Numerical Study of the Controlled Droplet Breakup by Static Electric Fields inside a Microfluidic Flow-focusing Device

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Introduction:

- Electric field has been proposed to be an additional approach to manipulate the droplet-based microfluidic systems (Link, 2006).
- Due to the difference of electric properties (permittivity, conductivity) between the two phases, charges are developed on the interface. The interaction between the electric field with these charges creates Maxwell stresses, which may helps to control droplet breakup, coalescence, sorting, etc.
- The traditional microfluidic flow-focusing device coupled with external electric field has been demonstrated to be able to generate sub-micron droplets (Link, 2006; Kim, 2007). For those circumstances that high viscous fluid is used as the dispersed phase, traditional microfluidics can not effectively tune the obtained droplet sizes (Nie, 2008). Applying electric fields is more feasible in terms of controlling the droplet breakup.
- Level-set method coupled with electric static model is used to study the dynamic of droplet breakup controlled by an external static electric field. The two phases are modeled as perfect dielectrics.
- The dispersed phase properties: ρ_d=960 kg/m^3, μ_d= 50/100 cp, $\varepsilon_{r,d}$= 2.8
  The continuous phase properties: ρ_c=1000 kg/m^3, μ_c= 1 cp, $\varepsilon_{r,c}$= 78

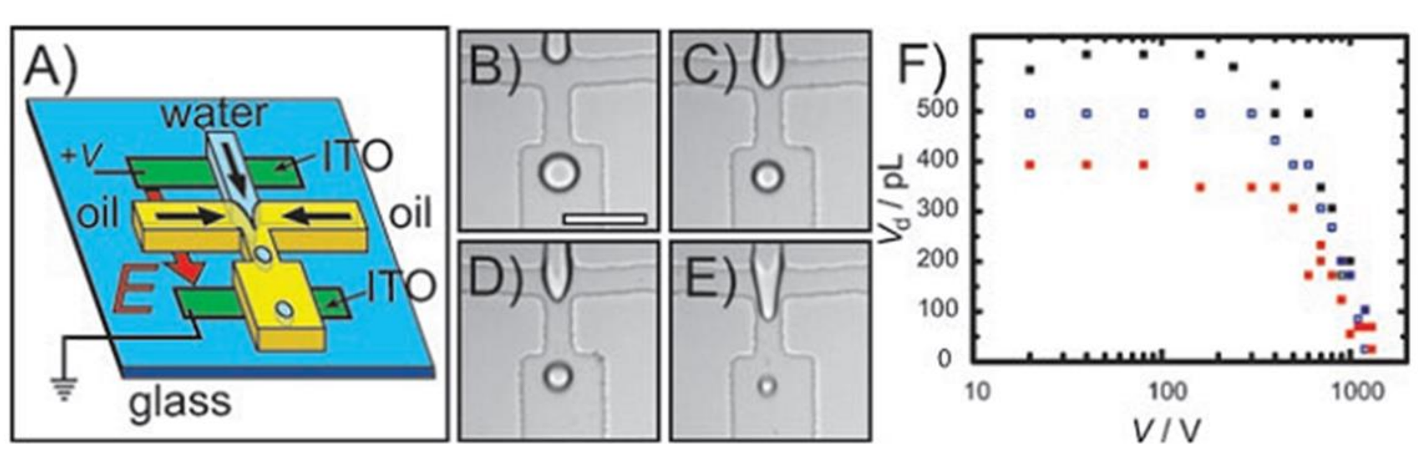

Figure 1. Using electric field as an additional approach to control the droplet size (Link, 2006)

Computational Methods:

- Poisson Equation (Electrostatics; AC/DC Module):

$$\nabla\cdot(-\varepsilon\nabla V)=\rho_f \quad (1)$$

$$\vec{E}=-\nabla V \quad (2)$$

- Conservative Level-set model (Two Phase, level-set; Fluid Flow Module)

$$\frac{\partial\phi}{\partial t}+\vec{u}\cdot\nabla\phi=\gamma\nabla\cdot\left(\epsilon\nabla\phi-\phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right) \quad (3)$$

$$\hat{n}=\frac{\nabla\phi}{|\nabla\phi|} \quad (4)$$

$$\kappa=-\nabla\cdot\hat{n}|_{\phi=0.5} \quad (6)$$

$$\vec{F}_{sf}=\sigma\kappa\delta\hat{n} \quad (7)$$

$$\delta=6|\nabla\phi||\phi(1-\phi)| \quad (8)$$

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\vec{u})=0 \quad (9)$$

$$\frac{\partial(\rho\vec{u})}{\partial t}+\nabla\cdot(\rho\vec{u}\vec{u})=-\nabla P+\nabla\cdot\left[\mu\left(\nabla\vec{u}+\nabla\vec{u}^T\right)\right]+\vec{F}_{sf}+\vec{F}_{ef} \quad (10)$$

$$\rho=\rho_1+(\rho_2-\rho_1)\phi$$

$$\mu=\mu_1+(\mu_2-\mu_1)\phi \quad (11)$$

$$\varepsilon=\varepsilon_1+(\varepsilon_2-\varepsilon_1)\phi$$

$$\vec{F}_{ef}=\nabla\cdot T_{MW}=-\frac{1}{2}(\vec{E}\cdot\vec{E})\nabla\varepsilon \quad (12)$$

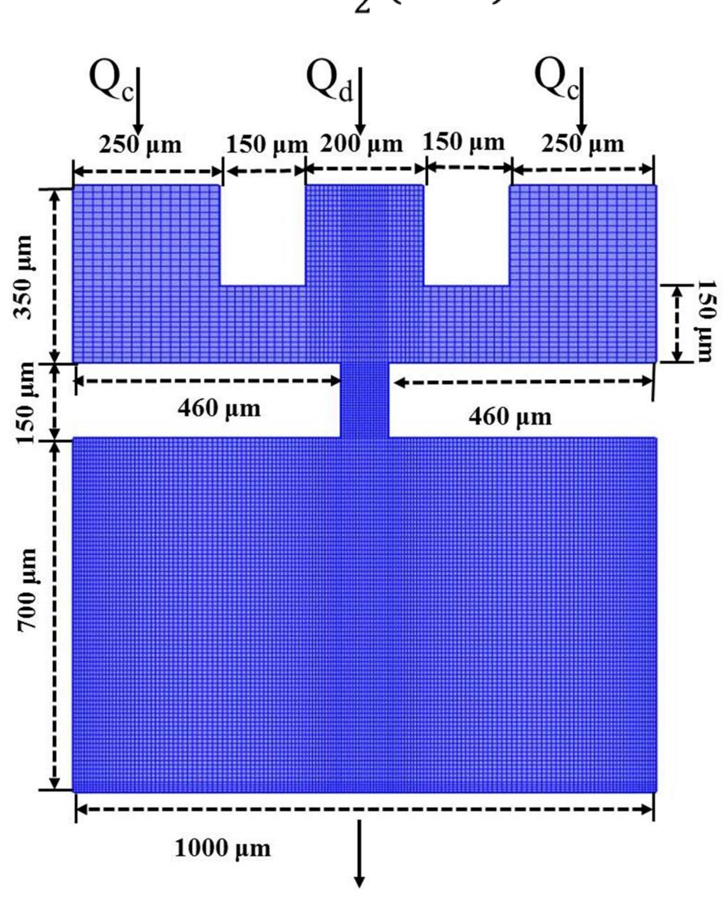

Figure 2. Geometric dimensions of MFFD
(2D domain with 13,160 grids)

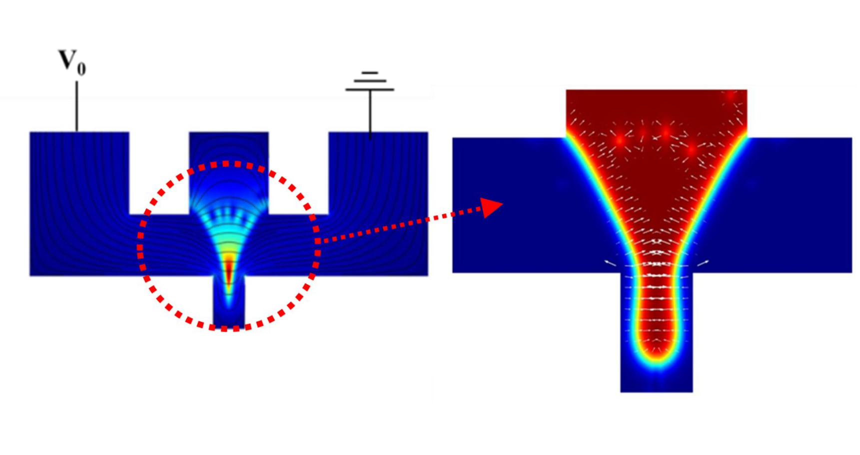

Figure 3. Left: electric field configuration;
Right: phase plot of the focusing region;
Color bar: electric field magnitude.

References:

1. D. R. Link and et al., Electric Control of Droplets in Microfluidic Devices, *Angew. Chem.-Int. Edit.*, **45**, 2556-2560 (2006).
2. H. Kim and et al., Controlled Production of Emulsion Drops Using an Electric Field in a Flow-focusing Microfluidic Devices, *Applied Physics Letters*, **91** (2007).
3. Z. H. Nie and et al., Emulsification in a Microfluidic Flow-focusing Device: Effect of the Viscosities of the Liquids, *Microfluid. Nanofluid.*, **5**, 585-594 (2008).
4. E. Olsson and et al., A Conservative Level-set Method for Two Phase Flow, *J. Comput. Phys.*, **210**, 225-246 (2005).

Results:

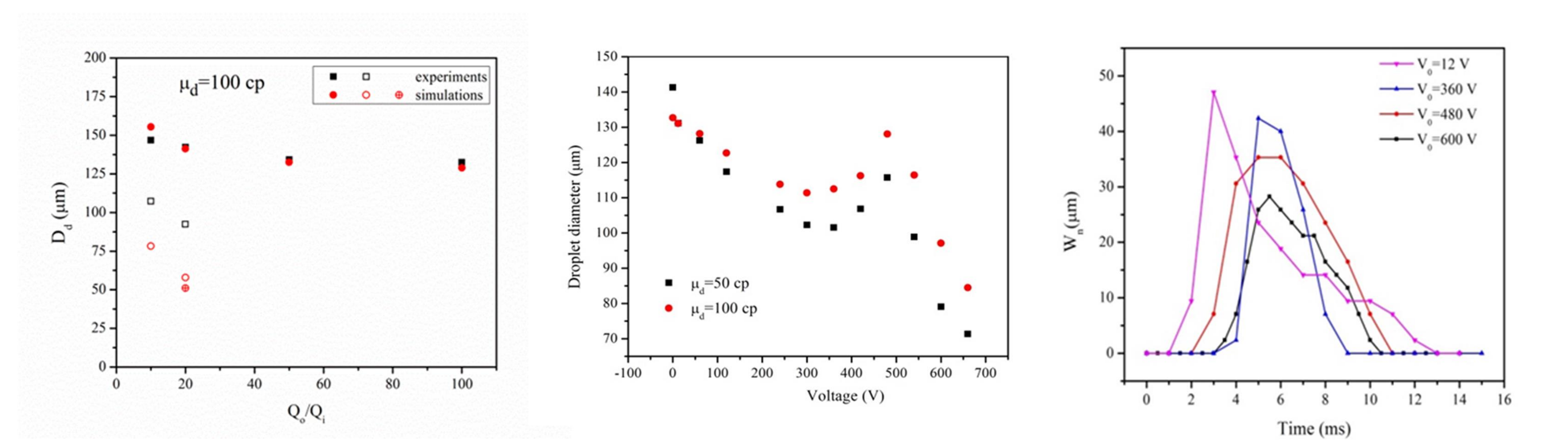

Figure 4. Left: droplet size as a function of flow ratio (without electric field);
Middle: droplet size as a function of applied voltages (Q_o/Q_i = 50);
Right: neck evolutions at different applied voltages (Q_o/Q_i = 50).

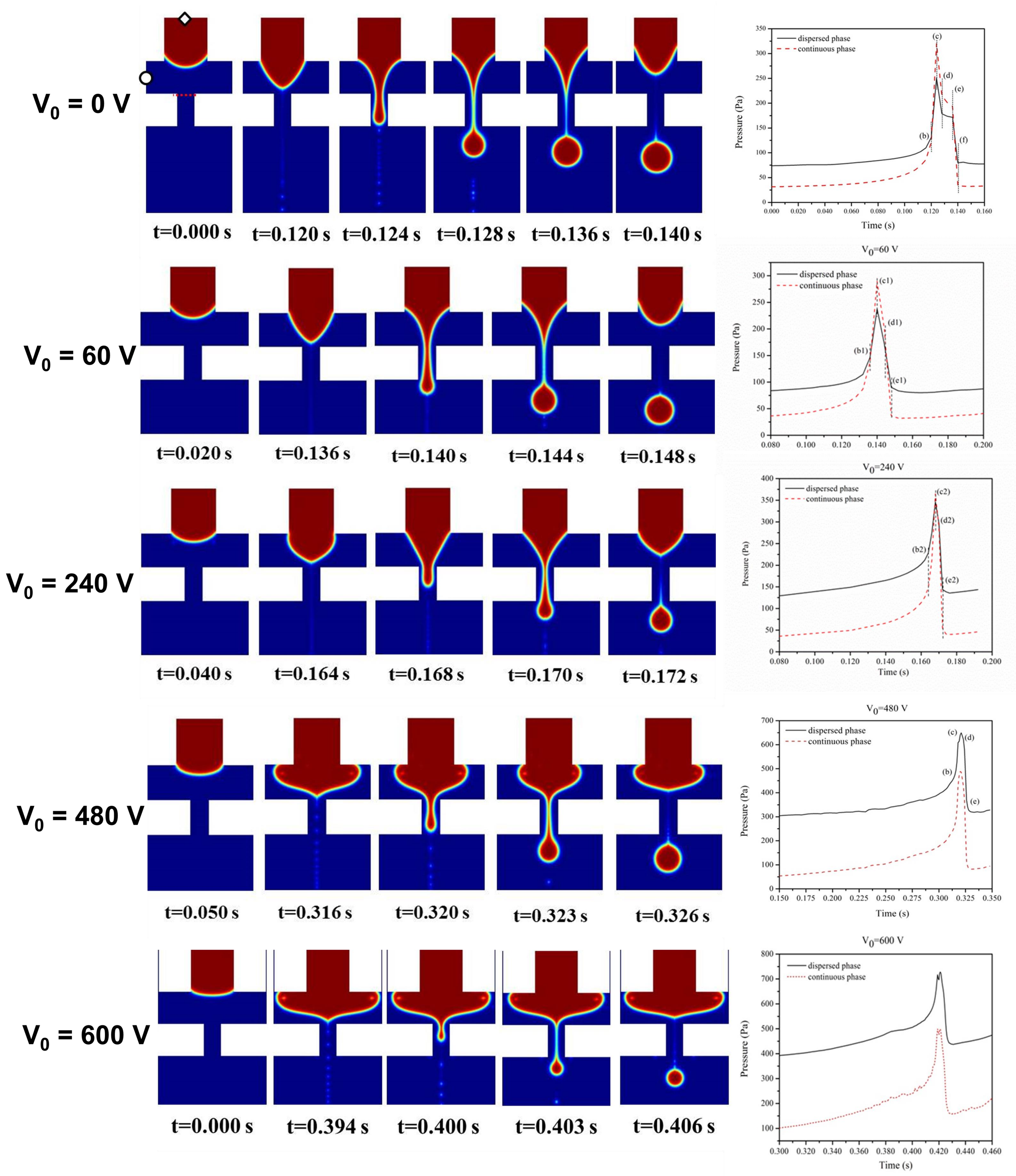

Figure 5. Left: Drop formation dynamics; Right: Upstream pressure evolutions of the two phases

Conclusions:

- Electric field can effectively control the droplet sizes especially when the dispersed phase is more viscous than the continuous phase.
- By exerting an electric stress that helps to squeeze the neck, the electric field can reduce the droplet formation time thus decreases the droplet size.
- The droplet breakup process exhibits different dynamics when electric fields of various voltages are applied.