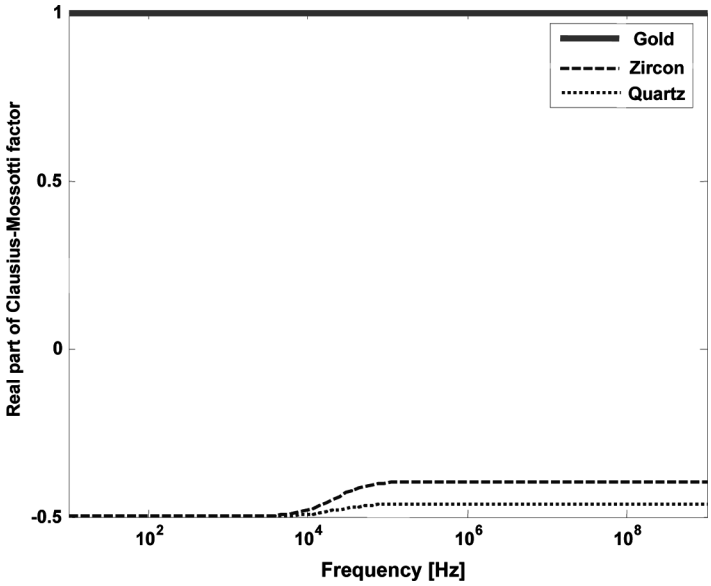


*Figure 5.* Theoretical simulation of the real part of Clausius-Mossotti factor as a function of frequency.

A batch process was examined to verify the reasonability of gold particle separation in the designed system and predict the influences from the side effect and constraint. The particles mixture was introduced from the upper inlet of the separation chamber, in which pure water had already been filled. Due to much higher density compared to water, heavy particles mixture settled very fast, while gold plates were attracted to the wire, where the electric field strength is the highest. The enhancement of the nonuniformity of the electric field around a trapped single particle will attract other particles to move towards it and form a ''pearl-chain,'' which is always along the direction of the electric field because only like particles could form a pearl chain directed along the electric field (8). This pearl-chain formation effect turns out to increase the rate, at which the gold particle is separated from the mixture and concentrated. As more gold particles were attracted to close to the wire, they formed chains, which directed along the electric field line, as shown in Fig. 6. These gold particles chains settled downwards along the wire into the gold particle collector, thereby being fractionated from the mixture. By counting gold particles in the samples gathered from two collectors, the separation efficiency could be given by comparing the gold particle number in the gold collector with the sum of gold particles collected in



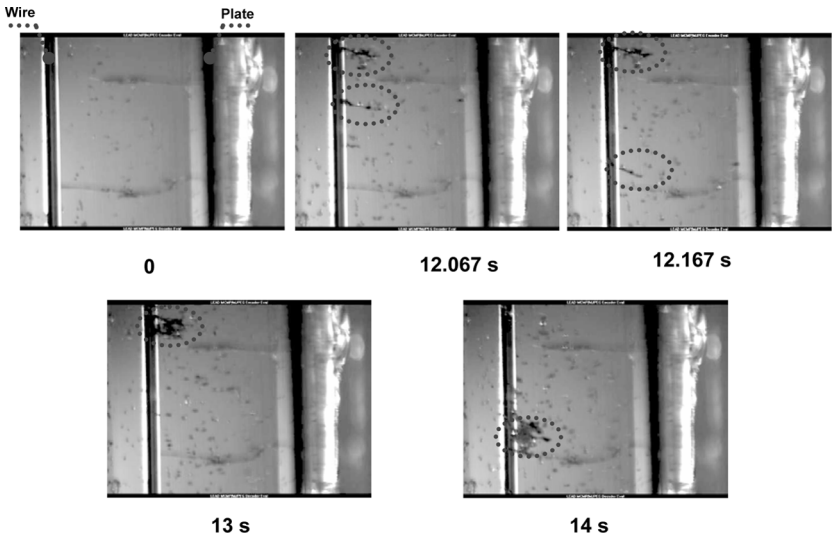


***Figure 6.*** Experimental phenomena for particles mixture of gold (dark chained big particles in blue circles), zircon and quartz (gray separated particles) in distilled water with and without electric field (AC voltage output 200 $V_{rms}$, frequency 200 kHz).

both collectors. The experimental results are shown in Fig. 7 in triplicate in an electric field. The maximum separation efficiency (78%) was reached when the voltage was 190 V, while the separation efficiency decreased to 63% (max: 71%, min: 56%) at the voltage of 200 V. This phenomenon does not follow theoretical prediction, in which more gold particles will be trapped on the wire of a certain length thereby being separated from the mixture as higher voltage is applied. This is due to Eq. (2), which gives the velocity of spherical particles that increases quadratically with the electric field strength. Accordingly, this is equal to a quadratic shortening of deposition length of the collecting electrode or an increase of separation particles at a certain critical length. The reason for the lowered efficiency could be explained with the electrothermal effect. With the increase of voltage, more gold particles indeed were trapped and formed longer pearl chains. The formed gold particle pearl chain shortened the distance between the opposite electrode (plate) and the chain, which replaces wire as an electrode. This shortened distance together with the increased voltage causes much higher temperature difference. Especially in such a closed channel in our experimental system, the heat caused by electricity can not be transferred out of the system. Therefore, in a certain experimental time $t$ the temperature increment



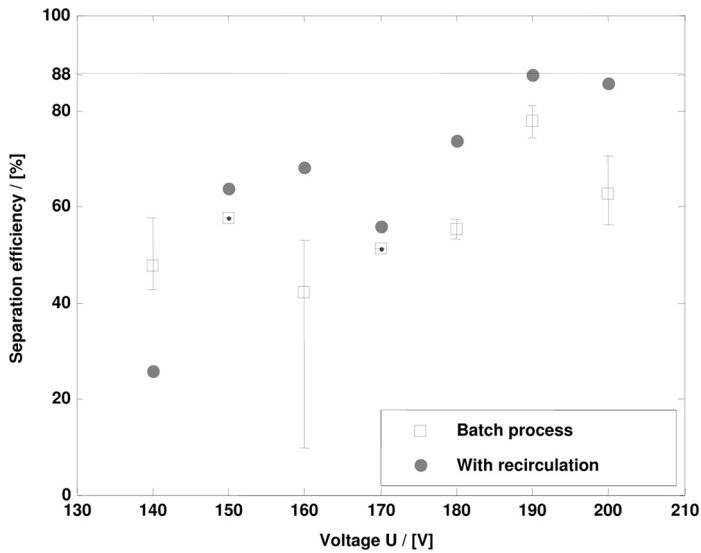


***Figure 7.*** Particle separation efficiency comparison between batch (3 repeated experiments) and batch separation process with recirculation (one experiment) as a function of voltage.

$\Delta T_t$ of the bulk medium in the channel could be estimated by balancing the inputted electric energy and the internal heat increment

$$\frac{U^2}{R}t = C_P V \rho_M \Delta T_t \tag{4}$$

The temperature increments of the bulk medium modeled as a function of voltage in a 5 minutes experiment were compared within a different distance between electrodes, as shown in Fig. 8. It is clear that the increment of voltage and decrease of length of the gold particle pearl chain will increase the medium temperature so high as to boil the medium from room temperature (20°C) in an about 5 minutes experiment. As an example, when the voltage is 200 V with a 1 mm long pearl chain formed (5 mm distance between tip of pearl chain and the opposite electrode), the temperature of the medium is increased about 95 K, thereby the medium is boiled. Compared with voltage 190 V and about a 6 mm distance between the tip of the pearl chain and the opposite electrode, the medium temperature is increased about 71 K, which could not boil the medium. The bubbles produced by the boiled medium will not only retard the particles motion towards the wire but bring the particle upwards by attaching the particles on the bubbles. Therefore, when the voltage is



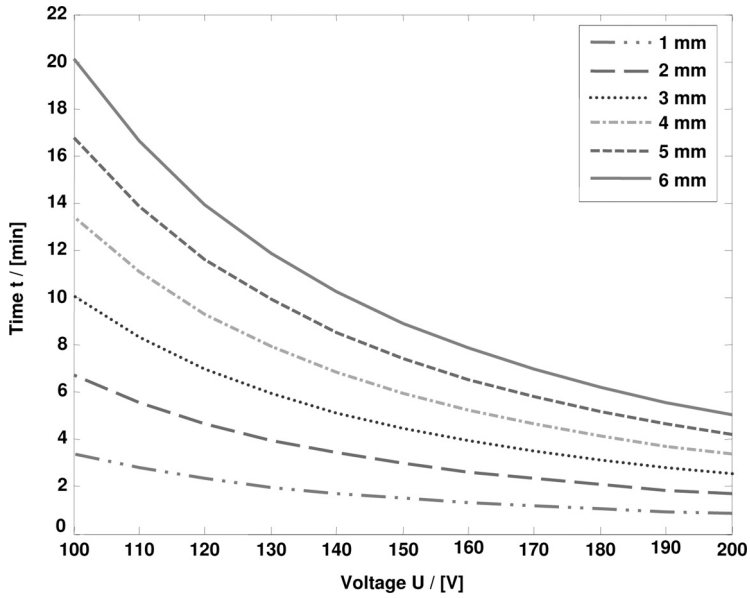


***Figure 8.*** Time for heat from electricity to boil (100°C) the medium from room temperature (20°C) as calculated from Eq. (4) at different electrode distances.

much higher and the distance between the pearl chain and the opposite electrode is shorter, the medium will be heated much faster, thus the particles motion is influenced. When the voltage is lower than 190 V, the number of gold particles trapped on the wire was fewer. Therefore, although the lower heat produced by the lower voltage was applied, the separation efficiency cannot achieve so high an efficiency as that with voltage 190 V. In addition, the gold separation process cannot last a longer time caused by the electrothermal effect. As shown in Fig. 8, if the experiment lasts longer than 5 minutes with voltage 190 V, the medium will be boiled and gas bubbles will be produced in the channel. In order to solve the problem caused by the electrothermal effect, a cycling medium system was designed as shown in Fig. 3. This separation process with a cycling medium system is named to be the batch separation process with recirculation. The medium was cycled with a pump at the volume rate of 2.36 mL/s, resulting in a specific flow rate (cross sectional velocity) of 408.78 $m^3$/(m h), to keep the temperature in a moderate range. The volume flow was controlled constant so as to keep the influence from the volume flow on the particle motion equally. With this cycling medium system, the heat could be transferred out of the channel so that the boiling effect was eliminated, while the increased particle settle speed by fluid flow decreased the trapped gold particle number on the wire thereby shortening the length of the pearl chain. It can be seen in Fig. 7, that the separation efficiencies with voltages 190 V and 200 V are very close. In addition, the separation efficiency at 140 V in the batch separation process with recirculation is lower than that in the batch process. It is caused by the higher settling speed of gold particles increased by the fluid flow by the cycling medium system compared to the batch process, while the electric field is not strong enough to attract particles to reach the wire before the particles sediment into particles collectors. When the applied voltage is between 150 V and 200 V, the separation efficiency of the process with the cycling medium is higher than that without the cycling medium, although the increased particle sedimentation speed could attenuate particle number attached to the wire. As shown in Fig. 7, the separation efficiency of the process with the cycling system is increased with the increment of the voltage, which fits the theoretical prediction. The maximum separation efficiency reached 88% at the applied voltage of 190 V, which equals to an electric field of 31666.67 V/m.

## CONCLUSION

In this work, we present a novel separation method without a further pretreatment to fractionate gold particles from a mineral mixture that

decreases the possibility of environmental pollution through toxic substances down to zero. Dielectrophoresis (DEP) as the main separation technology in the gold separation was verified to be reasonable.

The test of the lab-scale DEP separation process, which was investigated in batch operation mode with and without the recirculation of the liquid and with discontinuous feeding, shows the possibility to achieve 88% gold particle fractionated from the mixture. The separation efficiency depends also on the voltage, which showed an optimal range (140 V–200 V). Recirculation improved the separation efficiency significantly due to cooling. The investigated set-up allows also for a continuous separation mode.

In terms of the separation efficiency, this new DEP method is comparable to cyanidation, which has been the most efficient gold recovery process so far (10). But contrary to cyanidation, the DEP separation is free of hazardous effluents.

In general DEP is constrained by side-effects such as electrothermal and high-pass-filter effect. However, in its current set-up the DEP separation is limited by Joule heating, which interferes with the separation and wastes energy and costs. The presence of other elemental metals would also reduce the separation efficiency. A solution for a low cost and high efficient process would be a high-throughput dielectrophoretic particle separator. Therefore, the channels can easily be numbered up as long as temperature control is considered. An application at a pilot scale is intended by the authors.



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