Numerical simulation on the opto-electro-kinetic patterning for rapid concentration of particles in a microchannel

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This paper presents a mathematical model for laser-induced rapid electro-kinetic patterning (REP) to elucidate the mechanism for concentrating particles in a microchannel non-destructively and non-invasively. COMSOL®(v4.2a) multiphysics software was used to examine the effect of a variety of parameters on the focusing performance of the REP. A mathematical model of the REP was developed based on the AC electrothermal flow (ACET) equations, the dielectrophoresis (DEP) equation, the energy balance equation, the Navier-Stokes equation, and the concentration-distribution equation. The medium was assumed to be a diluted solute, and different electric potentials and laser illumination were applied to the desired place. Gold (Au) electrodes were used at the top and bottom of a microchannel. For model validation, the simulation results were compared with the experimental data. The results revealed the formation of a toroidal microvortex via the ACET effect, which was generated due to laser illumination and joule-heating in the area of interest. In addition, under some conditions, such as the frequency of AC, the DEP velocity, and the particle size, the ACET force enhances and compresses resulting in the concentration of particles. The conditions of the DEP velocity and the ACET velocity are presented in detail with a comparison of the experimental results. © 2015 AIP Publishing LLC.

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I. INTRODUCTION

Nanotechnology and microelectro mechanical systems (MEMS) technology are widely used in the field of biotechnology and bio-medical engineering. The technology for the processing/transfer/controls of micro/nano scaled particles quickly and reliably has been applied to a lab-on-a chip, μ -TAS (micro total analysis systems), medical diagnostics, and drug discovery.¹⁻⁶ In applications to biotechnology, DNA chips, and protein chips are used to screen and diagnose genes and proteins. Other biochemical applications include a lab-on-a-chip, which is used widely in the laboratory. Microfluidics is considered one of crucial technologies because nanoliter volumes of biological samples can be treated in a nano/micro-chip, so that biological/clinical analysis can be conducted quickly, non-destructively, and non-invasively.⁷⁻⁹ On the other hand, the challenging issues for highly efficient and accurate technology still remain in many application fields manipulating small numbers of particles.

Recently, the dielectrophoresis (DEP) and the AC electrothermal (ACET) technique have been adapted separately as a new potential technology to manipulate micro-particles ($0.2\ \mu\text{m} \sim 6\ \mu\text{m}$) rapidly with high accuracy.¹⁰⁻¹⁵ Although the two technologies are quite promising, there is a

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limitation on manipulation. For example, DEP is a phenomenon, where a force is exerted on a dielectric particle when it is exposed to a non-uniform electric field. DEP is a non-invasive and non-destructive technique that can be used to manipulate bioparticles, such as cells, proteins, DNA, viruses, and bacteria. Therefore, DEP has many medical applications. On the other hand, DEP depends on the particle size, dielectric constant, conductivity, and polarizability of the particle in a medium.^{10–12} Furthermore, a complex design of electrode and microfabrication technology is required to generate a non-uniform electric field. In addition, if the particle size decreases, the DEP force becomes smaller, so the bio-particles are fatally destructive in a high electric potential gradient.

For ACET technology, the ACET controls particles using a temperature gradient under a non-uniform AC electric field. This technology has the advantage of both the DEP effect and electrophoretic (EP) effect using the hydrodynamic force and a non-uniform electric field, but it also requires a complex design of electrodes to generate a non-uniform electric field. Moreover, a high electric field is required to produce a temperature gradient due to Joule-heating.

Therefore, the recent trend of particle transport technology is to combine two or more technologies to overcome the drawbacks. Opto-electrokinetic technology for particle processing can be carried out using simple plane electrodes and laser illumination in a non-destructive and non-invasive manner.^{16–19} Williams *et al.*¹⁶ first introduced the concept of this technique, which is called Rapid Electrokinetic Patterning (REP). Fig. 1 shows a schematic diagram of the REP. The electric field provides non-uniform temperature distribution by laser illumination only, in which a toroidal microvortex forms as an electro-hydrodynamic fluid flow that provides a force acting on a particle. F_D is caused by an electrothermal fluid, which is generated by the temperature gradient and AC field mix. F_E is an electrode to particle attractive force, and this holding force is generated by the AC field induced dipole effect. F_P is due to particle-particle repulsion resulting from an AC field induced polarization effect. When these forces are balanced, the particles can be concentrated. In recent years, there has been considerable experimental research on the REP technique. The concentration of particles was introduced using AC electrokinetic technology, which uses an IR laser and two flat ITO electrodes to generate an electrothermal microvortex. As a result, $0.1 \sim 2 \mu\text{m}$ -scale polyethylene particles were focused successfully in the area of the laser illumination spot. In addition, the cutoff (critical) frequency was found experimentally, at which the particles begin to disperse and are strongly affected by the microvortex. The cutoff frequency increased with decreasing particles size.^{17–19,24}

Kumar *et al.* also conducted 3D3C velocimetry measurements of an electrothermal microvortex using a particle tracking velocimetry (PTV) technique.²⁰ Although several experiments on the REP technique have been conducted, the full mechanism for focusing particles using the REP technique is not completely understood. Some studies on electro hydrodynamic flow used

FIG. 1. Schematic diagram of rapid electrokinetic patterning.

numerical simulations because the physics in the mechanism can be combined in the REP technique and it is quite complicated.

In this research, mathematical modeling was developed to determine the mechanism of the REP, and the simulation results were compared with the experiment results to examine the relationship between the DEP effect, which is the main force concentrating particles, and the ACET force, which is the force to aggregate particles using an electrothermal microvortex. In addition, REP has also been experimentally proven to have the same effect on some bio-particles, such as bead-based bioassays²⁴ and bacteria.²⁵ By simply changing the dielectric properties and physical parameters in response to the bio-particles used, the numerical model can be applied to simulate the particulate behavior. To the best of the authors' knowledge, this is the first successful comparison to elucidate the mechanism of the REP technique in detail. In addition, this numerical model is eventually helpful to understand individual DEP and ACET effect as well as combined REP effects on bio-particles and fluid motions in a microchannel and is also used as a useful tool to selectively control concentration, dispersion, and separation of bio-materials.

II. THEORY

The movement of suspended particles in the presence of an AC electric field is influenced by some important factors, such as the external temperature, particle size and range, electrical or thermal conductivity, and permittivity of the fluid. In addition, the interactions among particles and between the particles and fluid affect the motion of particles. Some important particle manipulation techniques in physiological fluids or buffer solution have been described for biological applications in this section.

In this section, a mathematical model is described to examine the temperature gradient in the specific area focused by a laser spot causing localized Joule heating, which gives rise to local electrothermal flow that enhances or compresses a DEP force under an AC electric field.

A. AC electrothermal flow

REP is an optoelectrokinetic technique under an AC electric field and light illumination. This process allows easy dynamic controllability and rapid manipulation of various particles in a fluid. Basically, the REP technique utilizes an electrothermal force, which is a body force exhibited on a fluid medium due to a temperature gradient that is generated from the Joule-heating effect between the cathode and anode.

The general fluid flow for the electrothermal force per unit volume on fluid is governed by

$$\rho_m \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = \nabla \cdot (\mu_m \nabla \vec{u}) + \langle f_{et} \rangle, \quad (1)$$

where ρ_m and μ_m are the density and viscosity of a fluid medium, respectively. The fluid motion is exerted only by a time average electrothermal force ($\langle f_{et} \rangle$), as expressed in Eq. (1).

The electrothermal force can be expressed as^{21–23}

$$\begin{aligned} \langle f_{et} \rangle = & \frac{1}{2} \text{Re} \left[\left(\left(\frac{\sigma_m \epsilon_m \left\{ \frac{1}{\epsilon_m} \frac{\partial \epsilon_m}{\partial T} + \frac{1}{\sigma_m} \frac{\partial \sigma_m}{\partial T} \right\}}{\sigma_m + i\omega \epsilon_m} \right) (\nabla T \cdot \vec{E}_0) \vec{E}_0^* \right) \right. \\ & \left. - \frac{1}{4} \epsilon_m \left\{ \frac{1}{\epsilon_m} \frac{\partial \epsilon_m}{\partial T} (\vec{E}_0 \cdot \vec{E}_0^*) \right\} \nabla T \right], \quad (2) \end{aligned}$$

where σ_m and ϵ_m are the conductivity of the medium and the permittivity of the medium, respectively, $\omega = 2\pi f$ is the electric field frequency, $\vec{E}_0$ is the applied field that removes the perturbation field from $\vec{E}$, and $\vec{E}_0^*$ is a conjugate of $\vec{E}_0$. The first term is defined as the Coulomb force, and the second term is the dielectric force.

B. Dielectrophoresis

The DEP force is a force exerted on a dielectric particle, which is in a non-uniform electric field.^{10,11} The DEP effect has two characteristics with respect to particle transport. One is a positive DEP, which moves a particle toward a higher density electric field. The other is a negative DEP, which moves a particle toward a lower density electric field. The strength of the DEP force depends strongly on the frequency of the electric field, as well as on the shape and size of the particles and electrical properties, such as the conductivity and dielectric constant of the medium and particles. As a result, an electric field with a specific frequency can be used to control a particle. The DEP force can be expressed using the following equation:

$$F_{DEP} = 2\pi\epsilon_m r^3 \text{Re}[f_{CM}] \nabla (\vec{E}_0 \cdot \vec{E}_0^*), \quad (3)$$

where ϵ_m is the permittivity of the medium, r is the radius of the particle, and $\text{Re}[f_{CM}]$ is the real part value of the Clausius-Mossotti (CM) factor. The CM factor is defined as follows:

$$f_{cm} = \frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_p^* + 2\epsilon_m^*}, \quad (4)$$

where ϵ_m^* is a complex dielectric constant of the medium and ϵ_p^* is the complex dielectric constant of the particle

$$\epsilon_i^* = \epsilon_i + \frac{j\sigma_i}{\omega}. \quad (5)$$

Equation (5) represents a complex dielectric constant, where ϵ_i is the dielectric constant, σ_i is the electrical conductivity, $\omega = 2\pi f$ is the electric field frequency, and j is an imaginary unit. Equation (3) can be expressed using Eqs. (4) and (5) as follows:

$$F_{DEP} = 2\pi\epsilon_m r^3 \text{Re} \left(\frac{(\epsilon_p - \epsilon_m) - i(\sigma_p - \sigma_m)/(2\pi f)}{(\epsilon_p + 2\epsilon_m) - i(\sigma_p + 2\sigma_m)/(2\pi f)} \right) \nabla (\vec{E}_0 \cdot \vec{E}_0^*). \quad (6)$$

A positive DEP is where the electrical conductivity of the particles is greater than the electrical conductivity of the medium (i.e., $F_{DEP} > 0$), and the particles move toward the larger electric field gradient. On the other hand, a negative DEP is where the electrical conductivity of the particles is smaller than the electrical conductivity of the medium (i.e., $F_{DEP} < 0$), and the particles move toward a smaller electric field gradient.

C. Temperature generation due to Joule heating

Typically, the generation of heat due to the Joule heating effect is governed by the following energy equation:

$$\rho_m c_p \left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right) = \nabla \cdot (k_m \nabla T) + \sigma_m (\vec{E}_0 \cdot \vec{E}_0^*), \quad (7)$$

where c_p is the heat capacity at a constant pressure, k_m is the heat conductivity coefficient, and σ_m is the electrical conductivity of the medium.

The experimental observations of the movement of particles in a microsystem show that the velocity of particles is too slow to change the temperature field. For general microsystems, heat convection is small compared to heat conduction so that the Peclet number is approximately²

$$\left| \frac{\rho_m c_p \vec{u} \cdot \nabla T}{k \nabla^2 T} \right| \ll 1. \quad (8)$$

Therefore, the energy equation reduces to Poisson's equation as follows:

$$\nabla \cdot (k_m \nabla T) = -\sigma_m (\vec{E}_0 \cdot \vec{E}_0^*). \quad (9)$$

III. METHOD

A. Numerical method

In a charged solution, an electric field is produced under an electric potential, so that charge conservation should be satisfied in that field as follows:

$$\frac{\partial \rho_q}{\partial t} + \nabla \cdot (\sigma_m \vec{E} + \rho_q \vec{u}) = 0, \quad (10)$$

where ρ_q is the local charge density, $\vec{u}$ is the fluid velocity, and σ_m is the conductivity of the fluid. The electric field ($\vec{E}$) obtained from charge conservation is coupled for temperature generation in a microchannel due to Joule heating as expressed in Eq. (7). In addition, a non-uniform temperature distribution, which is due to a laser irradiation, is applied to the surface of the electrode. Kumar *et al.*¹⁹ derived the temperature distribution experimentally as a Lorenz peak function.

$$T = T_0 + a \left(\frac{b}{4r^2 + b^2} \right), \quad (11)$$

where a and b are the fitting parameters. The temperature gradient causes a change in permittivity, conductivity, and density of a fluid. Furthermore, the density gradient induces natural convective flow, whereas the gradient of permittivity and conductivity induce electrothermal flow under an electric field. The primary flow is the electrothermal flow in the REP because natural convective flow is generally ignored because an electric force exists in the system. Although Joule-heating is considered as a possible contributing factor to the temperature distribution in a fluid, it does not provide a high local temperature gradient due to the uniform electric field. For this reason, temperature gradient is formed mainly by a laser source in the REP and coupled with the electric field, which causes electrothermal flow to transport the particles toward the laser irradiation area.

The movement of particles is caused by a balance of DEP forces, REP force, electrophoretic force, and diffusion force. The DEP force will concentrate the particles if the DEP force is greater than the diffusion effect. For faster and better concentration, a change in AC frequency can enable the electrothermal flow to expedite the DEP force. In other words, transport of the particles through a microchannel depends on the electrothermal effect, diffusion effect, and DEP force. The solute transport rate can be expressed in terms of diffusion, convection, electrophoresis, and DEP mobility as follows:

$$\vec{N}_i = -D_i \nabla C_i + (\vec{u} + \mu_{EP} \vec{E} + \mu_{DEP} \nabla (\vec{E}_0 \cdot \vec{E}_0^*)) C_i, \quad (12)$$

where D_i is the diffusion coefficient of the molecule, $\vec{u}$ is the hydrodynamic velocity, and μ is the mobility. The DEP mobility for spherical particles can be expressed as

$$\mu_{DEP} = \frac{\pi d_p^2 \epsilon_m}{12 \mu_m} f_{cm}, \quad (13)$$

where d_p is the diameter of the particles and μ_m is the viscosity of the medium. This study did not include the electrophoretic force in the channel flow to reduce the complexity of modeling. This can be useful for understanding the effects of the DEP force and REP force (electrothermal

effect) on the particle concentration according to the AC frequency. Using the aforementioned assumptions, time-dependent concentration distribution equation can be simplified as follows:

$$\frac{\partial C_i}{\partial t} + \vec{u} \cdot \nabla C_i = \nabla \cdot (-D_i \nabla C_i + \left(\vec{u} + \mu_{DEP} \nabla (\vec{E}_0 \cdot \vec{E}_0^*) \right) C_i). \quad (14)$$

B. Conditions of simulation

To simulate the effect of REP on the particle concentration, the four main governing equations, i.e., the current conservation equation (Eq. (10)), energy conservation equation (Eq. (7)), momentum conservation equation (Eq. (1)), and concentration equation (Eq. (14)), were solved simultaneously. For the conservation equation, Fig. 2 shows all the boundaries of the microfluidic channel. The end columns of the channel were assumed to be a symmetric boundary

FIG. 2. Boundary conditions: (a) Electric current module, (b) heat transfer module, (c) laminar flow module, and (d) concentration module.

condition $((\sigma_m \nabla \vec{u}) \cdot \vec{n} = 0)$ for insulation, whereas the top wall was set to ground and a constant potential was applied to the bottom wall. Gold (Au) was used as the electrode for the top and bottom walls. In Fig. 2(b), the boundary condition of the energy equation is shown. The ambient temperature (293.15 K) is assumed at the top and bottom except for the laser illumination region, and the temperature insulations are applied to the left and right sides. The Lorenz peak function that was introduced by Kumar *et al.*¹⁹ was used to express the change in temperature at the laser illumination area due to the laser illumination source. The Lorenz peak function shown in Eq. (11) describes the 2D temperature field for the laser spot. In Fig. 2(c), the boundary conditions are presented for simulating the fluid flow due to the electrothermal effect. The no slip boundary conditions were used for all channel walls. The volumetric body force shown in Eq. (2) can be summarized simply for water as follows:¹³

$$\langle F_{et} \rangle = -0.012 \cdot \nabla T \cdot \frac{\epsilon_m (\vec{E}_0 \cdot \vec{E}_0^*)}{1 + (\omega\tau)^2} + 0.001 \cdot \nabla T \cdot \epsilon_m (\vec{E}_0 \cdot \vec{E}_0^*). \quad (15)$$

The time averaged volumetric body force can be controlled both by $\tau = \epsilon_m / \sigma_m$ as the charge relaxation time, and $\omega = 2\pi f$ as the frequency of an external AC. If τ and ω are very high and the first term of the volumetric body force approaches zero, the time averaged volumetric body force becomes positive. In addition, the temperature gradient and electric field are the main sources to produce the time averaged volumetric body force, which affects the movement of a fluid. Fig. 2(d) shows the boundary condition of the concentration equation. An initial particle concentration of 1 mM was used for the entire microchannel because a constant concentration is distributed uniformly along the channel length. No flux $(-n \cdot (\nabla \vec{N}_i) = 0)$ was utilized at the walls, so that the particles are not permeable in the wall or are not generated from the wall. This simulation examined how much and how fast the particles are concentrated or scattered around the laser spot region under certain conditions.

The details of the calculation procedure for the REP simulation are shown in Fig. 3. The REP simulation starts with the charge equation in order to solve the electric field. After then, the temperature inside the channel is solved from the energy conservation equation from the Joule heating, which is due to the electric field. The velocity of medium is solved from the Navier-Stokes equation. The electrothermal force as a volumetric force is the main source to generate the movement of the medium. It is noted that the electrothermal force is a function of the external frequency. Finally, the concentration of particles is solved by the concentration equation which has the mobilities of both the DEP flow and the electrothermal flow. After solving all equations subsequently, the convergence should be checked by user's criteria. If the criteria are satisfied, the simulation can go the next time step.

In this study, the flow chart was revealed to study the relationship between the ACET effect and DEP effect on the particles, as shown in Fig. 4. The program begins from a computation of the fully coupled equations. The next step is to calculate the two loops. The first loop is to study the effects of the DEP mobility and external voltage on the particle concentration. If the velocity by the DEP effect is higher than the velocity by the ACET effect, then the program moves to the next step; otherwise, the program begins to recalculate the ACET velocity and DEP velocity by updating the DEP mobility. The next step is to calculate the ACET velocity and particle concentration by increasing the external voltage. The second loop is to study the effect of the AC frequency. As the frequency changes, the ACET velocity and DEP velocity change simultaneously. The effect of frequency at which the particles are concentrated or scattered can be investigated by comparing the velocity by the DEP with the velocity by the ACET. Table I lists the input parameters of the simulation. The parameters used in the experiment²⁴ are used as the input parameters for the simulation. Finally, all simulation results obtained from the various study cases were compared with the experimental results.

For validation of the presented model, mesh independence test are performed. The changes in averaged concentration are checked with increasing the number of elements. The constant

FIG. 3. Calculation procedure for the REP simulation.

results are obtained above around 90 000 elements. In this study, the 95 897 elements are used for the simulation, and the number of degrees of freedom was measured for 561 304. The Backward Differentiation Formula (BDF) method was utilized as a nonlinear time-dependent solver for the solution.

FIG. 4. Flow chart for the multi-physics simulation.

TABLE I. Parameters and value used in the simulation.

Parameter	Value
Electrode width (m)	600×10^{-6}
Particle aggregation region (m)	50×10^{-6}
Voltage (V_{pp})	16.5, 19.5, 22
Frequency (kHz)	Case study
Dynamic viscosity (Pa·s)	1.002×10^{-3}
Density of medium (kg/m^3)	1000
Electrical conductivity of medium (S/m)	0.3×10^{-3}
Electrical conductivity of particle (S/m)	0.038×10^{-3}
Relative permittivity of medium	80.08
Relative permittivity of particle	40
Thermal conductivity of medium (W/m·K)	0.58
Heat capacity of medium (J/(kg·K))	4186
Temperature peak increase (ΔK)	10
Simulation time (s)	90
Particle size (μm)	5
Fitting parameter a	0.0015
Fitting parameter b	0.00015
Diffusion coefficient (m^2/s)	10^{-9}
μ_{DEP}	Case study

IV. RESULTS AND DISCUSSION

A. Electrothermal-hydrodynamic results

After generating a non-uniform electric field induced by two electrodes under an AC electric field within the micro-channel, the formation of a 3-dimensional toroidal microvortex due to the REP effect was analyzed numerically using COMSOL® software. In addition, the local heating by laser illumination and Joule-heating due to the non-uniform electric field were examined to form a temperature gradient inside the micro-channel. Fig. 5 shows the uniform electric field generated at 22 V_{pp} and 5 kHz. The surface color shows the strength of the electric potential, and the arrow color shows the current density norm. For 16.5 and 19.5 V_{pp} , the electric

FIG. 5. Electric field profile near the illumination region.

field distribution was similar to the result obtained from 22 V_{pp} with 5 kHz. The current density is high at the left side (physically at center of the channel), which is the laser illumination region, because changes in the dielectric constant and conductivity gradient due to the non-uniform temperature gradient made by the laser illumination source occur near the location with a high concentration of particles. Therefore, the high attractive force produced by the effect of the dipole on the particles and non-uniform electric field near the gold (Au) electrode with high temperature generates a high current density. The Joule-heating source by the electric field and the local temperature condition according to the Lorenz peak function produce a temperature distribution inside the micro-channel by solving the energy equation (Eq. (7)).

Fig. 6(a) shows the calculated temperature field profile. The isothermal boundary condition was set to the top of channel as the ambient temperature (293.15 K). The maximum change in temperature at the center of laser spot region was approximately 10 K higher than that of the other. Fig. 6(b) compares the temperature profile along the channel length in the present simulation with that obtained from Kumar *et al.*¹⁹ As the laser power increases, the maximum change

FIG. 6. Temperature field: (a) Temperature profile in microchannel, (b) temperature field distribution near the illumination region.

in temperature increases near the center of the laser spot region. Table II shows the change in temperature under the condition of both Joule-heating and laser illumination along with that under the condition of Joule-heating only. The simulation shows that laser illumination makes a much more effective contribution to increase the change in temperature than the Joule-heating effect. As a result, the effect of natural convection due to laser illumination is of importance for obtaining the maximum temperature gradient.

Fig. 7(a) shows the hydrodynamic flow motion by the REP effect. The surface color means the velocity of the fluid inside the channel. The streamline and arrow are overlapped to clarify the flow direction and the velocity strength during the concentration process. The simulation shows that the REP force enhances the electrothermal flow to lead the particles into the center of the laser illumination region. When laser illumination was applied to the spot region, the maximum velocity of the hydrodynamic flow was $7.7\mu\text{m/s}$ and the circulation of flow took place at the off-spot region. In addition, in the case where the external voltage was provided to the electrodes, miniscule hydrodynamic flow occurred due to the non-uniform electric field. The velocity of flow was only $4.4\mu\text{m/s}$. On the other hand, in the case that both laser illumination and electric field contributed together in the system, a strong microvortex was induced due to several factors, such as changes in density due to the non-uniform temperature gradient, dielectric constant, and conductivity. The maximum velocity reached up to $20.44\mu\text{m/s}$. The fluid flows to the upward at the centerline (y-axis) of the channel center and flows from the left to the right at the bottom of channel, so that the sink-type vortex can enhance the micro/nano particles floating on the fluid to concentration on the surface of the laser spot region.

Fig. 7(b) presents the vorticity field with respect to the electric potential. The vorticity increases with increasing electric potential. The high vorticity due to the high electric potential enables a strong toroidal microvortex to enhance the concentration of particles. On the other hand, there is a limitation to increase electric potential because a very high voltage source generates bubbles due to the high temperature, which is due to Joule-heating, so that the undesirable bubbles disturb the particle concentration. Therefore, it is desirable to determine the optimal electric potential for the system.

B. Concentration results

Fig. 8(a) presents the concentration of particles with respect to the electric potential at a constant DEP mobility. In the simulation, the conductivity, permittivity, and size of the particles were used for the constant DEP mobility. The high voltage induced the electrothermal velocity; hence, the DEP force due to non-uniform polarization induces the rapid concentration of particles with the help of the electrothermal velocity.

For a more detailed and precise comparison, dimensionless graphs were overlapped using e-folding time ($1/e$) for both the simulation result and experimental result. The dimensionless graphs show that simulation results were well matched with the experimental results, regardless of the electric potentials after the e-folding time of 2 as shown in Fig. 8(b). A discrepancy between the simulation results and experimental results occurs due to experimental errors within an e-folding time of 2.

The change in the concentration of particles was also investigated to determine the effects of the frequency of AC by sweeping the AC frequency, while maintaining a constant DEP mobility remained constant for the simulations. Fig. 9(a) shows the concentration distribution with

TABLE II. Comparison of the temperature increase with Joule-heating and Laser illumination.

Voltage (V_{pp})	Only Joule-heating Temperature increase ΔT (K)	Joule-heating + laser Temperature increase ΔT (K)
16.5	1.05	10
19.5	1.47	
22.0	1.87	

(a)

(b)

FIG. 7. Microfluidic flow regime: (a) Microfluidic flow field profile, (b) vorticity field with respect to the electric potential.

respect to the AC frequency at 16.5 V_{pp} . Particle aggregations occurred successfully when the DEP force was higher than the ACET force. The important feature is that the concentration efficiency decreases with the increase in AC frequency. This is caused by the decreasing attraction drag force by the ACET term as the input frequency increases, so that the particles disperse toward the outside. To clarify this phenomenon, the maximum velocities of the ACET effect and DEP effect were examined with respect to the AC frequency.

FIG. 8. Concentration of particles in microchannel: (a) Concentration profile with respect to the voltage, (b) comparison between the simulation and experimental results with dimensionless parameters.

Fig. 9(b) shows the two maximum velocities, the maximum velocity due to the ACET effect and the maximum velocity due to the DEP effect at different AC frequencies. Two maximum velocities were not changed for 1 MHz ($< f_L$) under the condition that the DEP force remains higher than the ACET force. Over this frequency range, the concentration of particles was well focused. On the other hand, the velocities decreased rapidly over the frequency range ($f_M \sim f_H$), which is called the transient frequency range. After the cutoff frequency, (f_H), the velocity due to the DEP force approached a negative value, so that the concentration of particles was not focused. ACET flow plays a role in sending particles quickly to the laser illumination region, and the DEP force helps focus the particles at that position.

Fig. 10(a) presents a mapping plot in which the focused concentration obtained from the simulation was compared with the experimental result by Wang *et al.*²⁴ In macrophysics, the concentration of particles was strongly focused at low frequency because of the strong electrothermal force, but after a transient frequency, the concentration decreased and after the cutoff frequency, the concentration became dispersed due to the weak electrothermal force.

In this study, the *Staphylococcus aureus* (bacteria) as a real bio-particle is applied into the proposed model using the dielectric properties which are obtained from Sanchis *et al.*²⁶ in order to validate the our numerical model. The red line in Fig. 10(a) shows the change in concentration

FIG. 9. Effect of particle concentration with respect to the frequency: (a) Concentration distribution with respect to frequency, (b) maximum velocity of the ACET effect and DEP effect with respect to frequency.

of the *Staphylococcus aureus* with respect to the external frequency. When the numerical simulation of the real bio-particle is compared with that of the artificial bio-particle (bead), it is shown that the concentration of the real bio-particle is lower than that of the bead. This is caused by which the DEP force decreases with decreasing the DEP mobility because the bio-particle has the lower electrical conductivity and permittivity than the bead. In addition, the cutoff frequency of the bio-particle takes place more quickly with respect to frequency than that of the bead. This is the reason why the DEP force of the bio-particle becomes faster negative value than that of the bead. As a result, the REP technique is applicable both for bead based bioassays and bio-particles as bacteria.²⁵

The simulation was also conducted under the condition of 16.5 V_{pp} with 5 kHz to examine the effect of the particle (bead) size on the focusing performance of particles, as shown in Fig. 10(b). The result shows that the focusing performance of the particles decreases and the ratio of the ACET velocity and the DEP velocity increases with increasing particle size. From this result, it is expected that the separation according to size would be possible in cases in which many particles with different sizes are mixed.

V. CONCLUSIONS

This study examined the concentration of particles in a microchannel under the condition of both the electric potential and laser illumination, which can be controllable and enhance the concentration performance using a 3-dimensional microvortex. A mathematical model of the REP technique coupled with the concentration equation of particles was introduced in detail to

FIG. 10. Applications of REP technique: (a) Characteristic map of the particles' concentration with respect to frequency, (b) characteristic map of the particles' separation with respect to the particle size.

show that the REP force generates local electrothermal flow that enhances or compresses a DEP force. In addition, the simulation model was validated by a comparison with the experimental results. The results showed that a stagnation point, which was made by the sink-type 3-dimensional microvortex, formed at the center of laser illumination spot, and the DEP force is

the main force to focus the concentration of microparticles on the center of the laser illumination spot. Furthermore, focusing was not made in the case when the DEP force was smaller than the ACET force or similar to the ACET force.

In this study, the main contribution of this paper is that the ACET effect is separated from the DET force in the REP technique. To the best of the authors' knowledge, the numerical simulation on focusing performance via the laser-induced REP technique was first conducted and compared with the experimental result. The REP technique was proved to be a powerful method for rapid concentration of particles in a microchannel by the precise new mathematical models being developed in this study.

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