ABSTRACT: This study addressed the dynamics of capillary-driven flow for different surface wettabilities by concentrating on the influence of electric potential. The capillary flow dynamics were investigated by varying the wettability (plasma-treated, hydrophobic, hydrophilic, and superhydrophilic) of a capillary surface, and the applied electric potential to the liquid ranged from 0 to 500 V. When an electric potential was applied to the liquid, the fluid flow penetration length increased by 30−50% due to the electrohydrodynamic (EHD)-driven flow by the Maxwell (electric) pressure gradient effect. The results showed that the EHD effect enhanced the fluid penetration through narrow gaps. The maximum fluid penetration was attained for every surface at 500 V, particularly for the superhydrophilic surface, which exhibited the highest value. The combined effect of the electric field and wettability resulted in an enhanced fluid penetration speed, reducing the underfill time. In addition, theoretical and numerical models were developed for comparison with the experimental results. The proposed models reinforce the observed fluid flow phenomenon on various surfaces under the influence of an electric field. These findings can provide alternative strategies for controlling the dynamic features of capillary imbibition by introducing an electric field and wettability effects, which has practical implications in flip-chip packaging, microfluidic devices, and the manipulation of biocells.

INTRODUCTION
Capillarity is the ability of a fluid to flow within a confined space.\(^1\)^\(^2\) Capillary flow occurs due to the interfacial forces between a fluid and capillary wall, regardless of external pressure, thermal, electric, and magnetic forces. Capillary flow has been widely utilized in various applications, including flip-chip packaging heat exchangers and microfluidic actuation of chemical and biological analytical systems.\(^3\)\(^−\)\(^12\) Recently, the combination of an electrohydrodynamic (EHD) phenomenon with capillary systems has been of interest in the precise manufacturing engineering field. EHD systems are hydrodynamic systems subjected to electric field that can enhance and control the mass flow distribution.\(^13\) Many applications of the EHD phenomenon have been developed, including capillary pumping, heat transfer improvement, and printed electronics.\(^14\)\(^−\)\(^17\) By regulating the wettability of surfaces, EHD pumping effects can increase the wetting efficiency of the liquid, and as a result, heat transfer can be improved.\(^18\)

In such a system, the electric field and surface wettability were major contributors to capillary dynamics. From reviewing the literature, we can briefly summarize key research outcomes: When the electric field is applied across capillary walls, it affects the fluid flow penetration length and reduces void defects.\(^19\)\(^,\)\(^20\) It has been demonstrated that in EHD pumping for dielectric
liquid flow in a microchannel, the polarization force increases the liquid flow length. Furthermore, the pressure-driven transport of immiscible fluids has been investigated under an electric field for multiphase electrokinetic applications. The results showed the effects of the surface potential and liquid conductivity on the filling dynamics. The electric current increases when an electromagnetic field is applied to capillary walls through attached electrodes, reducing the flow filling time. Moreover, numerical studies of the polarization force have revealed a significant reduction in the filling time and a further improvement in flow duration for filler particles in a microchannel.

Scientists and engineers agree that developing theoretical and numerical models is necessary to comprehensively understand the EHD phenomenon combined with the capillary system, which may be utilized in industrial applications. Lucas and Washburn studied capillary action and established their fundamental model. They investigated the kinetics of capillary filling in a narrow cylindrical tube at a macroscale and developed the Lucas–Washburn (L–W) model. However, the classical L–W model cannot directly predict the dynamics of capillary-driven flow in EHD-combined capillary systems because it was built without considering the electric field and other external driving forces (i.e., pressure, thermal energy, and magnetic). To achieve an accurate prediction based on the capillary model, the construction of a new model that considers the practical conditions is required, in which the L–W model is set as a foundation.

Therefore, different experiments and theoretical models have been studied, considering the effects of the electric field and surface wettability. The wetting kinetics of fluid flow have been investigated through experiments. The results reveal an improved filling, following modifications of the fluid properties and wettability of the substrate in flip-chip packaging. Furthermore, it has been found that the surface wettability and fluid composition significantly affect the nature of the dynamic contact angle. All tested liquids exhibited a higher spreading rate on a hydrophilic surface than on a hydrophobic surface. Other studies also showed a reasonable increment in the fluid flow penetration length through the application of an electric field when electrodes are in physical contact with the walls, which can cause damage (chemical reactions) and enhance the weight issues during underfill in flip-chip packaging. However, to the best of our knowledge, there is no literature on developing theoretical and numerical models that consider both the electric field and surface wettability effects and their comparison with experimental results.

In this study, we developed theoretical and numerical models for predicting capillary actions under an electric potential. Experimentally, we applied an electric potential to the nozzle edge to reduce the filling time for three different surfaces, namely, hydrophobic, hydrophilic, and superhydrophilic, to validate the effectiveness of the proposed models. The fluid flow penetration length increased by 30–50% due to the applied electric potential. In summary, both the models showed good agreement with the experimental data.

**EHD Flow Mechanism.** First, we will explain the basic mechanism to actuate the fluid flow by EHD pumping. The Korteweg–Helmholtz equation defines the electric body force density working on a fluid

\[
F_e = q_e E = \frac{1}{2} \left( \epsilon - \frac{1}{2} \nabla \cdot \left( \frac{\partial \epsilon}{\partial \rho} \right) \right) E \cdot E
\]

(1)

where the fluid permittivity, net volume charge density, applied electric field, fluid density, and a constant temperature condition are indicated by \( \epsilon \), \( q_e \), \( E \), \( \rho \), and \( T_r \), respectively. The first component of eq 1 is for the Coulombic force applied on free charges in a liquid in the existence of an electric field. The second component, in the company of a permittivity gradient, is related to an induced dielectric force. The presence of a liquid/liquid or liquid/vapor interface and nonisothermal circumstances or electric inhomogeneity in a single-phase liquid can provide the compulsory permittivity gradient. The third term causes electrostriction effects in a compressible material. As a result, a permittivity gradient develops across the field without an external pressure gradient. A weakly conducting incompressible dielectric fluid can only be pushed to flow if space charges are produced in the fluid in the presence of an electric field. Therefore, all EHD actuation mechanisms are built on the foundation of these two principles. There is a discontinuity in \( \epsilon \) at the interface between the materials, i.e., charge density can be controlled by Maxwell–Wagner equation, which affects \( D \). As shown in Figure 1, at the boundary between two dielectric materials, the displacement field \( D \) is

\[
D = \varepsilon E - \frac{1}{2} \nabla \left( \epsilon - \frac{1}{2} \nabla \cdot \left( \frac{\partial \epsilon}{\partial \rho} \right) \right) E \cdot E
\]

(2)

\[
\varepsilon = \varepsilon_0 (1 + \chi_e)
\]

(3)
(\(D_2 - D_1\) \(\mathbf{n} = \mathbf{q}\) (the macroscopic charge at the surface) \(4\) 
\[D = \varepsilon_0 E + P\] (polarizability) \(5\)
where \(\varepsilon_0\) is the electric permittivity of free space (vacuum) and \(\chi_0\) is the dielectric material’s electric susceptibility. Upon introducing Gauss’ law, \(\nabla \cdot (\varepsilon \nabla \phi) = -q_s\), where \(\phi\) is the electric potential, into the Korteweg–Helmholtz equation given by eq 1, it is converted to eq 6
\[F_e = (\nabla \cdot D)E - \frac{1}{2} \varepsilon E^2 \nabla \varepsilon\] \(6\)
for an incompressible medium
\[F_e = (\nabla \cdot D)E - \frac{1}{2} \varepsilon E^2 \nabla \varepsilon + \varepsilon E \nabla E\] \(7\)

As a result, EHD pumps require either a permittivity gradient or free space charges inside an incompressible liquid.

**Equation Derivation.** Maxwell’s electric pressure gradient can be achieved within fluids by introducing an electric field induced by the EHD flow.\(^{34}\) Moreover, a voltage supply generates an electric field at the end of the nozzle, which acts as an electrode near the meniscus of the parallel plates, which drives the fluid flow in the same way as the EHD. The fluid flow between parallel plates was considered laminar, incompressible, and fully developed in this model. The observed fluid flow was assumed as fully developed because the parallel plate gap we used was small compared with the plate length. The fluid flowed with a flow rate \(Q\) from the nozzle of area \(A\), causing an inlet pressure \(P_{\text{inlet}}\) at the entrance of the parallel plates. We modeled the fluid flow in the length \(x\) direction (Figure 1b) because we were interested in how deeply the capillary flow could penetrate the plates. Therefore, the momentum equation, which includes the electrostatic force acting on the fluid body, could be developed using reference studies\(^{1,34,35}\) as shown in eqs 1 and 7.

Momentum equation (conservation of momentum)
\[\frac{\partial V_x}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \frac{\partial^2 V_x}{\partial y^2} + \frac{\varepsilon E}{2\rho} \nabla \cdot \varepsilon \nabla E\] \(8\)
where \(t, p, \rho, E_x,\) and \(V_x\) are the time, pressure, viscosity, applied electric field, and velocity in the \(x\)-direction, respectively. The right-hand side of eq 8 is the sum of the three forces acting on the system, namely, the pressure force, viscous force, and electrostatic force, respectively. In our experiment, fluid flowed continuously from the nozzle near the inlet. In addition to the capillary pressure between the parallel plates, the pressure caused by the inlet fluid flow was considered. Therefore, as shown in eq 9, the pressure term could be further subdivided into capillary and inlet fluid pressures.
\[-\frac{\partial p}{\partial x} = \frac{1}{L(t)} \left( \frac{\rho_{\text{inlet}} + 2K \cos \theta \ h}{h} \right)\]
\[= \frac{1}{L(t)} \left( \frac{\rho (\frac{Q}{h})^2 + 2K \cos \theta \ h}{h} \right)\]
\[-\frac{\partial p}{\partial x} = \frac{1}{L(t)} \left( \frac{8\rho Q^2}{\pi^2 D^4} + 2K \cos \theta \ h \right)\] \(9\)
where \(D, K, h, \gamma, \theta, L\) are the diameter of the nozzle, correction factor, the gap between parallel plates, surface tension, contact angle, and length of spreading of liquid on plate, respectively. The velocity only varied along the \(y\)-axis, indicating that the gap was axisymmetric from the center (Poiseuille flow). Thus, the velocity at the center of the gap \((y = 0)\) could be used to determine the position of the meniscus, allowing us to calculate the position of the meniscus over time. The meniscus velocity can be realized as follows
\[V_x(y, t) = V_x(0, t) = \frac{dL(t)}{dt}\] \(10\)
\[V_x\left(\pm \frac{h}{2}, t\right) = 0\] (no boundary conditions) \(11\)
\[\frac{\partial V_x(0, t)}{\partial y} = 0 \text{ at } y = 0 \] (symmetric about centerline)

Equation 10 presents the position of the meniscus at the center of the gap. Equation 11 provides the boundary conditions for deriving eq 12. The parabolic solution was assumed based on the previous research\(^2\) to obtain velocity and viscous values. Here, the exact velocity variation along the \(y\)-direction is of minor concern in this governing model. We substitute a parabolic distribution eq 12 of \(V_x(y, t)\), which satisfies the symmetric and the non-boundary conditions (9) inevitably, into eq 8. Then, we derived eq 13 twice in the \(y\)-direction to establish eq 14.
\[V_x\left(\pm \frac{h}{2}, t\right) = V_x(y, t) = L^*(t) \left[ 1 - \left(\frac{4h^2}{y^2}\right)^2 \right]\] \(12\)
\[\frac{\partial V_x}{\partial t} = L^*(t) \left[ 1 - \left(\frac{4h^2}{y^2}\right)^2 \right]\] \(13\)
\[\frac{\partial^2 V_x}{\partial y^2} = -L^*(t) \left(\frac{8}{h^2}\right)\] \(14\)
The values of \(\frac{\partial p}{\partial x}, \frac{\partial V_x}{\partial y},\) and \(E_x^2\) in eq 8 were replaced with eqs 9, 13, 14, and ref 34 to obtain the detailed momentum (eq 16).
\[\frac{\partial V_x}{\partial t} = \frac{1}{\rho} \left[ \frac{8L^2Q^2}{\pi^2 D^4} + \frac{2K \cos \theta}{h} \right] + \frac{\mu}{\rho} \frac{\partial^2 V_x}{\partial y^2} + \frac{\varepsilon E}{2\rho} L^* \left[ 1 - \left(\frac{4h^2}{y^2}\right)^2 \right]\] \(15\)
\[= \frac{1}{\rho} \left[ \frac{8L^2Q^2}{\pi^2 D^4} + \frac{2K \cos \theta}{h} \right] - \frac{8\mu}{\rho h^2} L^* (t)\] \(16\)
\[\left(\frac{\partial V_x}{\partial t} - \frac{8\mu}{\rho h^2} L^* - \frac{\varepsilon E}{2\rho L^*} \right) L^* = \frac{1}{\rho} \left[ \frac{8L^2Q^2}{\pi^2 D^4} + \frac{2K \cos \theta}{h} \right]\] \(17\)
The initial conditions were as follows
\[V_x(y, 0) = 0 \text{ and } L(0) = L_0\] \(18\)
when \(t = 0, L(0)\) is \(L_0\), representing the starting inlet position of the capillary meniscus. Equation 15 indicates the force
balance between the pressure drop, inlet pressure flow from the nozzle, capillary pressure, and electric field effects. As there is no exact solution to the initial value problems (eqs 17 and 18), eq 19 must be solved numerically. Because we assumed fully developed fluid flow and it was observed t \gg V_x, the acceleration (second derivative) term in eq 15 could be ignored to simplify the asymptotic solution of L(t), which is the marching position with time t, as in eq 17.4

\[
\left( \frac{8\mu}{\rho h^2} L' - \frac{\nabla \epsilon \cdot 4V^2}{2\rho} \right) L = \frac{1}{\rho} \left[ \frac{8\rho Q^2}{\pi^2D^3} + \frac{2K\gamma \cos \theta}{h} \right] (19)
\]

Because the fluid flow phenomenon between the gap is a type of capillary flow, the final solution of eq 19 can be assumed to be in the form of eq 20, where \( \alpha \) is the coefficient, which depends on the electric potential, pressure, and surface tension in the capillary flow system.

\[
L = \sqrt{L_0^2 + \alpha t} \quad \text{let,} \quad L' = \frac{1}{2} \sqrt{L_0^2 + \alpha t} = \frac{\alpha}{2L} \quad \text{where} \quad \alpha
\]

\[
= \left[ \frac{\nabla \epsilon h^2V^2}{2\mu L^2} + \frac{2ph^2Q^2}{\mu \pi^2D^3} + \frac{K\gamma \cos \theta}{2\mu} \right]
\]

The value of L from eq 20 was put into eq 19 and solved to get eq 21. The quadratic relationship between the fluid flow penetration length and the applied voltage is given by eq 22.

**Table 1. Experimental Parameters and Conditions**

| substrate  | glass |
|------------|-------|
| liquid and properties | DI water |
| conductivity \( (\epsilon) \): 0.0305 \( \mu \)s |
| surface tension \( (\gamma) \): 72.7 dyn/cm |
| viscosity \( (\mu) \): 0.89 cP |
| density \( (\rho) \): 1000 kg/m³ |
| nozzle height from the substrate | 50 μm |
| distance between parallel plates | 100 μm |
| flow rate | 3 μL/min |
| voltage | 0–500 V |

The corresponding values in eq 22 are given in Table 1 and were used in the experiment.

\[
\left( \frac{8\mu}{\rho h^2} L' - \frac{\nabla \epsilon \cdot 4V^2}{2\rho} \right) L = \frac{1}{\rho} \left[ \frac{8\rho Q^2}{\pi^2D^3} + \frac{2K\gamma \cos \theta}{h} \right] (19)
\]

\[
\begin{align*}
\frac{4\mu}{\rho h^2} - \frac{\nabla \epsilon \cdot 4V^2}{2\rho} L & = \frac{1}{\rho} \left[ \frac{8\rho Q^2}{\pi^2D^3} + \frac{2K\gamma \cos \theta}{h} \right] \\
\alpha & = \left[ \frac{\nabla \epsilon h^2V^2}{2\mu L^2} + \frac{2ph^2Q^2}{\mu \pi^2D^3} + \frac{K\gamma \cos \theta}{2\mu} \right] (21)
\end{align*}
\]

**Numerical Simulation.** A two-dimensional (2D) numerical simulation analysis was performed to observe and validate the effect of an external electric field on the capillary flow between parallel plates. A simple geometric model was developed. A time-dependent simulation was run using COMSOL Multiphysics software, including a laminar two-phase flow, a level-set module, and a quasi-electrostatic module.

The effect on capillary flow due to the increasing magnitude of the applied electric field was observed, supporting the experimental observation in this study. The multiphase flow must be initiated for the simulation to begin in a stable position. The initial contact angle for the changing surfaces was set using the wetted-wall boundary condition on both inner edges of the plates, similar to the experiment. As a result, the Maxwell stress induced by the voltage at the fluid interface was the primary influencing factor in the fluid flow penetration length as the applied voltage was increased. The first step in modeling the simulation setup was to solve the Navier–Stokes equations; then, we had to describe the fluid motion and track the interfaces between the immiscible fluids. The level-set method was employed to accomplish the interface tracking. A mean position of the interface was required to support the experimental and theoretical results; hence, a simple interface tracking model (level set) was used. Due to surface charge appearance at the interfaces, the local electric fields were solved to account for the electric forces acting on the fluids. The charge appearance and, consequently, the localized force at the interface were due to the difference in conductivity and permittivity between the phases.36

The electrostatic force produced by a nonuniform electric field was defined within the Navier–Stokes equation by Maxwell electric tensor’s divergence. It can be shown mathematically that the electric force is given by the divergence of the Maxwell stress tensor.

\[
F = \nabla \cdot T
\]

The Maxwell stress tensor is given by \( T \), where \( E \) is the electric field and \( D \) is the electric displacement field.

\[
T = ED^T - \frac{1}{2}(E:D)I
\]

To save computational time, the simulation was solved in 2D, and the stress tensor was as follows37

\[
E = -\nabla V
\]

\[
D = \varepsilon_0\varepsilon_r E
\]

\[
T = \begin{bmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{bmatrix} = \begin{bmatrix} \varepsilon_0\varepsilon_r E_x - \frac{1}{2} \varepsilon_0\varepsilon_r E_y & \varepsilon_0\varepsilon_r E_x \\ \varepsilon_0\varepsilon_r E_y & \varepsilon_0\varepsilon_r E_y \end{bmatrix}
\]

\[
E = -\nabla V
\]

\[
D = \varepsilon_0\varepsilon_r E
\]

\[
T = \begin{bmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{bmatrix} = \begin{bmatrix} \varepsilon_0\varepsilon_r E_x - \frac{1}{2} \varepsilon_0\varepsilon_r E_y & \varepsilon_0\varepsilon_r E_x \\ \varepsilon_0\varepsilon_r E_y & \varepsilon_0\varepsilon_r E_y \end{bmatrix}
\]

The electric field components \( E_x \) and \( E_y \) were calculated according to the potential applied by COMSOL. The geometry of the simulation was constructed based on the experimental setup. The applied conditions were the same as those used in the experiments and mathematical model, including a flow rate of 3 μL/min, electrode location, and voltage variation of 0–500 V. The outlet boundary condition was set to 0 Pa; the same boundary was also set to ground. Finally, to achieve a realistic simulation of electrohydrodynamics, the electrical force calculated by COMSOL in the quasi-electrostatic simulation was coupled to the fluid dynamic simulation.
RESULTS AND DISCUSSION

The Reynolds number $R_e = \left( \frac{\rho u h}{\mu} \right)$ is the ratio of the inertial forces to viscous forces. The maximum $R_e$ was approximately 3, indicating laminar flow between the parallel plates. The capillary number $C_a = \left( \frac{\sigma}{\rho u h} \right)$, which is the ratio of viscous to surface tension, is commonly used to determine the capillary and viscous flows. We assumed the fluid flow to be capillary flow because the maximum $C_a$ in the experiment was approximately 0.00015. By applying a direct current (DC) voltage to the liquid–solid interface, the EHD effect reduces the energy of the liquid–solid interface, resulting in a fluid rise between parallel plates. The fluid started to spread between the parallel plates in the current system at approximately 100 V, and the threshold voltage was calculated to be around 90 V. The maximum fluid penetration length was measured at various voltages to investigate the effect of the electric field on the capillary flow between the parallel plates. The spreading phenomenon is shown in Figure 2 for three different surfaces at 0 and 500 V for 0.1 and 1.2 s. At 1.2 s, the capillary flow increased to a maximum for the superhydrophilic surface due to interfacial tension under 500 V. The induced electrostatic force accelerated the capillary flow due to the applied voltage. The fluid penetration between the parallel plates for the three different surfaces is shown in Figure 3, using capillary and electric field effects. The capillary flow dynamics was considered when the wetting liquid touched the parallel plates and spread.

Images for the three different surfaces (i.e., hydrophobic, hydrophilic, and superhydrophilic) in Figure 3a–c, respectively) were obtained at the times of 0.3, 0.6, 0.9, and 1.2 s at 0 and 500 V. The maximum time for the fluid to achieve constant flow was around 1.2 s. Images in the first row in Figure 3a are at 0 V, and the fluid flow is mainly due to the capillary effect only. The images in the second row in Figure 3a show the voltage (500 V) effect, which increases the fluid flow penetration length. The experiments demonstrated the generation of unidirectional fluid flow from the region of a high electric field to the ground electrode. Figure 3b,c shows a similar trend in the fluid flow penetration length under the electric field effect. The increase in fluid flow spreading was significantly enhanced under the influence of the electric field.

Owing to the low and high surface energies, the fluid covered a shorter length on the hydrophobic surface, while maximum spreading was observed on the superhydrophilic surface. When the measured contact angles were compared, it was apparent how the fluid flow shifted as the surface changed. Compared with the 0 V condition, the capillary reached maximum spreading within 1.2 s under the electric field effect (500 V) for all surfaces. Figure 4 shows the influence of the electric field on the fluid flow duration for the three different surfaces, plotted against time. We examined how fluid spreads between parallel plates when a voltage and pressure gradient-driven flow is applied simultaneously. As the fluid penetrated the gap between the parallel plates, its profile began to spread, demonstrating the capillary effect in the absence of the applied voltage on all three surfaces (0 V). As the voltage was increased from 0 V, the fluid flow penetration length increased for all time conditions and surfaces. At 500 V, the maximum fluid flow penetration lengths covering the hydrophobic, hydrophilic, and superhydrophilic surfaces were approximately 1.3, 2.1, and 2.5 mm, respectively (Figure 4a–c). The combined influence of surface wettability and electric potential on capillary flow dynamics at 500 V (Figure 4d) was discussed to understand fluid flow penetration better. At 500 V, the superhydrophilic surface had the most significant fluid flow length penetration compared to the other two surfaces. We showed that wettability significantly impacts fluid flow when it is exposed to an electric field. It is observed that the less wettable the surface (i.e., lower contact angle), the weaker the electric potential essential to accelerate the fluid flow.
between parallel plates. A flow length vs voltage comparison is shown in Figure S2 of the Supporting Information for 0.3, 0.6, 0.9, and 1.2 s at 0–500 V. The fluid flow penetration length was approximately 0.48 mm at 0.3 s and 0 V, but increased to 0.65 mm when 100 V was applied to the hydrophobic surface. Meanwhile, at 500 V and for the same hydrophobic surface and time, the fluid flow penetration length increased to 1.0 mm, accounting for approximately half of the increase in the fluid flow penetration length.

Similarly, the fluid flow penetration length increased at a similar 30–45% value for the other two surfaces, hydrophilic and superhydrophilic. The results of the capillary flow experiment presented herein explain not only the surface tension-driven phenomenon but also the external driving forces. The findings indicate that the smaller contact angle and a larger applied electric field increase the fluid flow penetration length. Additionally, the simulation results demonstrated an increase in velocity with increasing the applied voltage in the contour plot, which depicts the velocity variation across the system. Simultaneously, the streamline describes the electric field (V/m) direction from the voltage terminal to the ground electrode (Figure S3). The color expression of the streamline depicts the variation in the applied voltage within the fluid domain. The advancing fluid front was also observed along with the meniscus deformation, demonstrating the effect of the applied external electric field on the fluid flow penetration length, which supports the experimental and mathematical findings. A simulation comparison of the three different surfaces at different voltages is shown in Figure 5a. The electric permittivity is defined as a constant of proportionality between the electric displacement and electric field strength in the simulation. The greater the electric permittivity, the better the molecules polarize and the greater the resistance to an external electric field. We were able to simulate the effect of a nonuniform electric field on the liquid in this study owing to the difference in air and water permittivity across our setup. The applied voltage and the contact angle were varied to represent the three types of surfaces considered in the experiments. Because of the low surface polarity, which reduces fluid attraction, the capillary flow speed is slower on the hydrophilic and super-
Increasing the voltage from 0 to 300 and 500 V resulted in an increased fluid flow penetration length on all three surfaces.

The simulation and averaged experimental data from multiple timesteps were compared to analyze the meniscus location of deionized (DI) water using the updated Washburn model. An analytical model can define the flow length of the liquid until it touches the gap and the distribution profile between parallel plates.41 The fluid flow penetration length was calculated as a function of three driving forces: electric pressure, inlet pressure,
and capillary pressure, as shown in eq 22. The Young–Laplace equation is primarily due to the pressure drops at the inlet and outlet in the capillary pressure term. In contrast, external parameters, such as pressure losses due to upstream air and bubble formation, were ignored. Therefore, a correction factor \( K \) was introduced into the capillary pressure term in eq 22, which differed depending on the surface. Moreover, the fluid flow penetration length in eq 22 was compared with the experimental and simulation data for the three surfaces. The following values were used in eq 22: flow rate \( Q = 8.33 \times 10^{-11} \text{ m}^3/\text{s} \), nozzle outer diameter \( D = 0.000250 \text{ m} \), and channel length \( L = 0.004 \text{ m} \), along with other parameters mentioned in Tables S1 and 1. We determined the system’s permittivity in relation to the dynamic fluid interface by volume fraction in our investigation. The steps are as follows

\[
\nabla \varepsilon = c_1 + (1 - c) c_2
\]

The gradient of permittivity is dependent on the volume fraction of two fluids (air \( c_1 \) and DI water \( c_2 \)). We calculated the volume fraction and evaluated it at various timesteps to determine the interface point lengths. As a result, we obtained different permittivity gradient values at different timesteps. The calculated permittivity gradient values were entered into the governing eq 22 to obtain the flow length based on the different permittivity gradients and timesteps. In our numerical model, we also considered a permittivity gradient.

Figure 5b shows the experimental, numerical, and theoretical results for the fluid flow penetration length of the hydrophobic surface (0–500 V). For all data sets, increasing the voltage maximized the fluid flow penetration length. Thus, the penetration length of the fluid flow is proportional to the applied voltage. This trend is similar to those of the other two surfaces (hydrophilic and superhydrophilic; Figure 5c,d, respectively). Comparing the experimental results with the developed model and experimental results were found to agree well, as shown in Table 1.

#### CONCLUSIONS

This study analyzed the EHD flow driven by the Maxwell (electric) pressure gradient phenomenon to control the fluid flow spread for different surfaces by visualizing the capillary flow between parallel plates. Plasma treatment was used to modify the wettability of the parallel plates to investigate the effects of the surface energies under the influence of an electric field. The superhydrophilic surface exhibited the highest fluid flow rate compared with the hydrophilic and hydrophobic surfaces. Furthermore, the hydrophobic surface presented the lowest fluid flow of the three surfaces because of its low surface energy. However, when the voltage was increased in the range of 0–500 V, all three surfaces experienced a similar increase in the capillary flow by 30–50%. A mathematical model and simulation were developed, and the results were compared with those of the experiment to trace the dynamics of liquid spreading. The developed model and experimental results were found to fit well, with an average deviation of 3–6% at different timesteps for each surface. The proposed models and experimental results demonstrate that an applied electric field can accelerate the fluid flow between parallel plates. This research, which employed simple control of the electric field and wettability, can be easily applied for various practical applications, including flip-chip packaging, microfluidic devices, and biocell manipulation.

#### EXPERIMENTAL SECTION

**Materials and Properties.** Deionized (DI) water and ethanol were obtained from Daeguhe Chemicals and Materials, South Korea, which were used to clean the surfaces of glass slides (Duran Wheaton Kimble) before their use. A plastic nozzle of 34 μm diameter was mounted horizontally by microscale gauge and allowed to move in the vertical (\( y \)) direction to determine the capillary gap position (Figure S1). The rectangular channel was not closed from the sides and was specifically kept open to simulate a realistic industrial condition as seen during underfilling. The liquid was dispensed through the 34 gauge stainless nozzle with a flow rate of 3 \( \mu \text{L/min} \) using a syringe pump. The underfill meniscus and capillary fluid growth phenomena were captured using a high-speed camera (Mini UX100, Photron). An LED (SPO Inc.) was applied to the coaxial zoom lens to visualize the marching meniscus. Photographs and videos were captured at 50 fps with a timestep of 100 ms and a shutter speed of 1/5000 s. To investigate the fluid spreading in response to different electric fields, a function generator (33220A, Keysight) and an amplifier (10/40A high-voltage power amplifier, TREK) were used to apply various direct-current (DC) voltages (100, 200, 300, 400, and 500 V) to the nozzle tip. ImageJ software was used to crop, scale, and measure the captured spreading behavior of the liquid between the parallel plates. Figure 1a shows a schematic of the experimental setup, and Figure 1b shows a side-view schematic of the fluid flow domain, which includes the parameters and coordinates. The experimental conditions are shown in Table 1.

**Surface Modification.** Many physical and chemical processes, such as silane coating or plasma treatment, can alter the wettability of a substrate. Here, we utilized atmospheric radio frequency (RF) plasma treatment (IHP-100, A.P. Plasma Co.) to modify the surface wettability of the bare glass slide, which is hydrophilic (16.2°). Plasma treatment can be used to make both hydrophilic and hydrophobic surfaces. The choice of gases and processing parameters of the atmospheric pressure RF plasma can readily vary the surface wettability. For hydrophobic and hydrophilic surface processing, we employed helium (He) as the carrier gas and octafluoropropane (C₄F₈), mixed methane (CH₄, 6%, Ar mixed), and oxygen (O₂) as the reactive gases. By treating plain (hydrophilic) glass slides with plasma, hydrophobic (102.3°) and superhydrophilic (4.1°) glass substrates (Table S1) were prepared.

**Viscosity, Surface Tension, and Contact Angle Measurements.** The DI water surface tension and viscosity (various share rates) at room temperature were measured using a surface tension analyzer (DST 60A, South Korea) and a viscometer (ARES-G2, Rheometer). In addition, the contact angles of a 10 μL distilled water droplet on the modified substrates were measured using a droplet analyzer (Femtoseal Co., Ltd.) (Table S1).

#### ASSOCIATED CONTENT

**Supporting Information**

The Supporting Information is available free of charge at https://doi.org/10.1021/acsomega.1c04629.
Table of contact angles and images of the experimental setup, information on the influence of voltage on fluid flow over time, and a numerical simulation setup (PDF)

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### Author Contributions

This manuscript was written through the contributions of all authors. All of the authors approved the final version of the manuscript.

### Notes

The authors declare no competing financial interest.

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