
Scaling EWD Actuators for Picoliter Applications

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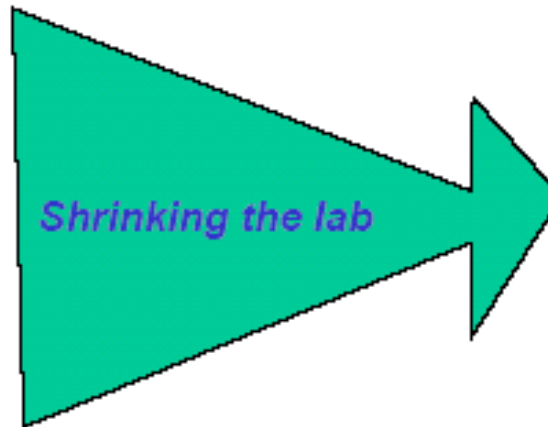
Outline of Presentation

- Background and motivation for scaling
- Development of a scaling model
 - Force balance on droplet
 - Optimum velocity
- Actuator scaling
 - Threshold voltage
 - Droplet splitting models
 - Static and dynamic
 - Uniform splitting conditions
 - Dispensing
 - Combined effects
- Actuator voltage limits
- Picoliter devices
- Summary and conclusions



Promise of Biochips

Applications : Biotechnology (eg: high throughput screening , Diagnostics...)



mm, or cm



- **Scaling required for integration on silicon**
- **Scaling for parallel biochemical processing**

EWD Actuator Scaling

- Scaling parameters:
 - Threshold voltage
 - Splitting voltage
 - Dispensing voltage
 - Optimum droplet velocity
 - Mixing time
 - Maximum safe operating voltage
- Approach:
 - Develop hydrodynamic-based scaling model
 - Compare scaling model with data
 - Fabrication of scaled picoliter devices



Droplet Transport Model

- Effects considered:
 - Contact angle hysteresis
 - Drag from filler fluid
 - Drag from actuator walls
 - Dynamic actuation forces during transport
- Models:
 - Lippmann-Young
 - Force balance/unit length over electrodes
 - Beard-Pruppacher filler medium drag model
 - Brochard plate drag model
 - Berthier's contact angle hysteresis model

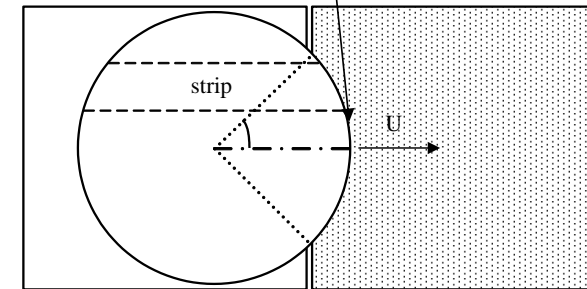


Droplet Transport Model

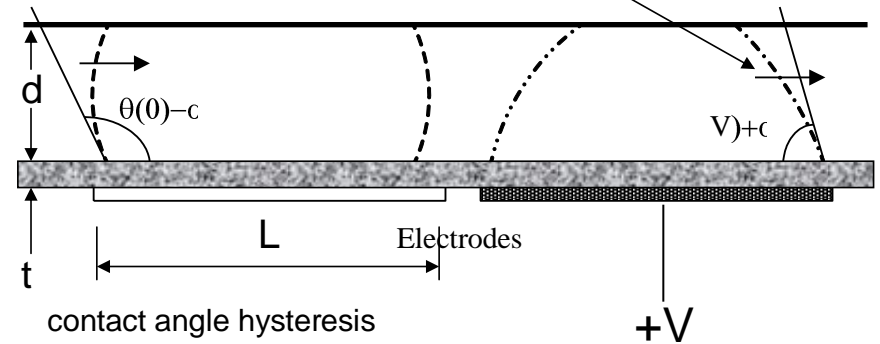
Droplet velocity

$$U = \frac{\sin \phi \left\{ \cos \alpha \frac{\epsilon_r \epsilon_o V^2}{2t} - \gamma_{lg} \sin \alpha [\sin \theta(V) + \sin \theta(0)] \right\}}{12\mu_o \frac{d}{L} + 2C_v \frac{\mu_d}{d} L}$$

plate shear force
oil viscous drag



angle of advancement



contact angle hysteresis

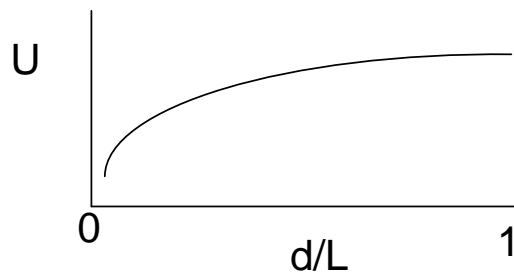
$d/L = \text{aspect ratio}$

Scaling Effects on Velocity

- Model predicts increasing droplet velocity with increasing d/L :

$$U = \frac{\sin \phi \left\{ \cos \alpha \frac{\epsilon_r \epsilon_o V^2}{2t} - \gamma_{lg} \sin \alpha [\sin \theta(V) + \sin \theta(0)] \right\}}{12\mu_o \frac{d}{L} + 2C_v \frac{\mu_d}{d} L}$$

- If $\mu_d = \mu_o$ and $C_v = 6$, then $U \sim 1/12(d/L + L/d)$



Droplet Transport Scaling

- Optimum aspect ratio for maximum velocity:

$$\left(\frac{d}{L}\right)_{\text{opt}} = \left(\frac{C_v \mu_d}{6\mu_o}\right)^{1/2}$$

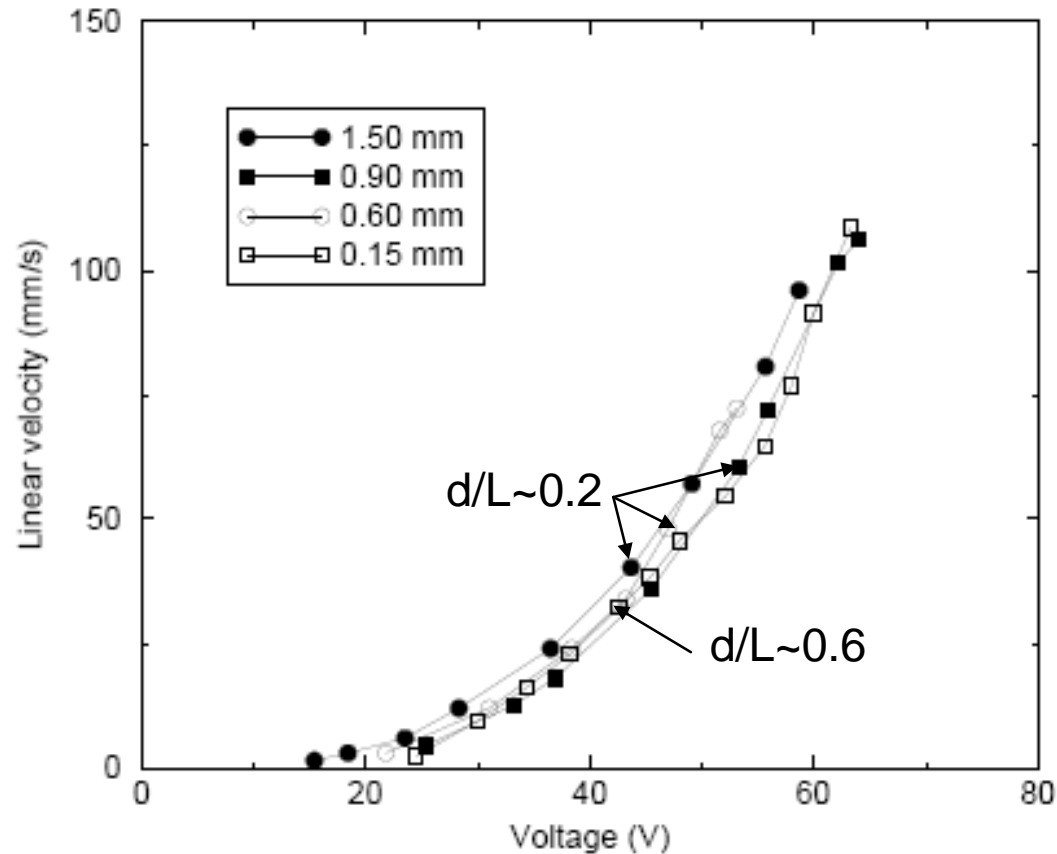
- where C_v is empirical constant in viscous drag force:

$$F_{\text{dv}} = 2C_v \frac{\mu_d U}{d} L^2$$

- $C_v=6$ for parabolic droplet velocity profile
- If $\mu_d=\mu_o$, then $(d/L)_{\text{opt}} = 1$
 - Unconstrained droplet
 - No plate shear force



Aspect Ratio Effect on Transport (Pollack)



Scaling Effects on Threshold Voltage

- Threshold voltage from model:

$$U = \frac{\sin \phi \left\{ \cos \alpha \frac{\epsilon_r \epsilon_o V^2}{2t} - \gamma_{lg} \sin \alpha [\sin \theta(V) + \sin \theta(0)] \right\}}{12\mu_o \frac{d}{L} + 2C_v \frac{\mu_d}{d} L}$$

- When $U=0$, $V=V_T$:

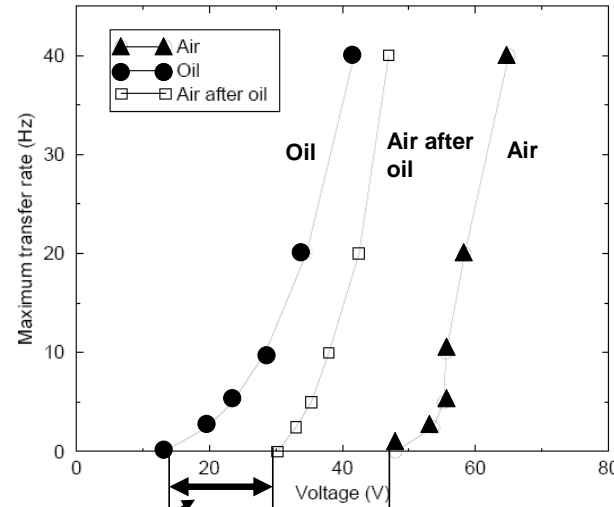
$$V_T \sim \left\{ 2t\gamma_{lg} / \epsilon_r \epsilon_o [\sin \alpha (\sin \theta(V_T) + \sin \theta(0))] \right\}^{1/2}$$

- where α is amount of contact angle hysteresis
- $\alpha = 1.5-2^\circ$ (water in silicone oil); $7-9^\circ$ (water in air)



Effect of α and γ_{lg} on V_T

Pollack 2001:



$$V_{Tair}/V_{Toil} \sim [(\gamma_{lg}(\text{air})/\gamma_{lg}(\text{oil}))^{1/2}]$$

$$\sim [72.8\text{mN/m}/47\text{mN/m}]^{1/2}$$

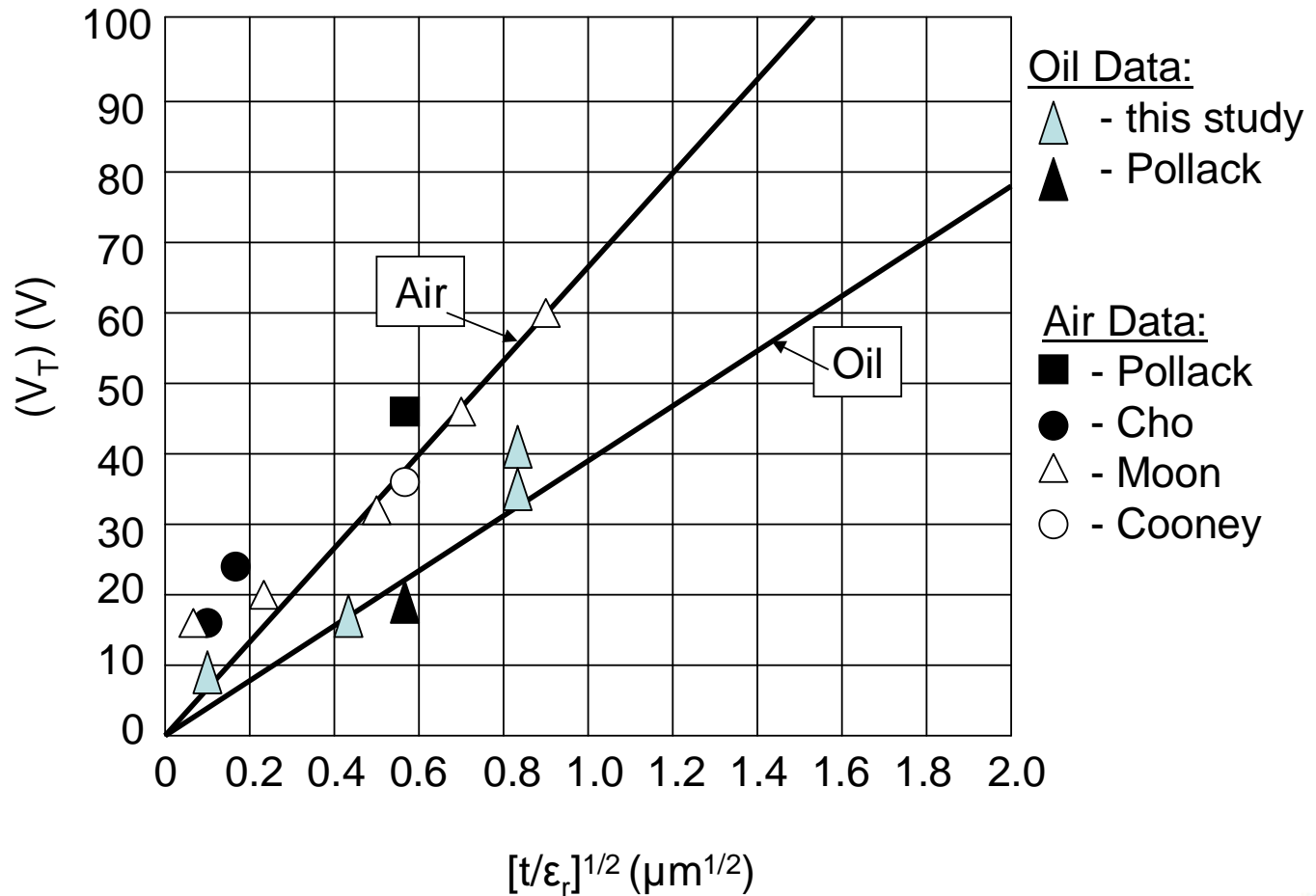
$$= 1.24$$

$$V_{Tair}/V_{Toil} \sim \frac{[\sin\alpha(\text{air})(\sin\theta(V_T)+\sin\theta_o)]^{1/2}}{[\sin\alpha(\text{air})(\sin\theta(V_T)+\sin\theta_o)]^{1/2}}$$

$$\sim [\sin(7-9^\circ)]^{1/2}/[\sin(1.5-2^\circ)]^{1/2}$$

$$= 1.9 - 2.5$$

Threshold Voltage Scaling



Effect of Aspect Ratio on V_T

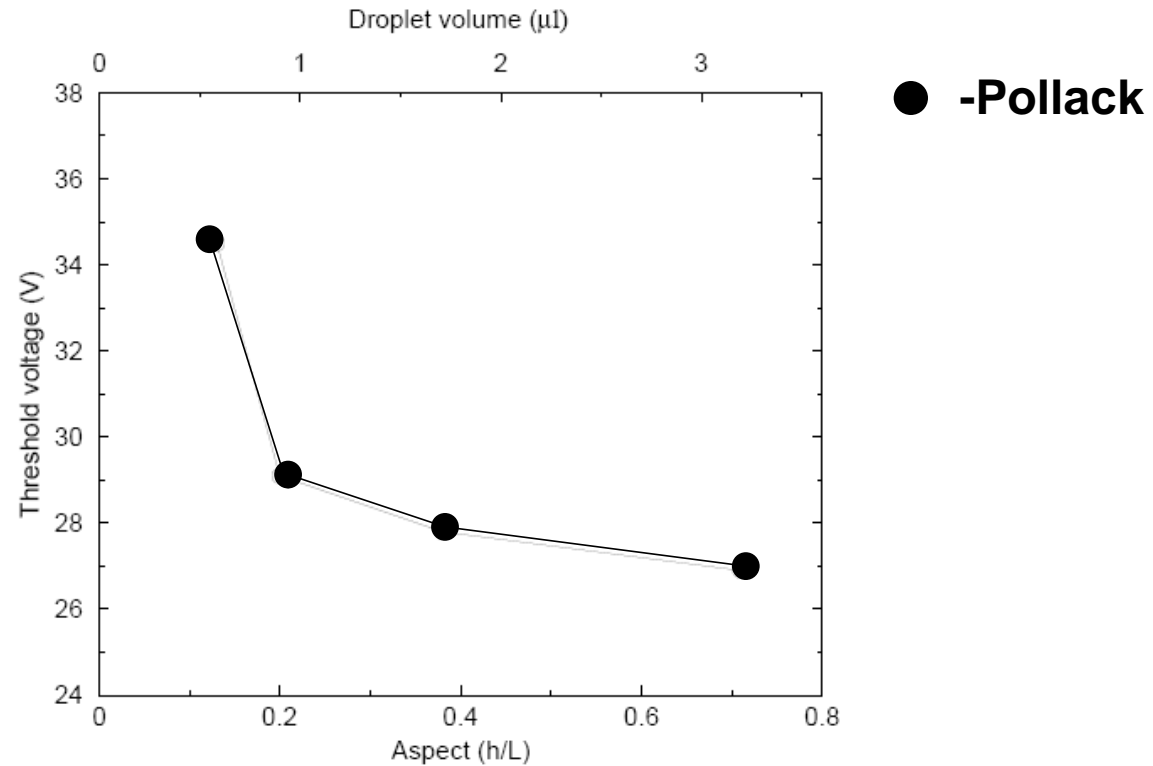


Figure 4.8: Effect of varying the gap height on the 10 Hz threshold voltage

Viscosity Effects on V_T

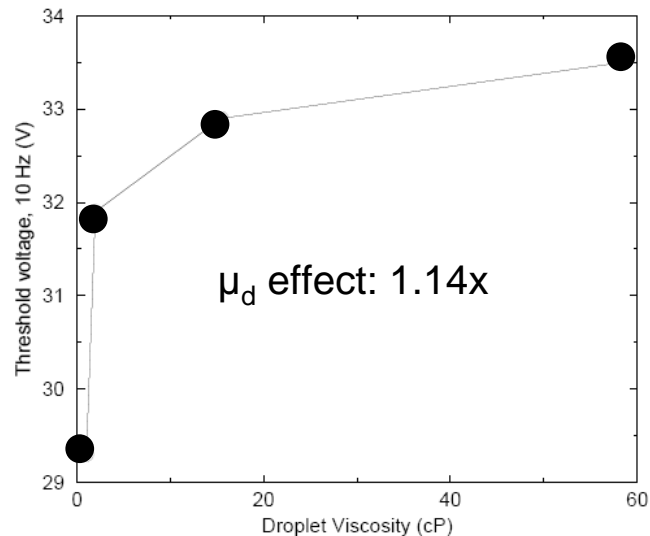


Figure 4.15: Effect of droplet viscosity on 10 Hz threshold voltage

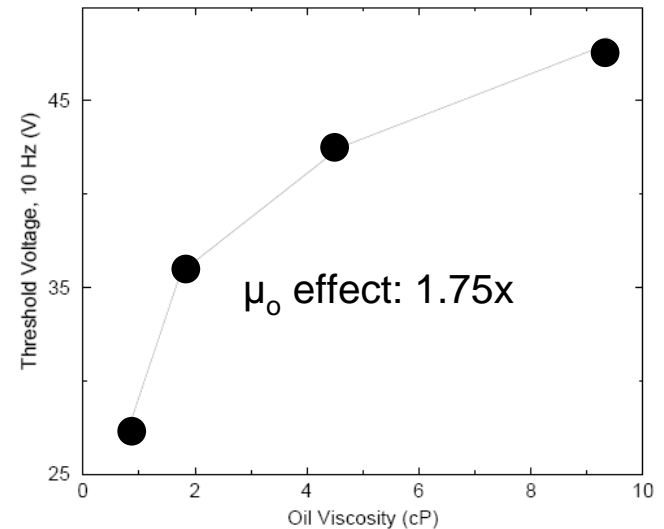


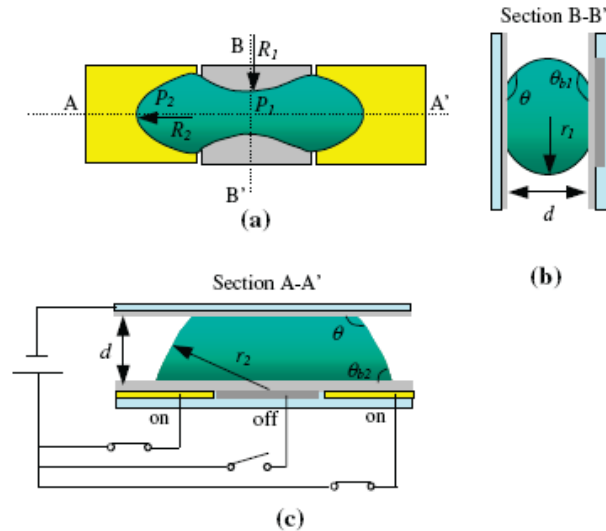
Figure 4.16: Effect of silicone oil viscosity on 10 Hz threshold voltage

$$V_T = \{2\gamma_{lg}/\epsilon\epsilon_o [\sin\alpha (\sin\theta(V_T) + \sin\theta_o)]\}^{1/2}$$

● -Pollack

Static Splitting Model

(Cho et al. 2002)



Criteria for static splitting:

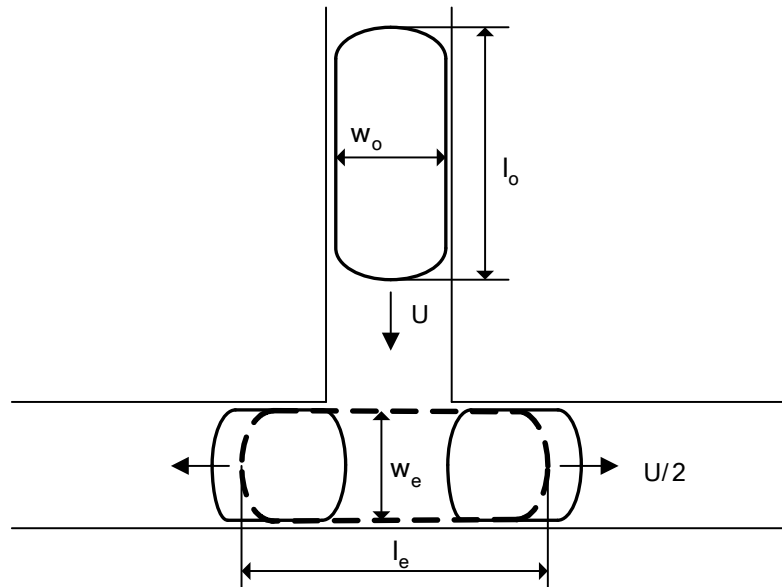
$$1/R_1 = 1/R_2 - (\cos \theta_{b2} - \cos \theta_{b1})/d$$

For N' electrodes, the minimum voltage for splitting is:

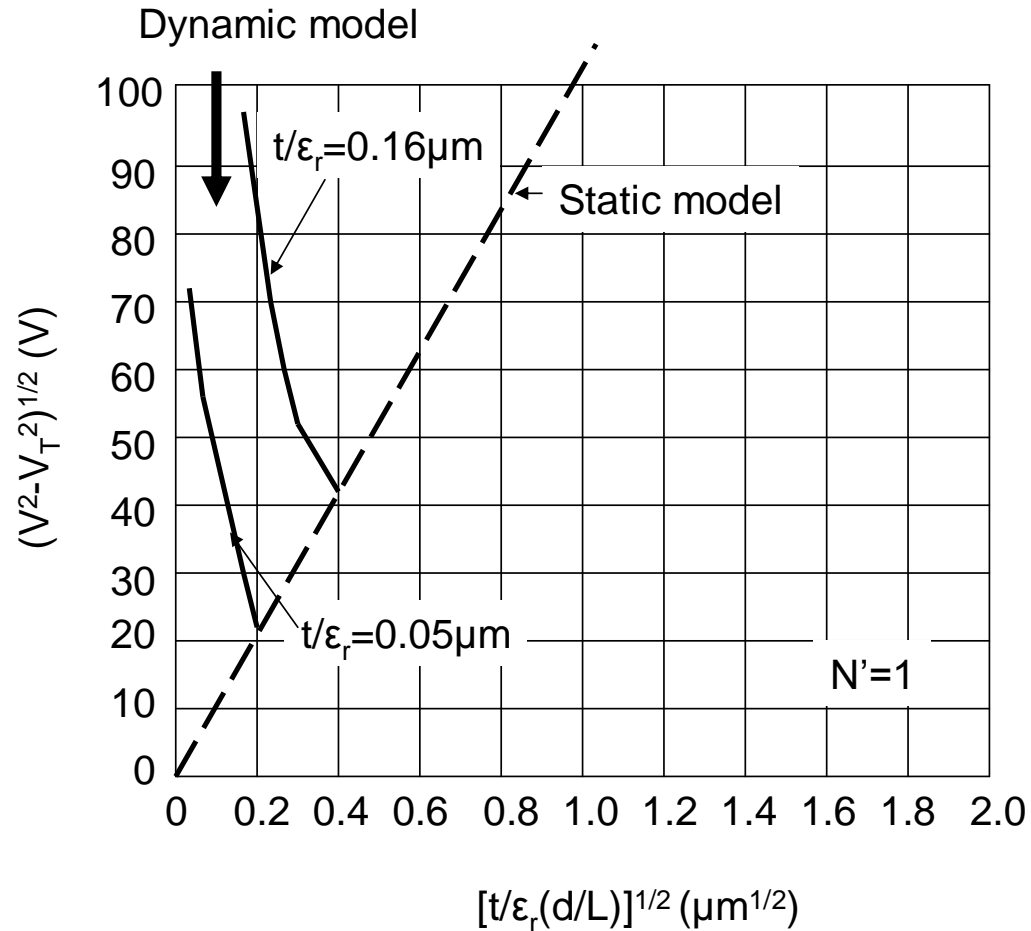
$$V^2 - V_T^2 \approx 4\gamma_{lg}[t(d/L)]/\epsilon_r\epsilon_o[1 - 1/(N'^2 + 1)]$$

Dynamic Splitting Model

- Link et al model: splitting depends on droplet extension $e_o = l_o / \pi w_o$
- Splitting occurs at T-junction when $e_o > 1$
- $[V^2 - V_T^2] \approx [2t\gamma_{lg} / \epsilon_r \epsilon_o] [0.012d/L + 0.002(\mu_d/\mu_o)C_V L/d]$



Splitting: Static vs. Dynamic Models

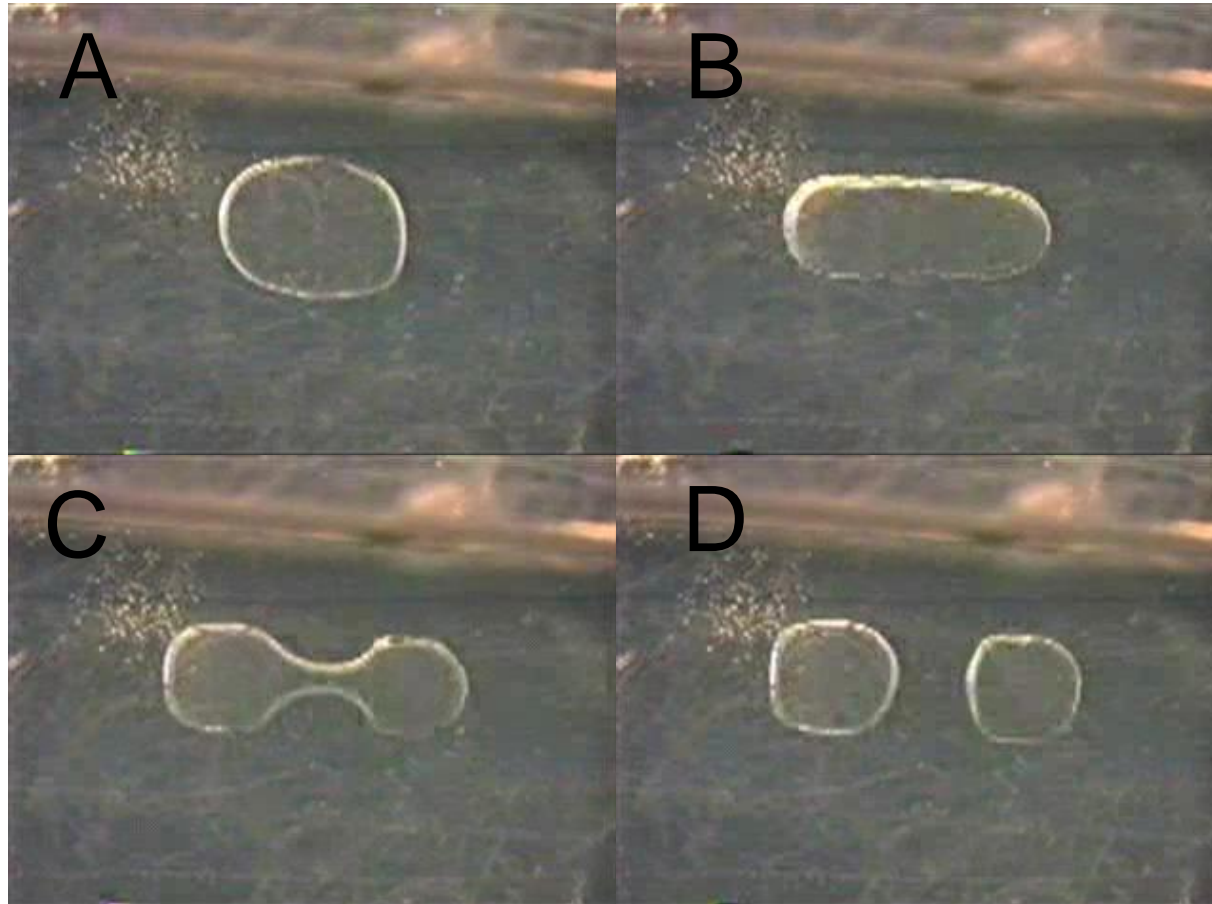


Splitting Model Comparison

- Static model:
 - splitting voltage increasing linearly with $[t/\epsilon_r(d/L)]^{1/2}$ due to lower internal pressure at higher aspect ratio
- Dynamic model:
 - Splitting voltage decreases with $[t/\epsilon_r(d/L)]^{1/2}$ due to reduced plate drag forces
- Static model and dynamic model agree at $d/L=1$
- Data support static model, but splitting depends on time sequencing of electrode voltages



Uniform Splitting



Variables in Uniform Droplet Splitting

- Aspect ratio, d/L
- ζ_{lg}
- Electrode shape
- Time sequencing
- Initial droplet position
- Contact angle saturation
- Electrode voltages

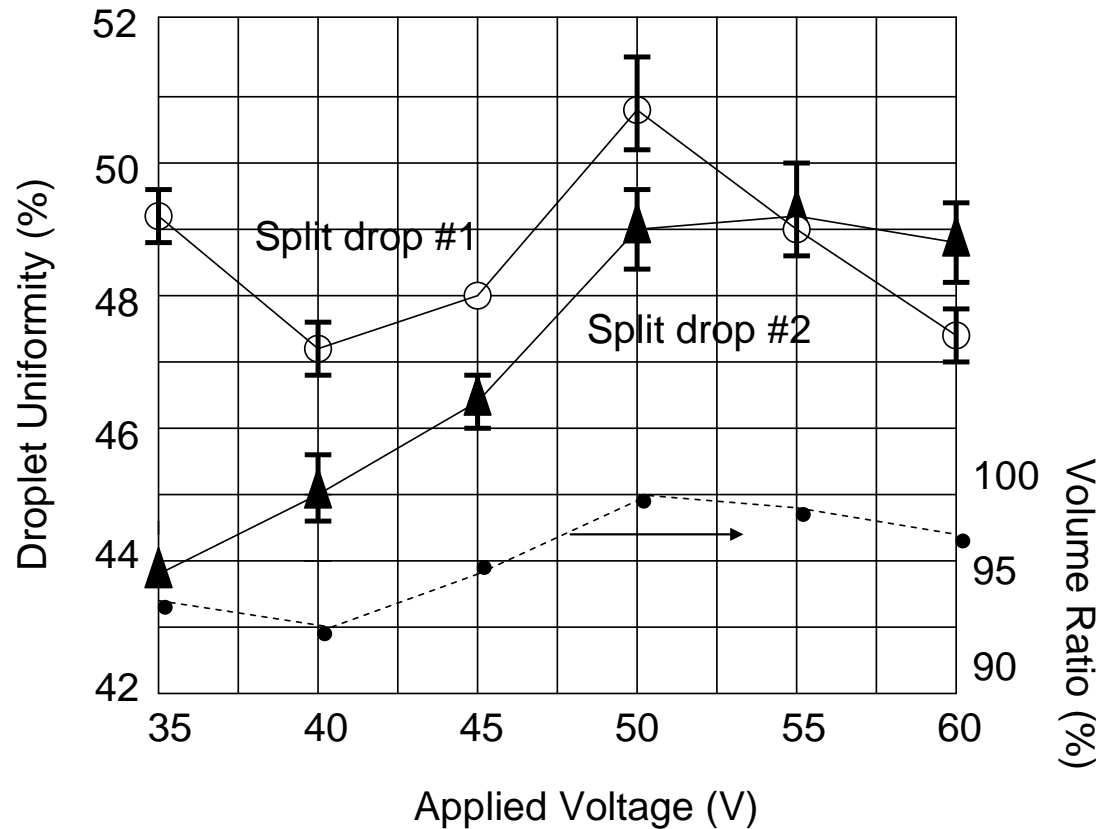


Best Splitting Conditions

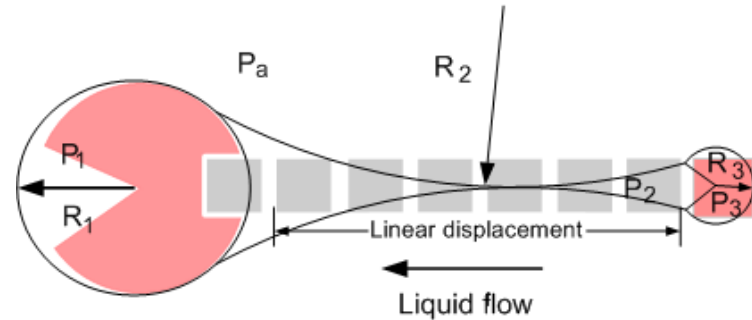
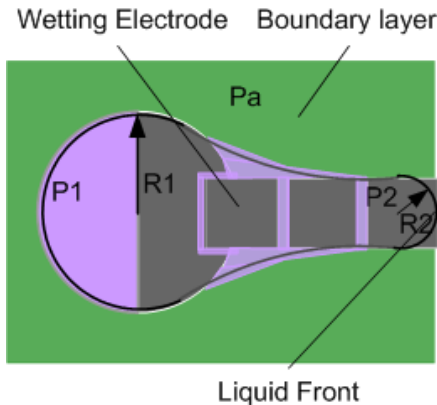
$d/L=0.2$, $V_T=16V$

Insulator: Teflon/ $0.5\mu\text{m}$ parylene C

$V_{\text{sat}} > 50V$



Dispensing



$$\frac{\epsilon_0 \epsilon}{2\gamma_{LM} t d} (V - V_T)^2 > \frac{1}{R_2} - \frac{1}{R_1}$$

$$P_2 > P_1 \Rightarrow \frac{1}{r_2} - \frac{1}{r_1} = \frac{\epsilon_0 \epsilon}{2\gamma_{LM} t d} V^2 > \frac{1}{R_1} - \frac{1}{R_2}$$

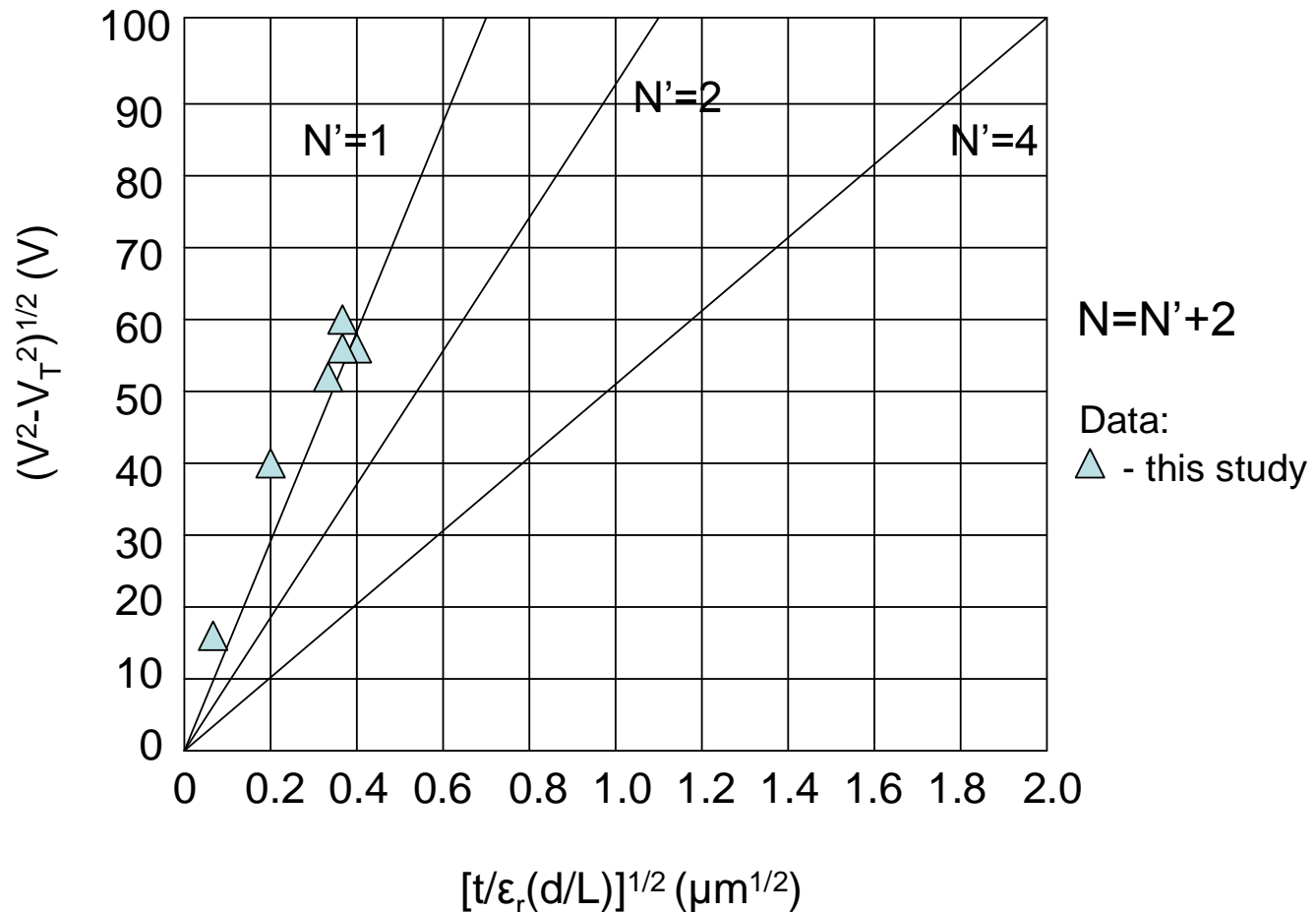
$$\Rightarrow \frac{\epsilon_0 \epsilon}{2\gamma_{LM} t} V^2 > \frac{d}{R_1} + \frac{2d}{(N^2 + 1)R_3} \quad (\text{Ren, 2003})$$

- If $R_1 = 2\text{mm}$, $R_2 = 250\mu\text{m}$, $d = 200\mu$, then $V_{\min} = 45\text{V}$
- If $R_2 = 250\mu\text{m}$, $d = 100\mu\text{m}$, $V_{\max} = 50\text{V}$, then $R_{1\max} = 2.3\text{mm}$

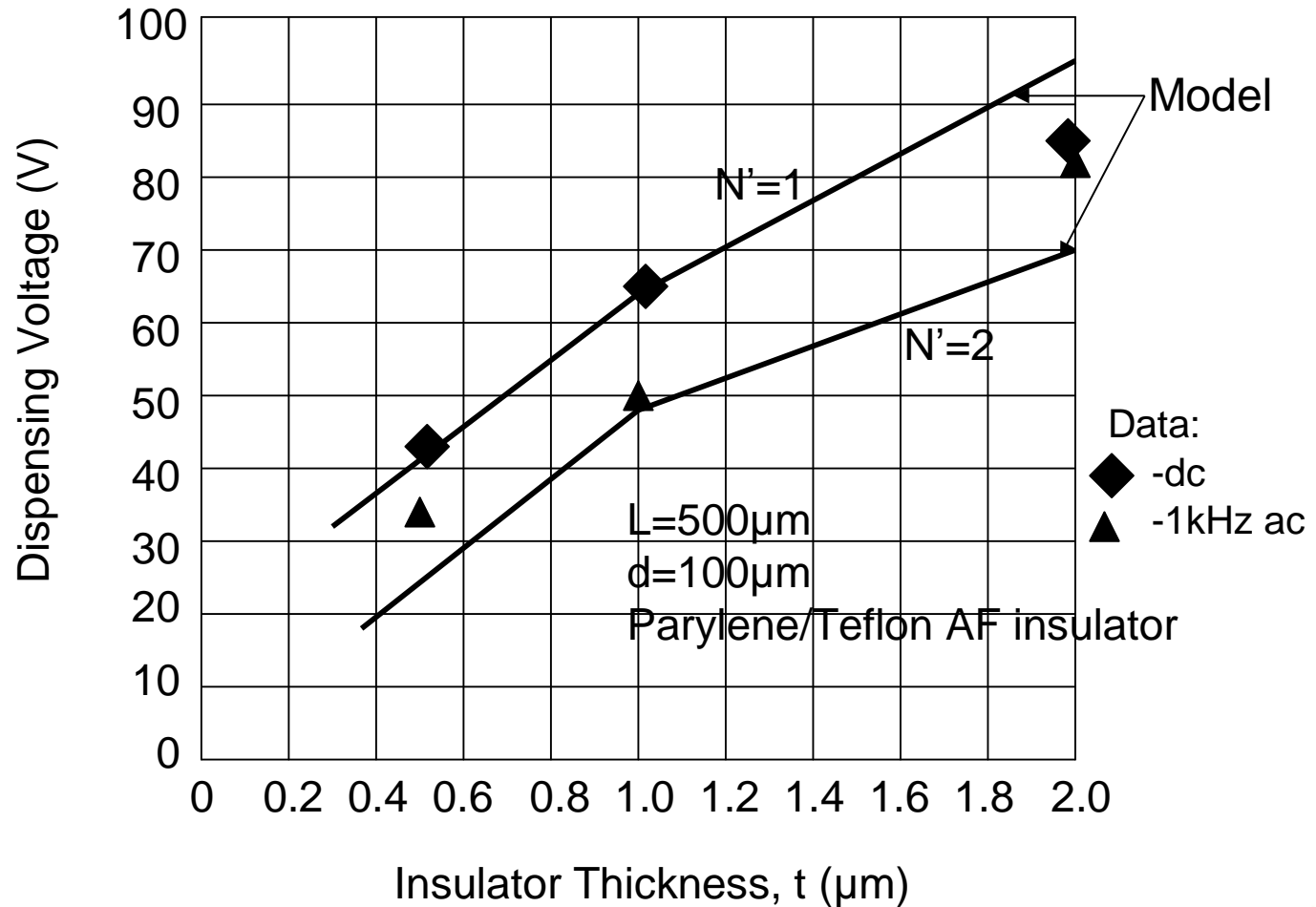
- if the aspect ratio is kept constant, scaling down leads to less linear displacement and fast pinch-off.
- large aspect ratio d/R_3 is favorable

Scaled Droplet Dispensing in Oil

$$(V^2 - V_T^2)^{1/2} > [8\gamma_{lg}/\epsilon_0 [t/\epsilon_r (d/L)] / (N'^2 + 1)]^{1/2}$$



Dispensing in Oil

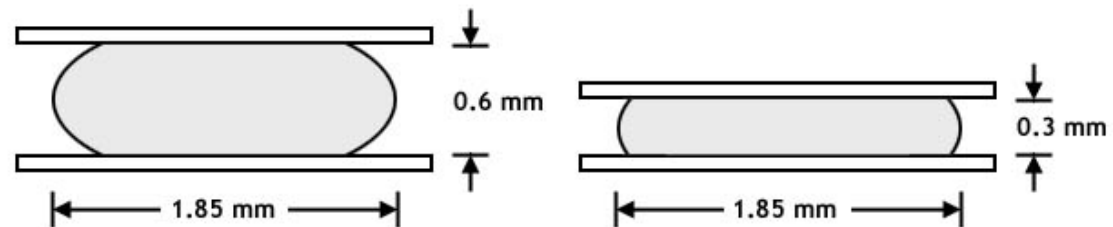


Mixing

- Aspect ratio dictates the shape of the droplet, which affects mixing times

$$\text{Aspect Ratio} = \frac{\text{gap height}}{\text{electrode pitch}}$$

- Higher ratios result in more spherical shapes, lower ratios of more cylindrical shapes



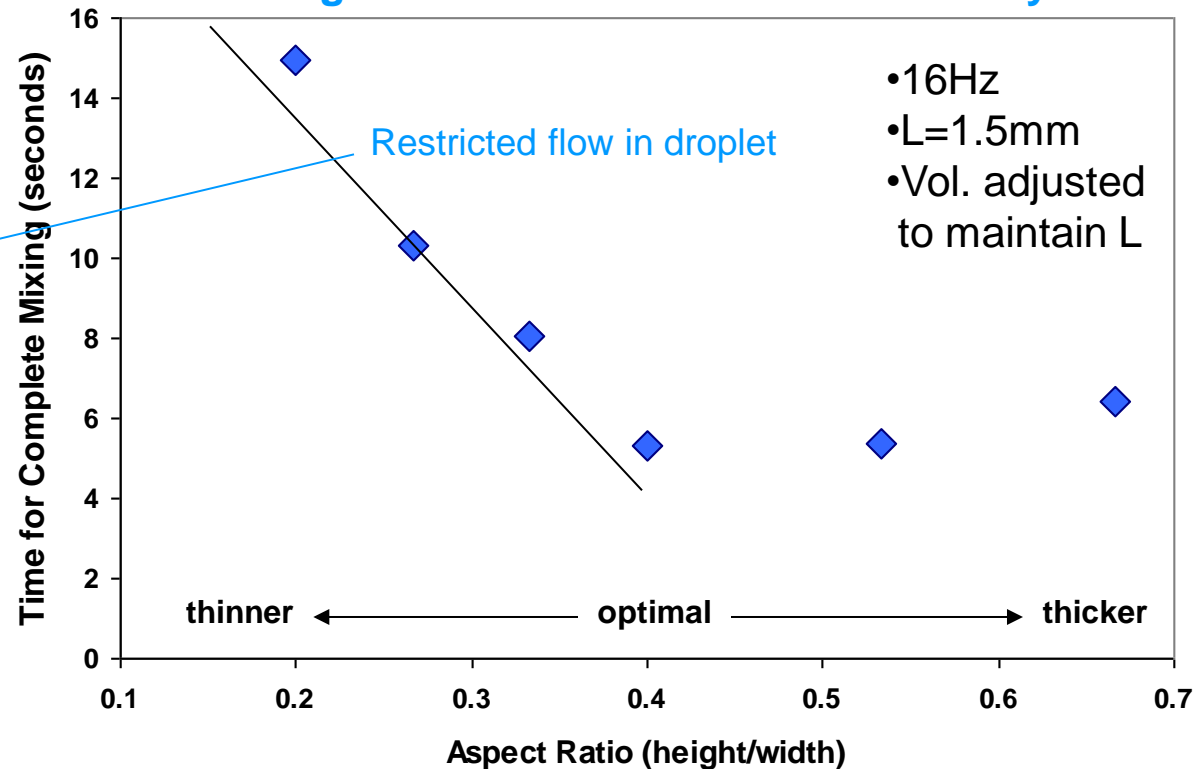
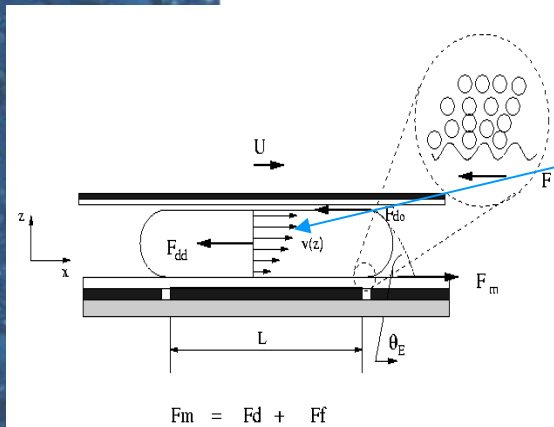
- Song et al.: mixing by chaotic advection:

$$t_{\text{mix}} \sim 1/f \log(L^2/Df)$$

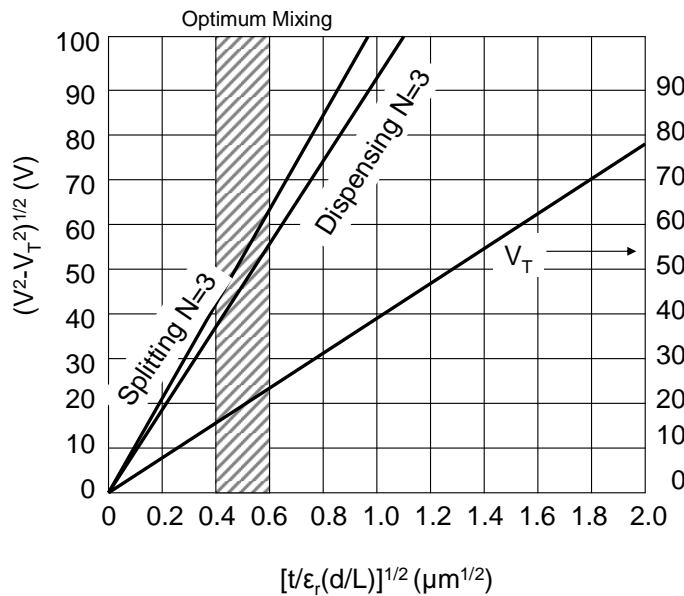
Mixing

(Paik-2003)

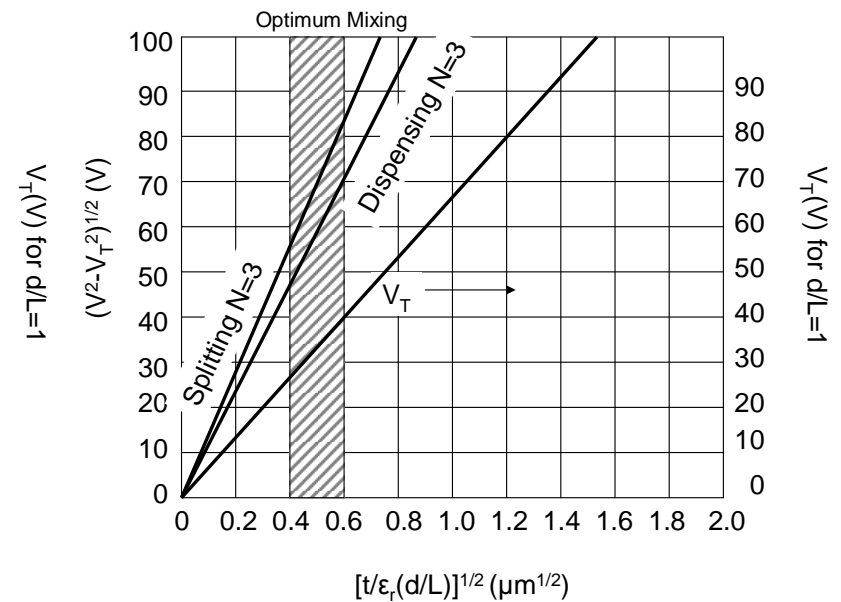
Mixing Times for 4 Electrode Linear Arrays



Combined Scaling



Silicone Oil



Air

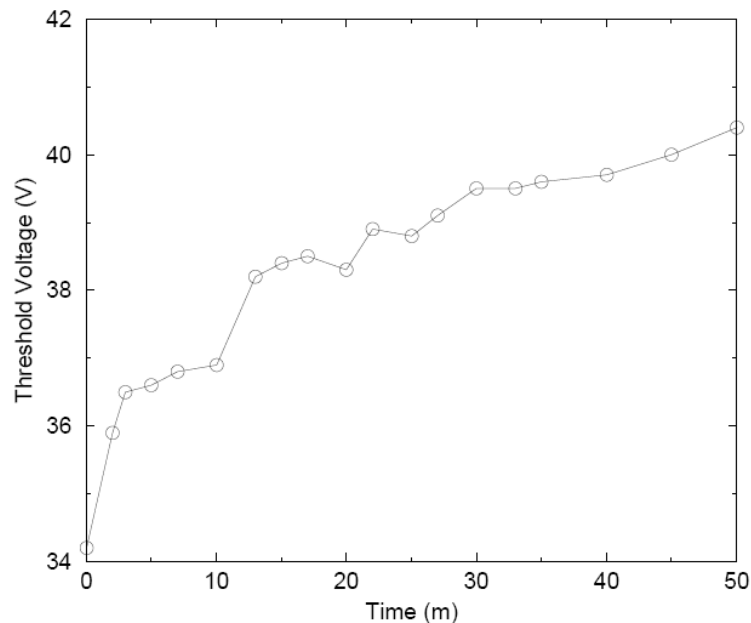
Scaling EWD Actuators

- Scaling variables: electrode size (L); aspect ratio (d/L), insulator thickness (t/ϵ_r), electrode gap (d)
 - Maximum droplet velocity $\rightarrow d/L \sim 1$
 - Low dispensing voltage $\rightarrow t/\epsilon_r(d/L)$ small
 - Optimum mixing rate $\rightarrow d/L \sim 0.4$
 - Low threshold voltage $\rightarrow d/L > 0.2$, t/ϵ_r small
 - Low splitting voltage $\rightarrow t/\epsilon_r(d/L)$ small



EWD Actuator Voltage Limits

- Lippman-Young equation valid up to V_{sat}
- Insulator charge trapping/leakage observed at V_{sat} (Berry et al.; Papathanasiou et al.)
- Time-dependent V_T results:



Teflon/Parylene/Oil
 $V \geq 60V$
Pollack

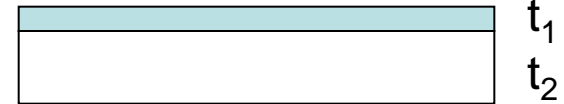
Contact Angle Saturation

Lippmann-Young Eq.:

$$V_{\text{sat}} = \{2\gamma_{lg}/\epsilon_0 \epsilon_1 [t_1 + t_2 (\epsilon_1/\epsilon_2)] [\cos\theta(V_{\text{sat}}) - \cos\theta(0)]\}^{1/2}$$

where

$$t/\epsilon_r = t_1/\epsilon_1 + t_2/\epsilon_2$$

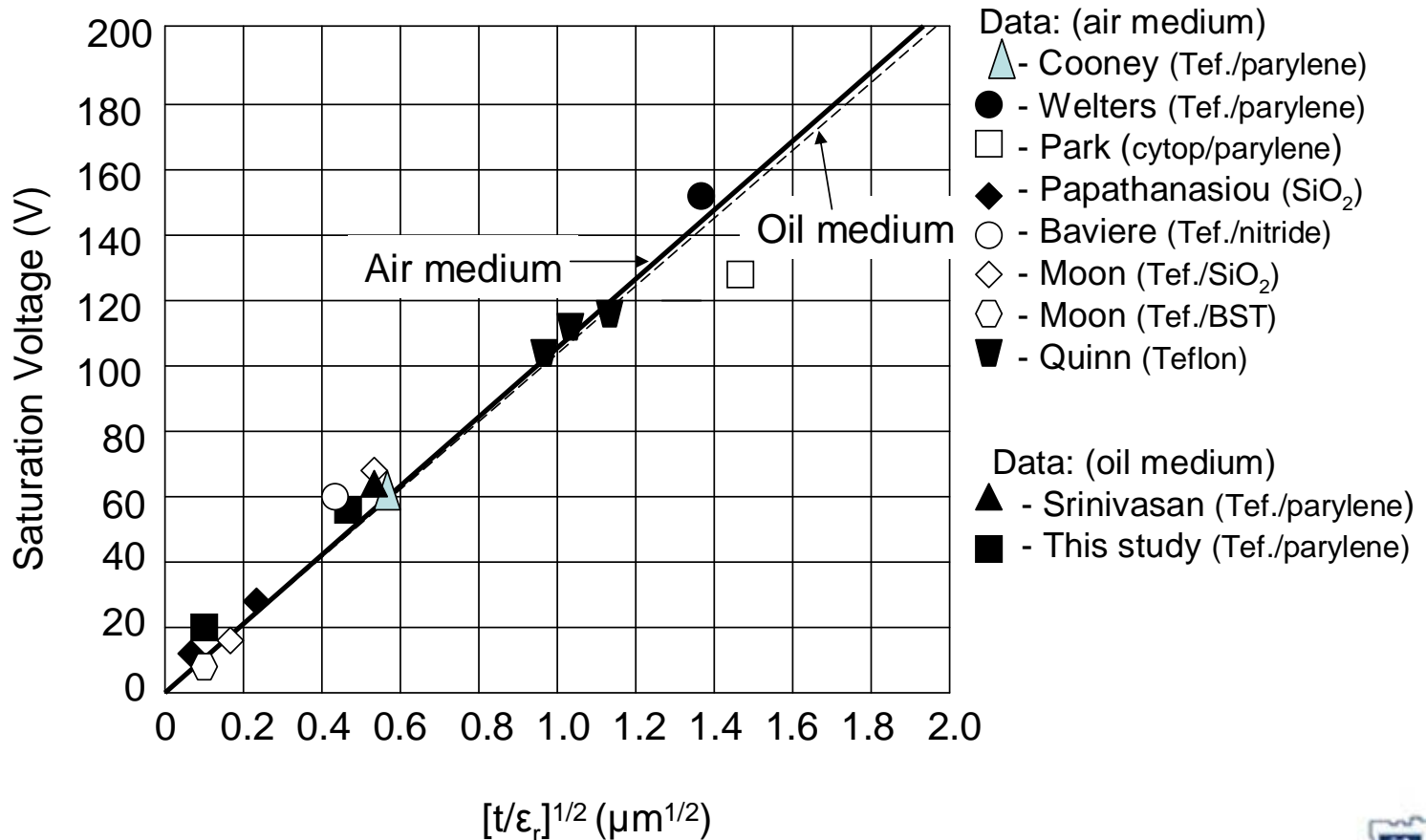


Pollack's actuator:

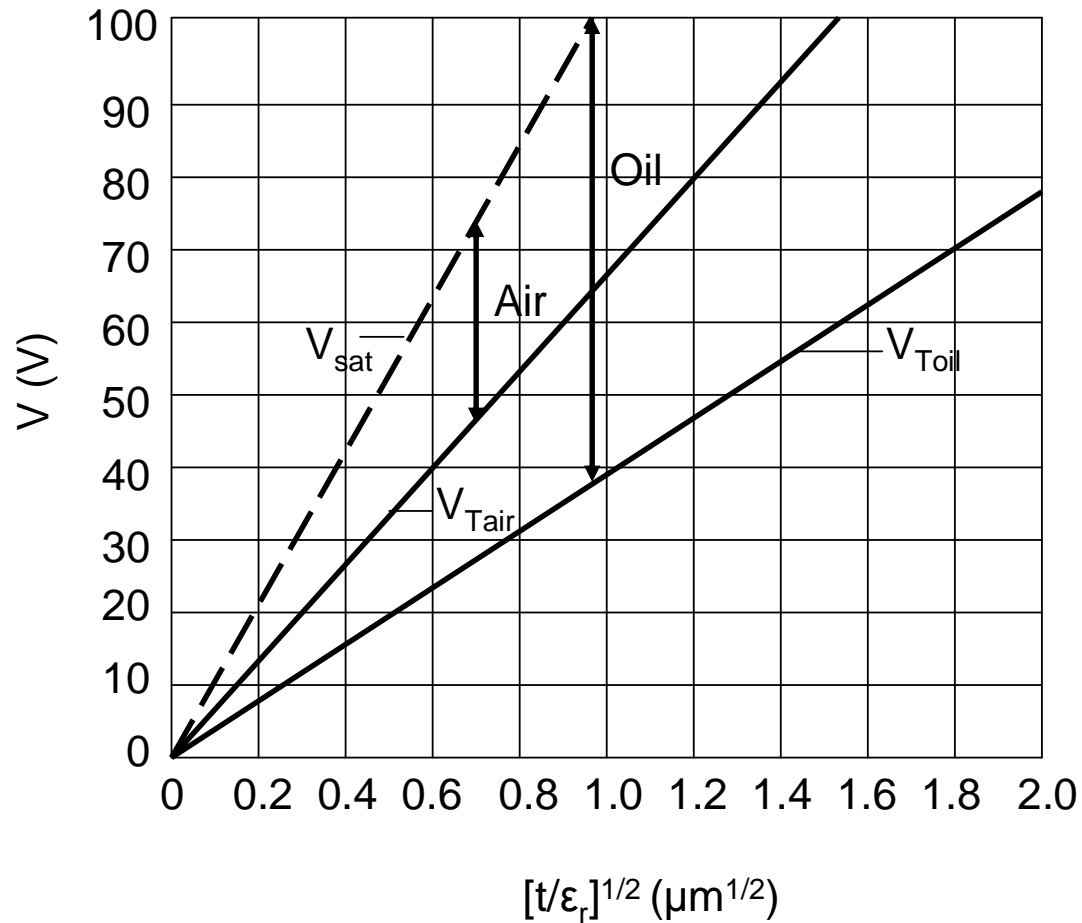
- $\theta(V_{\text{sat}}) = 63^\circ$
- $\theta(0) = 125^\circ$
- $V_{\text{sat}} = 56\text{V}$ (calculated)
- $V_{\text{exp}} = 60\text{V}$ (measured)

Contact Angle Saturation

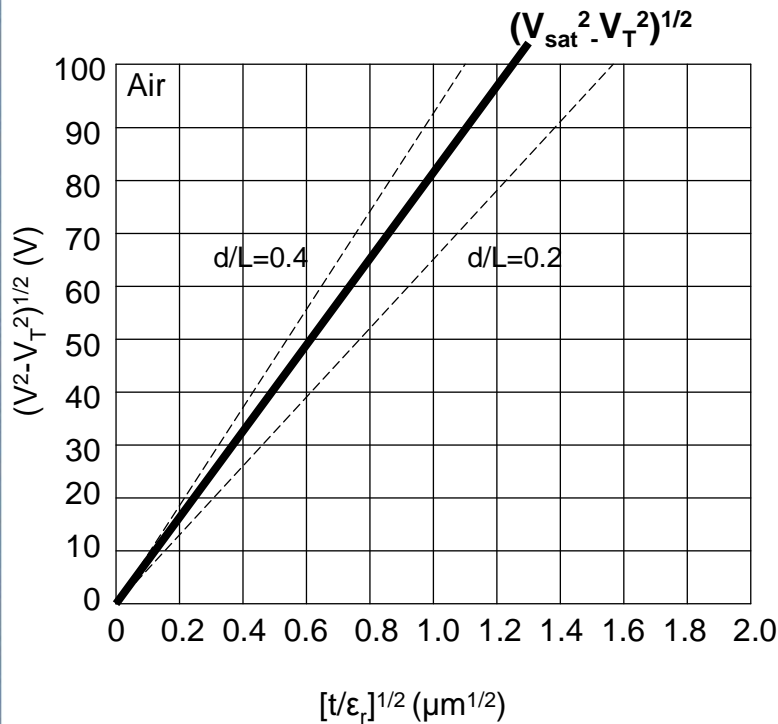
$$V_{\text{sat}} = \{2\gamma_{\text{lg}}/\epsilon_0\epsilon_1[t_1 + t_2(\epsilon_1/\epsilon_2)][\cos\theta(V_{\text{sat}}) - \cos\theta(0)]\}^{1/2}$$



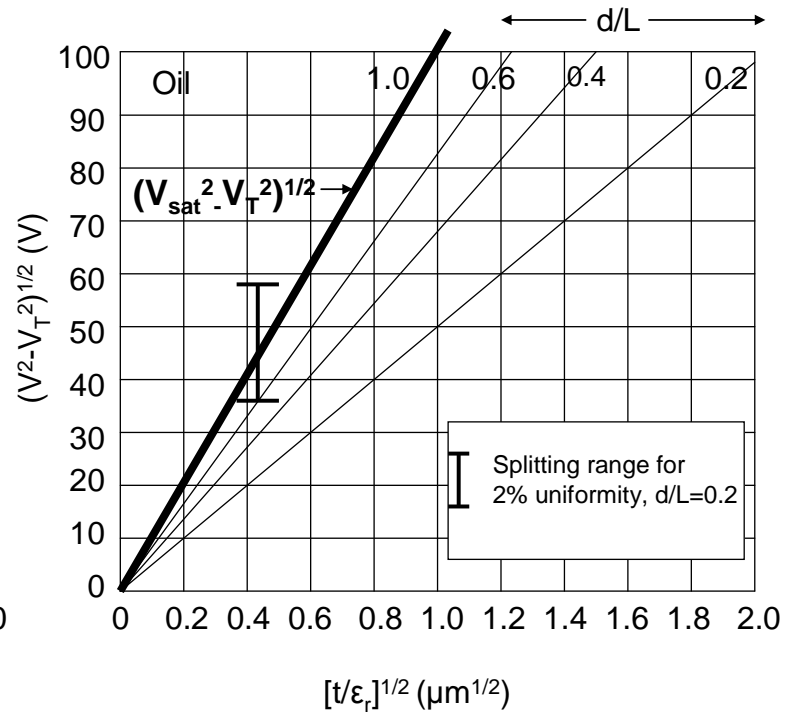
Safe Operating Ranges



Reliable 3-Electrode Splitting in Silicone Oil and Air



Air

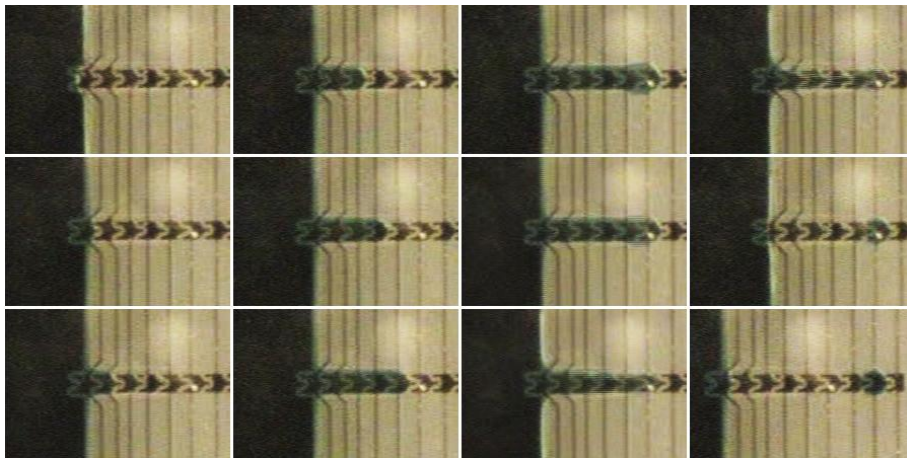


Oil

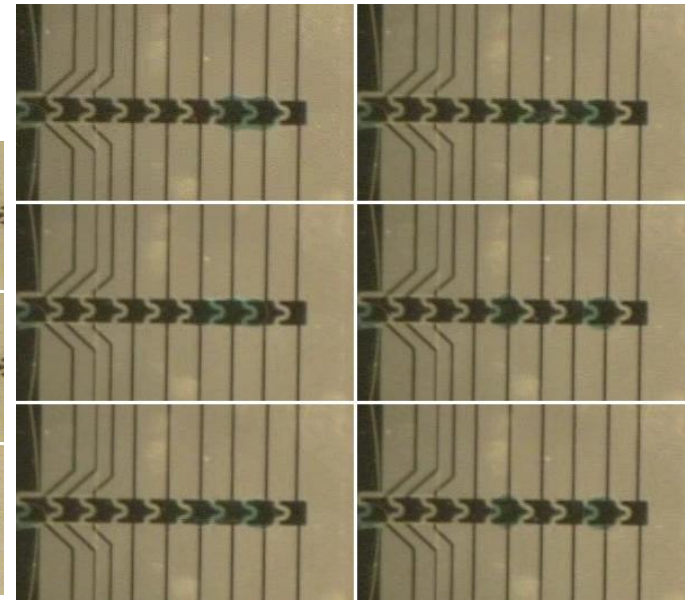


Picoliter Droplet Scaling

- Demonstrated dispensing, actuation, and merging/splitting of picoliter droplets

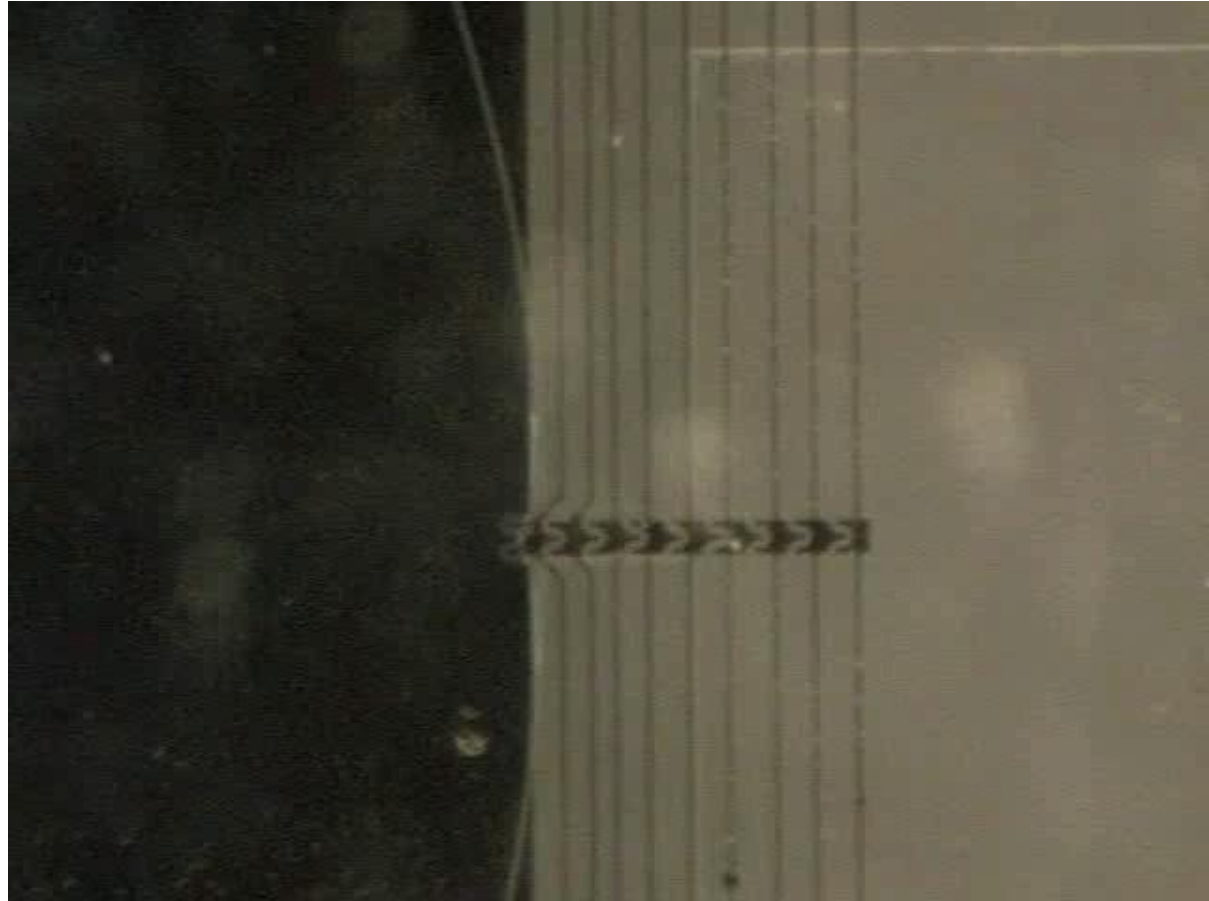


Dispensing and actuating 35pL droplet (40 μ m electrodes, 9.4 μ m gasket height, 70V, 2 μ m parylene)



Splitting ~100pL droplets (60 μ m electrode, 7.5 μ m gasket, 2 μ m parylene, 80V)

35 Picoliter Droplet Dispensing



Summary and Conclusions

- Scaling model developed
 - Useful for determining trends in V_T , V_{sat} , oil vs. air
 - Splitting, dispensing, protrusion all scale with on $[t/\epsilon_r(d/L)]^{1/2}$
 - With $t/\epsilon_r(d/L)$ held constant while L is decreased, number of dispensing electrodes is constant for constant V and V_T
- Reliable EWD actuator operation if $V \leq V_{sat}$
- Oil vs. air filler media
 - Lower V_T allows larger reliable safe operating voltages in oil
 - Minimum splitting/dispensing voltages in air may place limits on d/L for reliable operation
 - Uniform splitting may test reliable voltage limits
- Scaling to 5pl demonstrated



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