Microdevice With Planar Corrugated Electrodes for Dielectrophoretic Focusing of Micro-Particles

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ABSTRACT This paper conceptualizes and mathematically models a dielectrophoretic microdevice with planar corrugated electrodes for focusing micro-particles at any lateral location along the width of the micro-scale flow passage; two of these electrodes are placed on the top and bottom surfaces of the micro-scale flow passage with the electrodes on the top and bottom aligned with each other to form a pair. The mathematical model includes equations of motion, Navier-Stokes equations, and equations of electric voltage and field and considers the influence of several phenomena, including inertia, sedimentation, drag, virtual mass and dielectrophoresis on the focusing of micro-particles. The mathematical model is solved using the finite difference method. The mathematical model is used for parametric study, thereby revealing that the performance metrics related to focusing depend on the geometric (micro-scale flow passage and electrode dimensions) and operating (applied electric voltages and volumetric flow rate) parameters of the microdevice. The mathematical model allows for determining the operating and geometric parameters for achieving the desired performance metrics based on constraints. The mathematical model is validated using experimental data from the literature.

INDEX TERMS Dielectrophoresis, focusing, finite difference method, microfluidics, modeling, microelectrodes, Navier-Stokes equations, transducers.

I. INTRODUCTION Microfluidic devices employ flow passages smaller than 1 mm and thus, exhibit several positive attributes including minimal requirements of samples and reagents, high sensitivity and specificity, minimal consumption of power, small footprint, and portability. Microfluidic devices are employed for realizing several operations, including focusing [1], [2]. The arrangement of nonuniformly dispersed microparticles is known as focusing, and the ordering that puts them in a single line is called 3D focusing [1], [2]. Focusing is a prerequisite for separating microparticles [1], [2]. Micro-particles must be subjected to actuation forces to realize focusing, and a phenomenon of choice for actuation force is dielectrophoresis (DEP) [1], [2]. DEP is the movement of electrically inert but polarizable micro-particles while being dispersed in a dielectric solution and exposed to an electric field that varies spatially [3], [4]. pDEP (positive DEP) and nDEP (negative DEP) address the pull experienced by a micro-particle toward the highest and lowest variation of the electric field intensity, respectively [3], [4]. This article proposes a new design for planar electrodes for achieving DEP-based focusing in microfluidic devices. A schematic of the planar corrugated electrodes and the electrode configuration are provided in Fig. 1.a. The device consists of two sets of planar corrugated electrodes with each pair placed adjacent to a sidewall, as noticeable in Fig. 1. One planar corrugated electrode of each set is placed on the micro-scale flow passage’s upper surface, while the same pair’s other planar corrugated electrode is placed on the micro-scale flow passage’s lower surface. This electrode configuration makes it possible to focus micro-particles at any position in the direction of the width of the micro-scale flow passage. The working of the device is provided in Fig. 1. Each electrode pair on both sides subject the micro-particle to equal nDEP, thereby 3D focusing them at the center of the micro-scale flow passage (Fig. 1.b). Moreover, micro-particles are focused at any desired location along the width of the micro-scale flow passage when the nDEP...
generated by each set of electrodes is different, as shown in Fig. 1c.

Lin et al. [5] combined sheath flow and nDEP to realize 3D focusing of micro-particles in a microdevice employing planar electrodes on opposing surfaces in the vertical direction; horizontal and vertical focusing are realized using sheath flow and nDEP, respectively. Yu et al. [6] constructed a microdevice with circular electrodes arranged in an interdigitated transducer configuration (IDT) inside the micro-scale flow passage for DEP-enabled 3D focusing at the micro-scale flow passage center. Holmes et al. [7] realized a dielectrophoretic microdevice with two planar trapezoidal electrodes on opposing surfaces in the vertical direction of the micro-scale flow passage to achieve 3D focusing of micro-particles at the center of the micro-scale flow passage. Yan et al. [8] fabricated and tested a microdevice employing DEP and hydrophoresis simultaneously for 3D focusing of micro-particles next to the sidewalls; the device employed interdigitated transducer (IDT) electrodes on the lower surface, in the vertical direction, and ridges on the upper surface, in the vertical direction. Yung et al. [9] realized a microdevice with two continuous electrodes on each of the opposing surfaces in the vertical direction of the micro-scale flow passage for achieving 3D focusing at high throughput; all electrodes were independently controllable, which allowed for positioning microparticles at any desired location over the cross-section of the micro-scale flow passage. Alnaimat et al. [10], [11] modeled AC-DEP-based microdevices for 3D focusing of micro-particles at any location in the direction of the width of the micro-scale flow passage; Alnaimat et al. [10] employed several finite-sized IDT planar electrodes placed on the micro-scale flow passage on either side, while Alnaimat et al. [11] employed two sets of planar electrodes placed on the micro-scale flow passage on either side. Alazzam et al. [12] conceptualized a dielectrophoretic microdevice employing a continuous electrode on the micro-scale flow passage’s upper and lower surfaces for 3D focusing micro-particles simultaneously at multiple locations in the direction of the width of the micro-scale flow passage; the lower electrode has perforations. Krishna et al. [13] modeled 3D focusing in a dielectrophoretic microdevice using two planar right-triangular electrodes located on the micro-scale flow passage’s upper and lower surfaces.

This is the first work to propose the electrode design shown in Fig. 1 and to analyze the performance of the microdevice employing it. The chip-to-world electrical connection in the microdevice with the proposed electrodes is simpler than that employing vertical IDT electrodes, thus allowing the application of DEP over greater axial distances, which in turn enables the microdevice to handle high throughput. Additionally, the nDEP force in the upward direction can balance the downward sedimentation force, thereby eliminating problems related to sedimentation of the micro-particles. The mathematical model developed in this work is dynamic and allows for determining the transient behavior; knowledge of the transient behavior is required for estimating the length of the device for achieving the desired performance metrics.

II. MATHEMATICAL MODELING

Equations describing the motion of micro-particles, electric potential/field inside the micro-scale flow passage, and carrier fluid velocity inside the micro-scale flow passage make up the model. Equation (1) represents the equations of motion, while (2) and (3) detail the electric voltage and field inside the micro-scale flow passage, respectively. Equation (4) details the velocity of the carrier fluid in the micro-scale flow passage and is a reduced version of the Navier-Stokes equations based on the assumption that flow is one dimensional. In microdevices processing micro-particles, the volumetric flow rate is usually small, which enables the flow to be fully developed almost from the inlet of the same; additionally, the small size of the flow passage of the microdevice allows us to neglect the influence of gravity on the fluid flow. The left-hand side term of (1) corresponds to the phenomenon of inertia [8]. The 1st term on the right-hand side of (1) accounts for the influence of drag; the 2nd and 3rd terms on the same side of (1) represent sedimentation and DEP forces, respectively [8]. The right-hand side’s last term represents the virtual mass force [8]. The inclusion of
where \( \mathbf{x} \) is the displacement vector, \( m \) is the mass, \( r \) is the radius, \( \rho \) is the density, \( g \) is the acceleration due to the gravity vector, \( \mu \) is the viscosity, \( \varepsilon \) is the dielectric constant, \( E_{RMS} \) is the RMS electric field vector, \( \varphi_{RMS} \) is the RMS voltage, \( \mathbf{u} \) is the velocity vector, \( P \) is the pressure, \( x \) represents the x-direction, \( e \) represents micro-particles, and \( cf \) represents the carrier fluid. As mentioned earlier, the micro-particles must be subjected to nDEP, so the operating frequency must be very high (>10 MHz) [14]; operating at high frequency eliminates the influence of electrical conductivity of the micro-particle and carrier fluid on the DEP and the risk of electrolysis on the electrodes [9], [13], [14]. The variation in the Clausius-Mossotti factor with respect to frequency for micro-particles such as polystyrene and silica micro-particles as well as cells are available in the literature [13], [14]. The initial conditions of (1) are the displacements and velocities at the inlet of the microdevice. At the beginning, micro-particles can be anywhere along the lateral and vertical directions of the inlet of the micro-scale flow passage; the initial x-displacement is thus zero. The initial velocities are the carrier fluid velocities at the above-mentioned initial displacements. The displacements at the starting position are shown in (5), and the velocities at the starting position are shown in (6); as indicated in Fig. 2, \( Y \) and \( Z \) represent any displacement along the lateral and vertical directions of the micro-scale flow passage, respectively.

\[
\begin{align*}
\mathbf{x}_e|_{t=0} &= X_e = [0, Y, Z]^T \\
\frac{d}{dt} \mathbf{x}_e|_{t=0} &= \mathbf{u}_{ef}\mathbf{x}_e = [u_{ef,x}, x_e, 0, 0]^T
\end{align*}
\]

The finite difference method (FDM) is employed for solving (1) in conjunction with (5) and (6). The 1st and 2nd order differential terms of (1) are replaced with central difference terms resulting in (7); the time step in (7) is taken to be \( 10^{-5} \) s, and \( n \) represents the time step. Terms such as the velocity of the carrier fluid and electric field appearing in (7) are evaluated at the current position of the micro-particle.

\[
\begin{align*}
\mathbf{x}_e^{n+1} &= \frac{2\mathbf{x}_e^n - \left( 1 - \frac{3\pi \mu_{ef}\Delta t}{m_{eq}} \right) \frac{\partial^2 \varphi_{RMS}}{\partial x^2} \mathbf{x}_e^n}{1 + \frac{3\pi \mu_{ef}\Delta t}{m_{eq}}} \\
&+ \left( \frac{\rho_{ef} V_e \Delta t^2}{2m_{eq}} \right) \mathbf{u}_{ef}\mathbf{x}_e^n + \frac{\left( \frac{\rho_{ef}}{\rho_{ce}} - 1 \right) \Delta t^2 \mathbf{g}}{m_{eq}} \\
&+ \frac{2\pi \varepsilon_{ef}\varepsilon_{cf} \Delta t^2}{m_{eq}} \mathbf{u}_{ef}\mathbf{x}_e^n + \frac{\left( \frac{\rho_{ef}}{\rho_{ce}} - 1 \right) \Delta t^2 \mathbf{g}}{m_{eq}} \\
&+ \frac{\varepsilon_{ef} \varepsilon_{cf} \Delta t^2}{m_{eq}} \mathbf{u}_{ef}\mathbf{x}_e^n + \frac{\left( \frac{\rho_{ef}}{\rho_{ce}} - 1 \right) \Delta t^2 \mathbf{g}}{m_{eq}}
\end{align*}
\]

Equation (2) is also solved using FDM. However, it is computationally cumbersome to solve it for the entire micro-scale flow passage; thus, Eq. (2) is solved just for a repeating unit of the micro-scale flow passage, and the voltage in the repeating
unit is adapted over the whole micro-scale flow passage. The repeating unit is shown in Fig. 3. The boundary conditions of (2) include a known voltage on each of the electrodes while the remaining surfaces of the micro-scale flow passage are kept insulated; the boundary conditions of the repeating unit are shown in Fig. 3.

For applying FDM, the $2^{nd}$-order differential terms of (2) are exchanged with $2^{nd}$-order central difference terms to obtain (9). Equation (9) is applied to all nodes, except those on the electrodes, in the computational domain, thereby leading to the generation of multiple linear equations that, when solved simultaneously, provide the electric voltage inside the nodes. The Gauss-Seidel method is used for solving the system of linear equations, and the stopping criterion is $10^{-15}$ V. In (9), $\alpha$ represents the node number along the $x$-direction, while $\beta$ and $\gamma$ represent the node numbers along the $y$- and $z$-directions, respectively. Figure 4 provides a schematic of the distribution of nodes on the bottom surface of the repeating unit. The internode distance in the $x$-direction (axial direction), i.e. $\Delta x$, is kept at 4 $\mu$m, while the internode distance in the $z$-direction, i.e. $\Delta z$, is kept at 1 $\mu$m. The total nodes along the $x$-direction is $N_x$, while those in the other two directions ($y$-direction and $z$-direction) are $N_y$ and $N_z$. The internode distance in the direction along the width, i.e. the $y$-direction, must be selected such that nodes are present on the edge of the electrodes, as shown in Fig. 4. Thus, the internode distance in the $y$-direction is determined using (10) while ensuring that $N_y$ is an integer.

Application of (9) to nodes on the boundaries other than those occupied by the electrodes reveals the need for electric voltage outside the boundaries. For instance, the application of (9) to all nodes with $\alpha = 1$ requires electric voltage on nodes with $\alpha = -1$. The electric voltage on nodes outside the boundaries can be obtained from the boundary condition associated with these boundaries; thus, the electric voltage on nodes immediately outside the boundary is equal to the electric voltage on nodes immediately inside the boundary, as shown in the Appendix. Equations, similar to (9), relevant for determining the electric voltage on the boundaries are also provided in the Appendix.

The electric field is determined numerically using (3) based on information related to electric voltage, and for this, the differential term of (3) is replaced by $2^{nd}$-order central difference terms. For all interior boundaries, $2^{nd}$-order central difference terms are used, while for those nodes on the faces/edges/corners, either forward/backward $2^{nd}$-order difference terms are used. Moreover, it is stressed here that among all nodes on the faces/edges/corners, the electric field is determined only for those nodes on the electrodes. Equations (11.1) to (11.3) can be used to determine the electric field on the nodes in the interior of the repeating unit. There are no electrodes on the boundaries in the $x$- and $y$-directions, so the electric field is zero on the same. The boundaries in the $z$-direction have electrodes; thus, the electric field on the regions occupied by electrodes needs to be determined, and the equations for determining the electric field are provided in the Appendix.
A central difference scheme (2\textsuperscript{nd} order) is used to determine the electric field as calculated from (12). The gradient of the square of the magnitude of the electric field can be determined for the purposes of calculating the DEP force. The gradient of the square of the electric field is numerically determined as shown in (12).

Once the different components of the electric field are determined, the gradient of the square of the magnitude of the electric field can be determined for the purposes of calculating the DEP force. The gradient of the square of the electric field is numerically determined as shown in (12). A central difference scheme (2\textsuperscript{nd} order) is used to determine this parameter for all nodes except those on the faces in each direction. Forward/backward difference schemes (2\textsuperscript{nd} order) are used to determine the same parameter on nodes located on the faces, in each direction, of the repeating unit.

\[
\frac{\partial}{\partial x} E_{\text{RMS}}^2 = \frac{\left( E_{\text{RMS}}^2|_{\alpha+1,\beta,\gamma} - E_{\text{RMS}}^2|_{\alpha-1,\beta,\gamma} \right)}{2\Delta x} \\
\text{for } 1 < \alpha < N_x, \quad 1 \leq \beta \leq N_y, \quad 1 \leq \gamma \leq N_z
\]  
(12.1)

\[
\frac{\partial}{\partial y} E_{\text{RMS}}^2 = \frac{\left( E_{\text{RMS}}^2|_{\alpha,\beta+1,\gamma} - E_{\text{RMS}}^2|_{\alpha,\beta-1,\gamma} \right)}{2\Delta y} \\
\text{for } 1 \leq \alpha \leq N_x, \quad 1 < \beta < N_y, \quad 1 \leq \gamma \leq N_z
\]  
(12.2)

\[
\frac{\partial}{\partial z} E_{\text{RMS}}^2 = \frac{\left( E_{\text{RMS}}^2|_{\alpha,\beta,\gamma+1} - E_{\text{RMS}}^2|_{\alpha,\beta,\gamma-1} \right)}{2\Delta z} \\
\text{for } 1 \leq \alpha \leq N_x, \quad 1 \leq \beta \leq N_y, \quad 1 < \gamma < N_z
\]  
(12.3)

\[
\frac{\partial}{\partial x} E_{\text{RMS}}^2 = \frac{\left( E_{\text{RMS}}^2|_{\alpha+1,\beta,\gamma} - E_{\text{RMS}}^2|_{\alpha-1,\beta,\gamma} \right)}{2\Delta x} \\
\text{for } \alpha = 1, \quad 1 \leq \beta \leq N_y, \quad 1 \leq \gamma \leq N_z
\]  
(12.4)

\[
\frac{\partial}{\partial x} E_{\text{RMS}}^2 = \frac{\left( E_{\text{RMS}}^2|_{\alpha,\beta+1,\gamma} - E_{\text{RMS}}^2|_{\alpha,\beta-1,\gamma} \right)}{2\Delta x} \\
\text{for } \alpha = N_x, \quad 1 \leq \beta \leq N_y, \quad 1 \leq \gamma \leq N_z
\]  
(12.5)

\[
\frac{\partial}{\partial y} E_{\text{RMS}}^2 = \frac{\left( E_{\text{RMS}}^2|_{\alpha,\beta+1,\gamma} - E_{\text{RMS}}^2|_{\alpha,\beta-1,\gamma} \right)}{2\Delta y} \\
\text{for } 1 \leq \alpha \leq N_x, \quad \beta = 1, \quad 1 \leq \gamma \leq N_z
\]  
(12.6)

The gradient of the square of the magnitude of the electric field as calculated from (12) can be directly used in (5) and (8) when the micro-particle occupies a node; however, when the micro-particle occupies other locations, the average of the gradient of the square of the magnitude of the electric field associated with the eight neighboring nodes is used in (5) and (8).

The flow is one dimensional in the micro-scale flow passage because the carrier fluid velocity in the direction of the width and depth of the micro-scale flow passage is nonexistent. Equation (4) is the governing equation of the axial fluid flow equation. A no-slip boundary condition exists on the boundaries of the micro-scale flow passage, and this is the boundary condition associated with (4), as shown in Fig. 5. Equation (4) is calculated using FDM. For this, the 2\textsuperscript{nd}-order differential terms are exchanged with 2\textsuperscript{nd}-order central difference terms, which upon rearrangement results in (13). Equation (13) is applied to all nodes.
across the cross-section, except those on the boundaries, and this results in a system of linear equations. The system of linear equations is solved simultaneously to obtain the carrier fluid’s velocity over the cross-section of the micro-scale flow passage; the Gauss-Seidel method is used for solving the system of equations, and the stopping criterion is $10^{-10}$ m/s.

The internode distances, i.e. $\Delta y$ and $\Delta z$, are maintained at 0.5 $\mu$m for solving (4); $r$ and $s$ are the node numbers along the directions of the width ($y$-direction) and height ($z$-direction) of the micro-scale flow passage. It is stressed here that it is not necessary for the node numbers employed in (9) to match those employed in (13). The total numbers of nodes along the direction of width ($y$-direction) and height ($z$-direction) of the micro-scale flow passage are taken as $m$ and $n$, respectively.

$$u_{cf,x} \bigg|_{r,s} = \left( \frac{u_{cf,x} \bigg|_{r+1,s} + u_{cf,x} \bigg|_{r-1,s}}{2 \Delta y} + \frac{u_{cf,x} \bigg|_{r,s+1} + u_{cf,x} \bigg|_{r,s-1}}{2 \Delta z} - \frac{1}{\mu_{cf}} \frac{dp}{dt} \right)$$

for $1 < r < m, \quad 1 < s < n$ (13)

In (7), the total derivative of velocity of the carrier fluid is required and is determined as provided in (14). For the steady-state condition, the right-hand side’s final term is nonexistent. The total derivative of the carrier fluid velocity in the $y$- and $z$-directions is zero, as the velocity in these directions is zero.

$$\frac{du_{cf}}{dt} = \frac{\partial u_{cf,x}}{\partial x} \frac{dx}{dt} + \frac{\partial u_{cf,x}}{\partial y} \frac{dy}{dt} + \frac{\partial u_{cf,x}}{\partial z} \frac{dz}{dt} + \frac{\partial u_{cf}}{\partial t}$$

Equation (13) is solved by assuming a value for the pressure gradient, and based on the velocities subsequently determined, the volumetric flow rate is determined using (15). If the volumetric flow rate is not equal to the desired value, a new value for the pressure gradient is assumed, and the whole procedure is repeated. The volumetric flow rate must be determined since it rather than the pressure gradient is the widely accepted operating parameter.

$$Q = \int \int u_{cf,x} dA$$

$$= \sum_{1 \leq r \leq m-1} \sum_{1 \leq s \leq n-1} \left( \frac{u_{cf,x} \bigg|_{r+1,s} + u_{cf,x} \bigg|_{r,s+1} + u_{cf,x} \bigg|_{r+1,s+1} + u_{cf,x} \bigg|_{r+1,s+1}}{4} \right) \Delta y \Delta z$$

(15)

The performance metrics of the device are the horizontal ($\Delta w$) and vertical ($\Delta d$) focusing parameters, as shown in (16) and (17), respectively [13]. $\bar{Y}$ and $\bar{Z}$ represent the micro-particle displacements along the horizontal and vertical directions for perfect 3D focusing. $N$ represents the number of micro-particles released from the inlet; for all calculations, micro-particles are released from 81 different locations, and $y_{cf}$ and $z_{cf}$ represent the final displacement of each of the $N$ micro-particles. Mathematically, focusing parameters represent the standard deviation of the final displacements of $N$ micro-particles; the magnitude of focusing parameters decreases with improvement in focusing.

$$\Delta w = \sqrt{\frac{\sum_{i=1}^{N} (\bar{Y} - y_{cf})^2}{N - 1}}$$

(16)

$$\Delta d = \sqrt{\frac{\sum_{i=1}^{N} (\bar{Z} - z_{cf})^2}{N - 1}}$$

(17)

A code in MATLAB is developed to solve all equations and to calculate the parameters. The code requires the geometric and operating parameters as well as internode distances and time steps as inputs. Equation (2) is initially solved using the code to obtain the electric potential inside the repeating unit, following which (3) is calculated. The next part of the code involves solving (4), and the final part of the code involves solving (1). The equation associated with drag assumes that the particle Reynolds number is negligible; this is true for microdevices, as the micro-particles are dragged in the axial direction by the carrier fluid. The model detailed here assumes that the presence of the micro-particle does not influence the velocity of the carrier fluid and profile of electrical parameters in the micro-scale flow passage; thus, the model is applicable to all cases where the size of the micro-particle is much smaller than the size of the micro-scale flow passage. Additionally, the model assumes that the sample is dilute, thereby eliminating the interaction between micro-particles; Loth [15] provided a criterion for satisfying this assumption.

### III. MODEL VALIDATION

Experimental data from Holmes et al. [7] are employed to validate the model. Fig 6.a provides the diagrammatic representation of the microdevice of Holmes et al. [7], and the trajectories of the latex micro-particles in the device for applied voltages of zero and 20 $V_{pp}$ are shown in Fig. 6.b and Fig. 6.c, respectively. Holmes et al. [7] provided the trajectory of the micro-particles only at the end section of the electrodes, as shown in Fig. 6.b and Fig. 6.c. Appropriate choice of the dimensions of the device, conceptualized in this work, will make it resemble the device of Holmes et al. [7]. The data extracted from Holmes et al. [7] include micro-scale flow passage width (250 $\mu$m), micro-scale flow passage height (40 $\mu$m), electrode widths (55 $\mu$m and 105 $\mu$m), electrode length (500 $\mu$m), micro-particle type and diameter (latex and 6 $\mu$m), applied electric voltage (20 $V_{pp}$), type of carrier fluid (water) and maximum velocity of flow (1 mm/s at $\varphi_1 = \varphi_2 = 20$ $V_{pp}$). The microdevice developed by Holmes et al. [7] resembles the microdevice detailed in this work when $H_{ch} = 40$ $\mu$m, $W_{ch} = 250$ $\mu$m, $L_1 = L_2 = 500$ $\mu$m, $w_{1} = 105$ $\mu$m, $w_{2} = 55$ $\mu$m, and $n = 1$. Figure 6.d and Fig. 6.e show the trajectories of the latex micro-particles determined using the model developed in this work for...
applied electric voltages of zero and 20 $V_{pp}$, respectively. Figure 6.f and Fig. 6.g provide the comparison between trajectories obtained from the experiment and model and are generated by overlaying Fig. 6.d and Fig. 6.e on Fig. 6.b and Fig. 6.c, respectively. It is noticeable that there is very good agreement between the trajectories from the experiment and model, thereby validating the latter. Holmes et al. [7] conducted experiments using additional applied voltages; however, they did not provide any information on flow rate, so those cases are not considered for validation purposes. Holmes et al. [7] did not provide information on the flow rate for the experiments in the absence of applied voltages; however, knowledge of flow rate is not required for purposes of comparison, as trajectories are not influenced by flow rate in the absence of applied voltages. Fig. 6.b shows that latex micro-particles are more concentrated near one of the sidewalls than the other, unlike in Fig. 6.d. The reason for this is the difference in the distribution of latex micro-particles at the inlet of the microdevice; latex micro-particles are nonuniformly distributed at the inlet of the microdevice during experiments, while they are released uniformly in the case of the model. The distribution of latex micro-particles at the inlet does not lead to unequal concentration across the width of the micro-scale flow passage when the applied voltage is 20 $V_{pp}$ since focusing occurs.

**IV. RESULTS AND DISCUSSIONS**

The effect of parameters (operating and geometric) on the performance of the microdevice is analyzed in this section. The performance of the device is evaluated in terms of...
performance metrics (horizontal and vertical focusing parameters). The parameters analyzed include micro-scale flow passage width/depth, applied electric voltages, electrode dimensions, and volumetric flow rate. For this analysis, polystyrene micro-particles \( (r_e = 3 \, \mu m, \epsilon_e = 2.55 \) and \( \rho_e = 1050 \, kg/m^3) \) are used as the microparticles and water is used as the carrier fluid \( (\epsilon_{cf} = 78.5, \rho_{cf} = 998 \, kg/m^3, \) and \( \mu_{cf} = 0.001 \, Pa.s) \) [10].

Fig. 7 provides the velocity distribution over a cross-section of the micro-scale flow passage. The velocity profile shown here is the same as that on all cross-sections of the micro-scale flow passage. The velocities at the boundaries are zero, as dictated by the boundary conditions of (4). Additionally, the velocity increases from the boundaries to the center of the micro-scale flow passage, as expected. Fig. 8 shows the voltage profile on different planes along the vertical direction of the micro-scale flow passage for equal applied voltages, and Fig. 9 shows the same for the case of unequal applied voltages. These voltage profiles confirm proper calculation of (2) for both cases of applied voltage - equal and unequal. The number of electrodes \( (n) \) is set equal to 20 in Fig. 8 and Fig. 9. Figure 10 shows the trajectories (red colored) of the micro-particles for equal and unequal applied voltages; the projections of these trajectories onto vertical (black colored) and horizontal (blue colored) planes are also presented. The micro-particles are released from multiple locations, 81 to be specific, across the inlet of the microdevice. Fig. 10 shows that with equal applied voltages, the micro-particles are focused at the center of the micro-scale flow passage. For the situation of unequal applied voltages, the micro-particles are focused away from the center of the micro-scale flow passage; the micro-particles are focused next to electrodes with the minimum applied electric voltage. In Fig. 10, it is noticeable that better focusing is achieved with equal applied voltages compared with the case of unequal applied voltages.

In the case of equal applied voltages, the DEP force is greater than in the case of unequal applied voltages, which is the reason for the observed difference in focusing.
Fig. 11 presents the variation in focusing parameters with changes in micro-scale flow passage height ($H_{ch}$) and width ($W_{ch}$). Figs. 11.a and 11.b are associated with equal and unequal applied electric voltages, respectively. It is noticeable that the degradation of the focusing parameters associated with the device occurs with increasing micro-scale flow passage dimensions. Increase in microscale flow passage dimensions reduces the electric field variation and magnitude, thereby leading to a reduction in the forces associated with DEP, which negatively affects the focusing parameters. Additionally, there is an increase in the residence time of the micro-particles with increasing dimensions of the micro-scale flow passage, which has a positive effect on the focusing parameters. However, the influence of the reduction in the DEP force on the focusing parameters dominates the influence of the increase in residence time on the same parameters and thus, the observed degradation in the focusing parameters with increasing dimensions of the micro-scale flow passage. It is also noticeable in Fig. 11 that the vertical focusing parameter is better than the horizontal focusing parameter for a specific height and width of the micro-scale flow passage. The magnitude and nonuniformity of the electric field are better along the height than along the width, which is attributed to the design and configuration of the electrodes, thereby leading to the observed trend in focusing parameters. It can also be noticed that the focusing parameters of the microdevice are better for the case of equal voltages than for the case of unequal voltages. For the case of equal applied voltages, the applied voltages are 15 $V_{pp}$, while for the case of unequal applied voltages, the applied voltages are
15 V_{pp}$ and $5 V_{pp}$. Thus, the DEP force inside the microdevice for the case of equal applied voltages is greater than that in the same microdevice with unequal applied voltages; therefore, the focusing parameters are better for the former than for the latter.

Fig. 12 shows the influence of applied electric voltages ($\varphi_1$ and $\varphi_2$) on the focusing parameters of the device. The influence of equal applied voltages on the focusing parameters is shown in Fig. 12.a, while the influence of unequal applied voltages on the same parameters is shown in Fig. 12.b. It is noticeable from the figures that an increase in focusing of the micro-particles in the device and subsequently the focusing parameters occur with the rise in applied electric voltages for equal and unequal applied voltages. Raising the applied electric voltages enhances the nDEP force experienced by the micro-particles, which causes improvement in the focusing. Moreover, it can be observed that the vertical focusing parameter is always better than the horizontal focusing parameter for almost all applied electric voltages, for the same reasons as detailed earlier with respect to Fig. 11. It can also be observed that the focusing of micro-particles is initially better with unequal applied voltages, while it is better with equal applied voltages at higher applied electric voltages. For equal applied voltages, both applied electric voltages are kept equal and varied from 5 to 20 $V_{pp}$, and for unequal applied voltages, one of the applied electric voltages is kept at 15 $V_{pp}$, while the other applied electric voltage is varied from $5 V_{pp}$ to $20 V_{pp}$. Thus, the voltage inside the microdevice is greater for the situation of unequal applied electric voltages over the range of 5 to 15 $V_{pp}$ when compared with the case of equal applied electric voltages, which leads to a greater nDEP force acting on the micro-particles for the former case. For the range of applied electric voltage from 15 to 20 $V_{pp}$, the voltage inside the microdevice is greater for the case of equal applied voltages when compared with the case of unequal applied voltage, and subsequently, the nDEP force in the former case is greater, leading to it exhibiting better focusing parameters.

The electrode dimensions’ effects on the focusing parameters are shown in Fig. 13. Fig. 13.a demonstrates the change in focusing parameters in relation to the electrode dimensions, i.e. $w_e$ and $L_2$, for equal applied voltages, while Fig. 13.b represents the same for unequal applied voltages. It is noticeable that focusing parameters improve with increasing electrode dimensions for both cases, i.e. equal applied voltage and unequal applied voltages. Increase in dimensions increases the electric field’s magnitude and nonuniformity as well as the residence time, and the combination of these factors leads to improvement in focusing, as depicted in Fig. 13. When varying $w_e$, $L_2$ is kept at 100 $\mu$m, and when varying $L_2$, $w_e$ is kept at 25 $\mu$m; $w_e$ is varied between 5 $\mu$m and 30 $\mu$m, while $L_2$ is varied between 12 and 200 $\mu$m. It is also observable...
that the focusing parameter along the height is better than the focusing parameter along the width for both the case of equal applied voltages and the case of unequal applied voltages. It is also noticeable in Fig. 13 that the focusing parameters are better for the case of equal applied voltages when compared with the case of unequal applied voltages. The cause of these two observations is the same as that detailed previously.

Fig. 14 shows the variation in focusing parameters with volumetric flow rate; Fig. 14.a is associated with equal applied voltages, while Fig. 14.b is associated with unequal applied voltages. It can be observed that increasing the volumetric flow rate degrades the focusing of micro-particles for both equal and unequal applied voltages. Additionally, it can be noticed in Fig. 14 that the focusing, at a specific volumetric flow rate, is better in the vertical direction that in the horizontal direction for both cases of applied electric voltage. The reasons for these two observations are the same as those detailed in conjunction with previous figures.

The mathematical model presented here is useful for determining the parameters (geometric and operating) needed for realizing the preferred performance metrics of the microdevice. It is stressed here that there are several combinations of parameters (geometric and operating) that provide the preferred performance metrics. The choice of the combination of geometric and operating parameters depends on the associated constraints. Fig. 15 provides a flowchart for use by designers for determining the best combination of parameters (geometric and operating) needed for realizing the desired performance metrics. As indicated in the flowchart, the design process requires several input parameters, such as micro-scale flow passage dimensions (\(W_{ch}\) and \(H_{ch}\)), electrode dimensions (\(L_1, L_2, w_{e1}, w_{e2}\)), micro-particle radius (\(r_e\)), applied electric voltages (\(\psi_1\) and \(\psi_2\)), volumetric flow rate (\(Q\)), pressure drop (\(\Delta P\)), properties of micro-particles and carrier fluid, number of electrodes (\(n\)), number of micro-particles released from the inlet of the microdevice (\(N\)) and their initial locations (\(Y\) and \(Z\)) and desired performance metrics (\(\Delta w^*\) and \(\Delta d^*\)). Once the design variables are selected, the velocity of the carrier fluid, electric potential and field are determined. This is followed by determining the final locations in the case of perfect 3D focusing of one of the micro-particles released from the inlet, i.e. \(Y(1)\) and \(Z(1)\); for this, the number of electrodes is assumed to be infinite (or very high). Here \(Y^*\) and \(Z^*\)
are the desired final locations in the conceptualized microdevice with infinite number of electrode pairs. If the final locations are not acceptable, a new combination of design variables is selected, and the whole procedure is repeated. Otherwise, the final displacements, i.e., $x_{cf}$, $y_{cf}$, and $z_{cf}$, of all micro-particles released from the inlet are determined. Afterward, the final displacements, specifically $y_e$ and $z_e$, of all micro-particles are used to calculate the performance metrics ($\Delta w$ and $\Delta d$) of the microdevice. The calculated performance metrics are compared with the desired performance metrics ($\Delta w^*$ and $\Delta d^*$), and if the former is greater than the latter, then a new combination of design variables is selected, and the whole procedure is repeated. During the design process, it is necessary to satisfy the design constraints along with achieving the required performance metrics; the design constraints could include the overall length of the microdevice, volumetric flow rate, pressure drop, applied electric voltages, micro-scale flow passage dimensions, electrode dimensions, etc.

V. CONCLUSION

This work conceptualizes an electrode design and electrode configuration for employment in a microdevice to realize dielectrophoresis-enabled 3D focusing of micro-particles; subsequently, a mathematical model is developed for studying the working of the microdevice employing the conceptualized electrode design. The electrode design enables 3D focusing of micro-particles at any location in the direction of the width of the micro-scale flow passage. By keeping the applied voltages the same, it is possible to realize 3D focusing of micro-particles at the center of the micro-scale flow passage, and by keeping the applied voltages unequal, it is possible to realize 3D focusing of micro-particles at positions other than the center of the micro-scale flow passage. The mathematical model takes into effect the forces related to phenomena such as dielectrophoresis, inertia, virtual mass, drag, and sedimentation. The mathematical model is used for parametric study to understand the effect of parameters such as micro-scale flow passage dimensions, electrode dimensions, and volumetric flow rate. According to the model, an increase in micro-scale flow passage dimensions and electrode dimensions as well as a reduction in volumetric flow rate enhance 3D focusing; this behavior is related to the increase in residence time and/or enhancement of dielectrophoretic force. A flowchart is provided that allows designers to follow a structured approach for purposes of designing the conceptualized microdevice.

APPENDIX

Replacement of differential terms of the boundary conditions associated with (2) by difference equations and subsequent arrangement reveals that the voltage on nodes immediately outside the boundary is equal to the voltage on nodes immediately inside the boundary, as shown in (A.1) to (A.6).

\[
\varphi_{RMS}|_{-1, \beta, y} = \varphi_{RMS}|_{2, \beta, y} \quad (A.1)
\]
\[
\varphi_{RMS}|_{\alpha, -1, y} = \varphi_{RMS}|_{\alpha, 2, y} \quad (A.2)
\]
\[
\varphi_{RMS}|_{\alpha, \beta, -1} = \varphi_{RMS}|_{\alpha, \beta, 2} \quad (A.3)
\]
\[
\varphi_{RMS}|_{N_i + 1, \beta, y} = \varphi_{RMS}|_{N_i - 1, \beta, y} \quad (A.4)
\]
\[
\varphi_{RMS}|_{\alpha, N_i + 1, k} = \varphi_{RMS}|_{\alpha, N_i - 1, k} \quad (A.5)
\]
\[
\varphi_{RMS}|_{\alpha, \beta, N_i + 1} = \varphi_{RMS}|_{\alpha, \beta, N_i - 1} \quad (A.6)
\]

The above detailed relationships are plugged into (9) to obtain the equations for the nodes on the boundaries. Nodes on the boundaries can be categorized into three categories: nodes on the faces, edges, and nodes. Equations (A.7) to (A.16) represent the nodes on the faces. Equations (A.17) to (A.24) represent the nodes on the edges. The nodes on the corners are on the electrodes, so the voltage on these nodes is already known. The equations listed below along with those obtained by applying (9) to all interior nodes are simultaneously solved to obtain the voltage inside the repeating unit of
the micro-scale flow passage.

$$\varphi_{\text{RMS}}|_{1, \beta, \gamma} = \frac{1}{\varphi_{\text{RMS}}|_{1, \beta, \gamma}} = \frac{\frac{1}{\varphi_{\text{RMS}}|_{1, \beta, \gamma}} + \varphi_{\text{RMS}}|_{1, \beta, \gamma}}{\Delta z^2}$$

for $1 < \alpha < N_x$, $\beta = 1$, $1 < \gamma < N_z$  
(A.7)

$$\varphi_{\text{RMS}}|_{1, \beta, \gamma} = \frac{1}{\varphi_{\text{RMS}}|_{1, \beta, \gamma}} = \frac{\frac{1}{\varphi_{\text{RMS}}|_{1, \beta, \gamma}} + \varphi_{\text{RMS}}|_{1, \beta, \gamma}}{\Delta z^2}$$

for $\gamma = 1$  
(A.8)

$$\varphi_{\text{RMS}}|_{a, \beta, \gamma} = \frac{1}{\varphi_{\text{RMS}}|_{a, \beta, \gamma}} = \frac{\frac{1}{\varphi_{\text{RMS}}|_{a, \beta, \gamma}} + \varphi_{\text{RMS}}|_{a, \beta, \gamma}}{\Delta z^2}$$

for $\gamma = 1$  
(A.9)

$$\varphi_{\text{RMS}}|_{a, \beta, \gamma} = \frac{1}{\varphi_{\text{RMS}}|_{a, \beta, \gamma}} = \frac{\frac{1}{\varphi_{\text{RMS}}|_{a, \beta, \gamma}} + \varphi_{\text{RMS}}|_{a, \beta, \gamma}}{\Delta z^2}$$

for $\gamma = 1$  
(A.10)

$$\varphi_{\text{RMS}}|_{a, \beta, \gamma} = \frac{1}{\varphi_{\text{RMS}}|_{a, \beta, \gamma}} = \frac{\frac{1}{\varphi_{\text{RMS}}|_{a, \beta, \gamma}} + \varphi_{\text{RMS}}|_{a, \beta, \gamma}}{\Delta z^2}$$

for $\gamma = 1$  
(A.11)
\( \varphi_{RMS}^{x,\beta,N_1} = \left( \frac{\varphi_{RMS}^{x,\beta,N_1} + \varphi_{RMS}^{x,\beta,N_1 - 1}}{\Delta x^2} \right) \left( \frac{2}{\Delta x^2} + 2 \frac{\Delta y}{\Delta z^2} + 2 \frac{\Delta z}{\Delta z^2} \right) \) for \( L_1 + L_2 + 1 \leq \alpha \leq N_x \),
\[
\frac{2w_{e1} (i-1) \Delta x}{L_1 \Delta y} - \frac{(L_1 + L_2) \Delta y}{\left( L_1 \Delta y - N_z \right)} < \beta
\]
\[
\gamma = N_z
\]
\( \varphi_{RMS}^{1,\beta,1} = \left( \frac{2 \varphi_{RMS}^{1,\beta,1} + \varphi_{RMS}^{0,\beta,1}}{\Delta x^2} \right) \left( \frac{2}{\Delta x^2} + 2 \frac{\Delta y}{\Delta z^2} + 2 \frac{\Delta z}{\Delta z^2} \right) \) for \( \alpha = 1 \), \( 1 < \beta < N_y \), \( \alpha = 1 \)
\( \varphi_{RMS}^{x,\beta,N_1} = \left( \frac{\varphi_{RMS}^{x,\beta,N_1} + \varphi_{RMS}^{x,\beta,N_1 - 1}}{\Delta x^2} \right) \left( \frac{2}{\Delta x^2} + 2 \frac{\Delta y}{\Delta z^2} + 2 \frac{\Delta z}{\Delta z^2} \right) \) for \( \alpha = 1 \), \( 1 < \beta < N_y \), \( \gamma = N_z \)
\( \varphi_{RMS}^{1,\beta,1} = \left( \frac{2 \varphi_{RMS}^{1,\beta,1} + \varphi_{RMS}^{0,\beta,1}}{\Delta x^2} \right) \left( \frac{2}{\Delta x^2} + 2 \frac{\Delta y}{\Delta z^2} + 2 \frac{\Delta z}{\Delta z^2} \right) \) for \( \alpha = 1 \), \( 1 < \beta < N_y \), \( \gamma = N_z \)
\( \varphi_{RMS}^{x,\beta,1} = \left( \frac{\varphi_{RMS}^{x,\beta,1} + \varphi_{RMS}^{x,\beta,1 - 1}}{\Delta y^2} \right) \left( \frac{2}{\Delta y^2} + 2 \frac{\Delta x}{\Delta z^2} + 2 \frac{\Delta z}{\Delta z^2} \right) \) for \( \alpha = N_x \), \( 1 < \beta < N_y \), \( \gamma = 1 \)

The equations listed below can be used to determine the electric field on the electrodes on the bottom and top surfaces of the repeating unit.

\( E_{RMS,z}^{x,\beta,1} = \frac{3 \varphi_{RMS}^{x,\beta,1} - 4 \varphi_{RMS}^{x,\beta,1 + 1} + \varphi_{RMS}^{x,\beta,1 + 2}}{2 \Delta z} \) for \( 1 \leq \alpha \leq \frac{L_1 - L_2}{2 \Delta x} + 1 \),
\[
1 \leq \beta \leq \frac{2w_{e1} (\alpha - 1) \Delta x}{\Delta y (L_1 - L_2)} + 1, \quad \gamma = 1
\]
\( E_{RMS,z}^{x,\beta,1} = \frac{-3 \varphi_{RMS}^{x,\beta,1} + 4 \varphi_{RMS}^{x,\beta,1 - 1} - \varphi_{RMS}^{x,\beta,1 - 2}}{2 \Delta z} \) for \( 1 \leq \alpha \leq \frac{L_1 - L_2}{2 \Delta x} + 1 \),
\[
1 \leq \beta \leq \frac{2w_{e1} (\alpha - 1) \Delta x}{\Delta y (L_1 - L_2)} + 1, \quad \gamma = N_z
\]
\( E_{RMS,z}^{x,\beta,1} = \frac{3 \varphi_{RMS}^{x,\beta,1} - 4 \varphi_{RMS}^{x,\beta,1 + 1} + \varphi_{RMS}^{x,\beta,1 + 2}}{2 \Delta z} \) for \( 1 \leq \alpha \leq \frac{L_1 - L_2}{2 \Delta x} + 1 \),
\[
\frac{W_{ch} \Delta x}{\Delta y} - \frac{2w_{e1} (\alpha - 1) \Delta x}{\Delta y (L_1 - L_2)} + 1 \leq \beta \leq N_y, \quad \gamma = 1
\]
\[ E_{\text{RMS},z|\alpha,\beta,\gamma} = \left. -3 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma} + 4 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma-1} - \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma-2} \right/ 2\Delta z \]
for \( 1 \leq \alpha \leq \frac{L_1 - L_2}{2\Delta x} + 1, \)
\[ W_{\text{ch}} = \frac{2w_{e,1}(\alpha - 1)\Delta x}{\Delta y (L_1 - L_2)} + 1 \leq \beta \leq N_y, \quad \gamma = N_z \]
(A.28)

\[ E_{\text{RMS},z|\alpha,\beta,\gamma} = \left. 3 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma} - 4 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+1} + \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+2} \right/ 2\Delta z \]
for \( \frac{L_1 - L_2}{2\Delta x} + 1 \leq \alpha \leq \frac{L_1 + L_2}{2\Delta x} + 1, \)
\[ 1 \leq \beta \leq \frac{w_{e,1}}{\Delta y}, \quad \gamma = 1 \]
(A.29)

\[ E_{\text{RMS},z|\alpha,\beta,\gamma} = \left. -3 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma} + 4 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma-1} - \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma-2} \right/ 2\Delta z \]
for \( \frac{L_1 - L_2}{2\Delta x} + 1 \leq \alpha \leq \frac{L_1 + L_2}{2\Delta x} + 1, \)
\[ 1 \leq \beta \leq \frac{w_{e,1}}{\Delta y}, \quad \gamma = N_z \]
(A.30)

\[ E_{\text{RMS},z|\alpha,\beta,\gamma} = \left. 3 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma} - 4 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+1} + \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+2} \right/ 2\Delta z \]
for \( \frac{L_1 - L_2}{2\Delta x} + 1 \leq \alpha \leq N_x, \)
\[ W_{\text{ch}} - w_{e,1} \leq \beta \leq N_y, \quad \gamma = 1 \]
(A.31)

\[ E_{\text{RMS},z|\alpha,\beta,\gamma} = \left. 3 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma} - 4 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma-1} - \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma-2} \right/ 2\Delta z \]
for \( \frac{L_1 + L_2}{2\Delta x} + 1 \leq \alpha \leq N_x, \)
\[ 1 \leq \beta \leq \frac{2w_{e,1}(\alpha - 1)\Delta x - (L_1 + L_2)}{(L_1 - L_2)\Delta y}, \quad \gamma = 1 \]
\[ (A.32) \]

\[ E_{\text{RMS},z|\alpha,\beta,\gamma} = \left. 3 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma} - 4 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+1} + \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+2} \right/ 2\Delta z \]
(A.33)

\[ 1 \leq \beta \leq \frac{2w_{e,1}(\alpha - 1)\Delta x - (L_1 + L_2)}{(L_1 - L_2)\Delta y}, \quad \gamma = N_z \]
(A.34)

\[ E_{\text{RMS},z|\alpha,\beta,\gamma} = \left. 3 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma} - 4 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+1} + \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+2} \right/ 2\Delta z \]
for \( \frac{L_1 + L_2}{2\Delta x} + 1 \leq \alpha \leq N_x, \)
\[ W_{\text{ch}} - 2w_{e,2} \left( (\alpha - 1)\Delta x - \frac{(L_1 + L_2)}{2} \right) \leq \beta \leq N_y, \]
\[ \gamma = 1 \]
(A.35)

\[ E_{\text{RMS},z|\alpha,\beta,\gamma} = \left. 3 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma} - 4 \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+1} + \varphi_{\text{RMS}}|_{\alpha,\beta,\gamma+2} \right/ 2\Delta z \]
for \( \frac{L_1 + L_2}{2\Delta x} + 1 \leq \alpha \leq N_x, \)
\[ W_{\text{ch}} - 2w_{e,2} \left( (\alpha - 1)\Delta x - \frac{(L_1 + L_2)}{2} \right) \leq \beta \leq N_y, \]
\[ \gamma = 1 \]
(A.36)

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