Scaling EWD Actuators for Picoliter Applications

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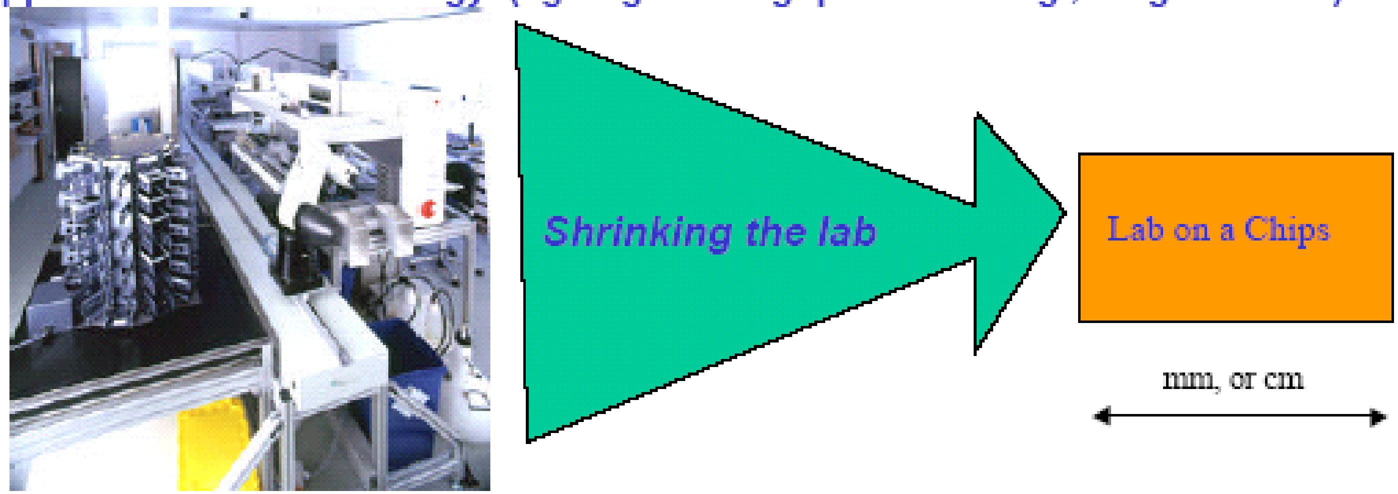
Outline of Presentation

- 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...)



- **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

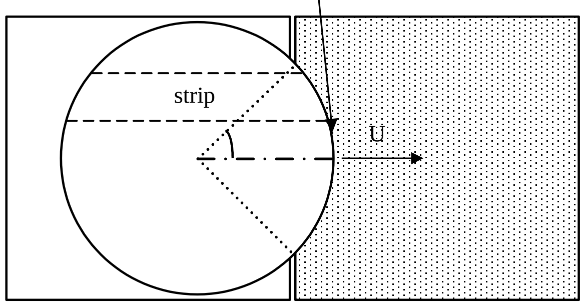
Droplet Transport Model

- 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

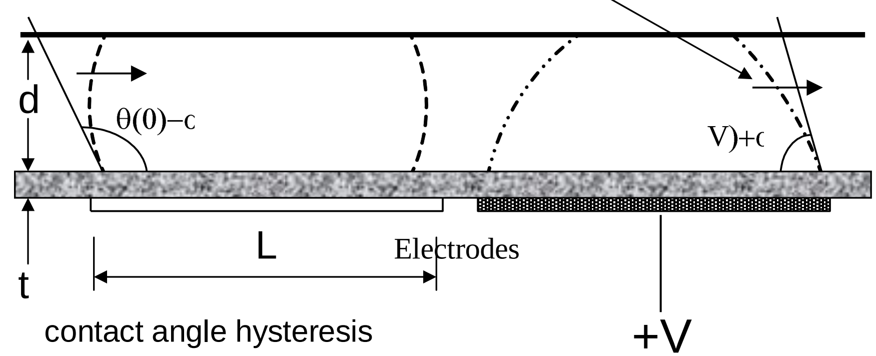
Droplet Transport Model

Droplet velocity

$$U=\frac{\sin\phi\left\{\cos\alpha\,\frac{\varepsilon_r\varepsilon_o V^2}{2t}-\gamma_{lg}\sin\alpha\,[\sin\theta(V)+\sin\theta(0)]\right\}}{\underbrace{12\mu_o\frac{d}{L}}_{\text{plate shear force}}+\underbrace{2C_v\frac{\mu_d}{d}L}_{\text{oil viscous drag}}}$$



angle of advancement



contact angle hysteresis

d/L=aspect ratio

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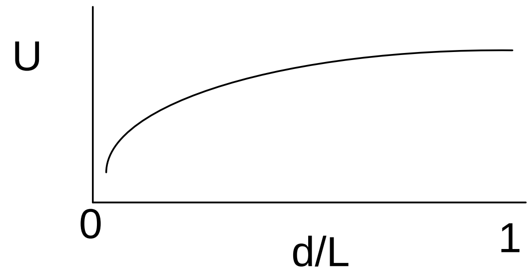
Scaling Effects on Velocity

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

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

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



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Droplet Transport Scaling

- Optimum aspect ratio for maximum velocity:

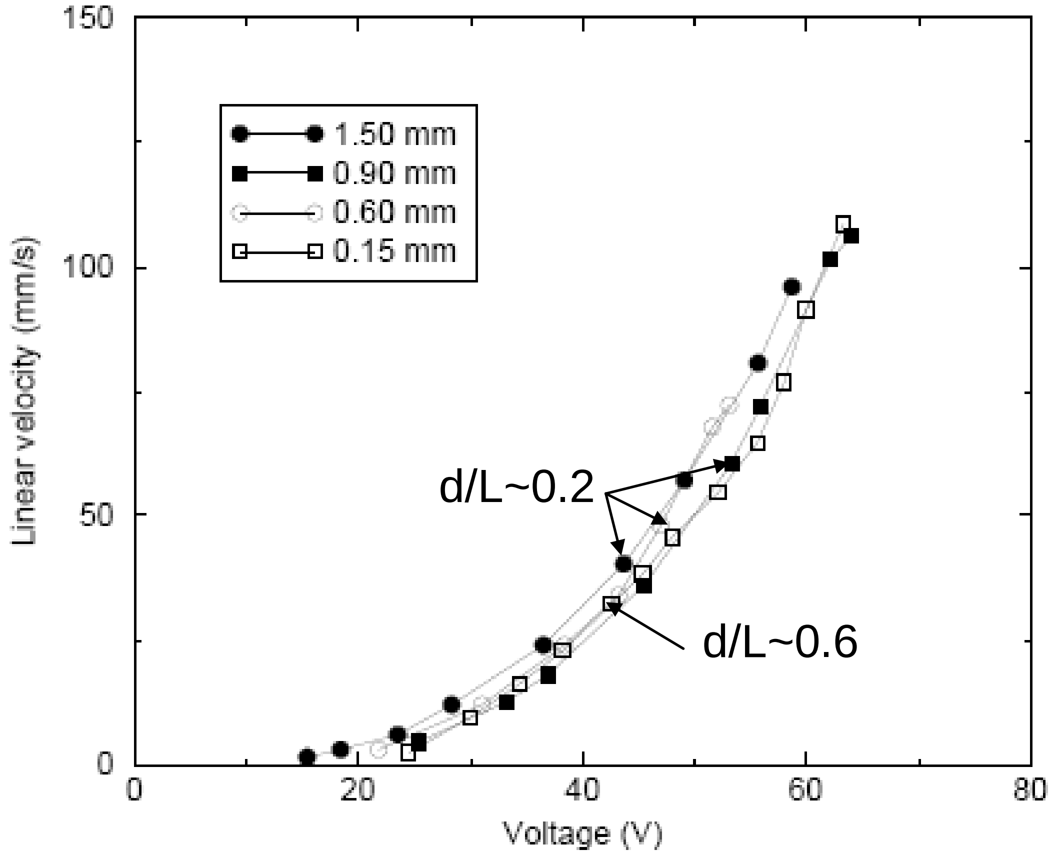
$$\left(\frac{d}{L}\right)_{opt} = \left(\frac{C_v \mu_d}{6\mu_o}\right)^{1/2}$$

- where C_v is empirical constant in viscous drag force:

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

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

Aspect Ratio Effect on Transport
(Pollack)



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Scaling Effects on Threshold Voltage

- Threshold voltage from model:

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

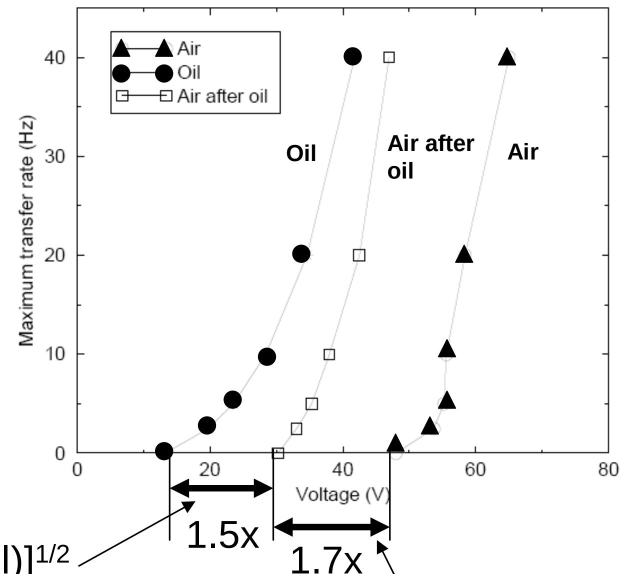
- When U=0, $V=V_T$:

$$V_T \sim \{2t\gamma_{lg}/\varepsilon_r\varepsilon_o\,[\sin\alpha\,(\sin\theta(V_T) + \sin\theta(0)]\}^{1/2}$$

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

Effect of α and γ_{lg} on V_T

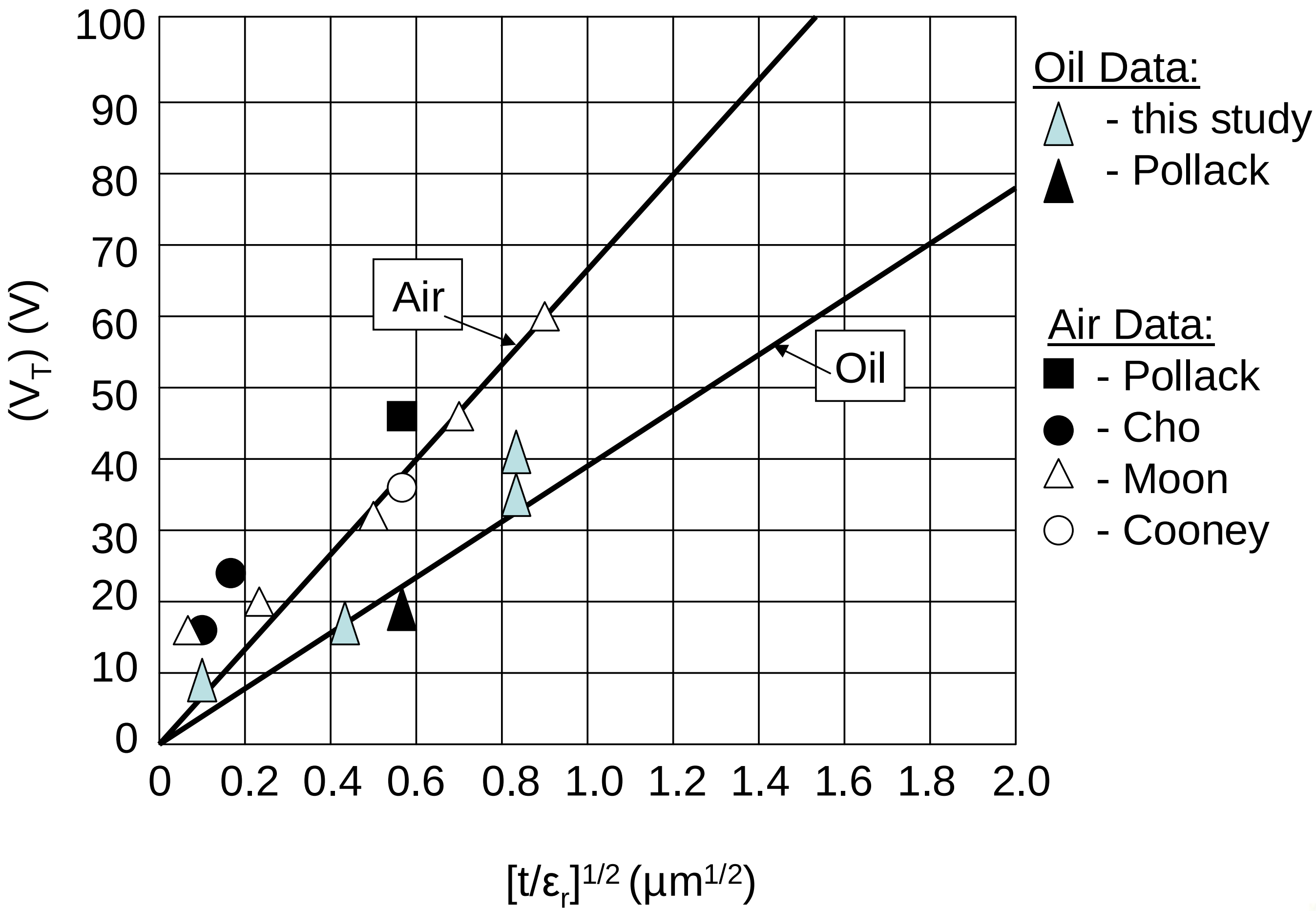
Pollack 2001:



$$V_{Tair}/V_{Toil} \sim [(\gamma_{lg}\,(air)/\gamma_{lg}\,(oil)]^{1/2} \sim [72.8mN/m/47mN/m]^{1/2} = 1.24$$

$$V_{Tair}/V_{Toil} \sim \frac{[\sin\alpha(air)(\sin\theta(V_T)+\sin\theta_o)]^{1/2}}{[\sin\alpha(air)(\sin\theta(V_T)+\sin\theta_o)]^{1/2}} \sim [\sin(7\text{-}9^o)]^{1/2}/[\sin(1.5\text{-}2^o)]^{1/2} = 1.9 - 2.5$$

Threshold Voltage Scaling



Effect of Aspect Ratio on V_T

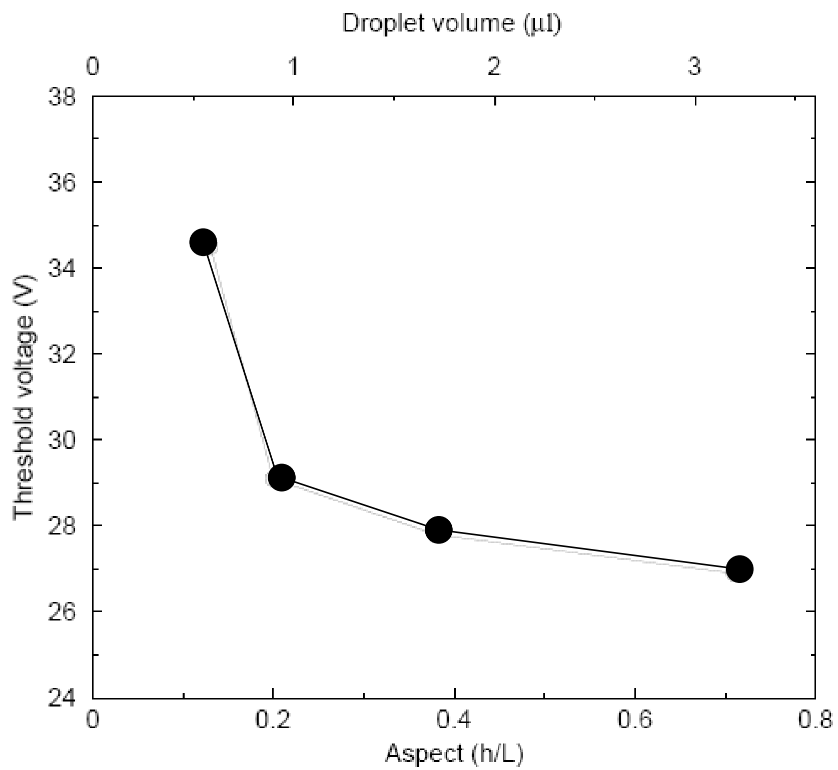


Figure 4.8: Effect of varying the gap height on the 10 Hz threshold voltage

● **-Pollack**

Viscosity Effects on V_T

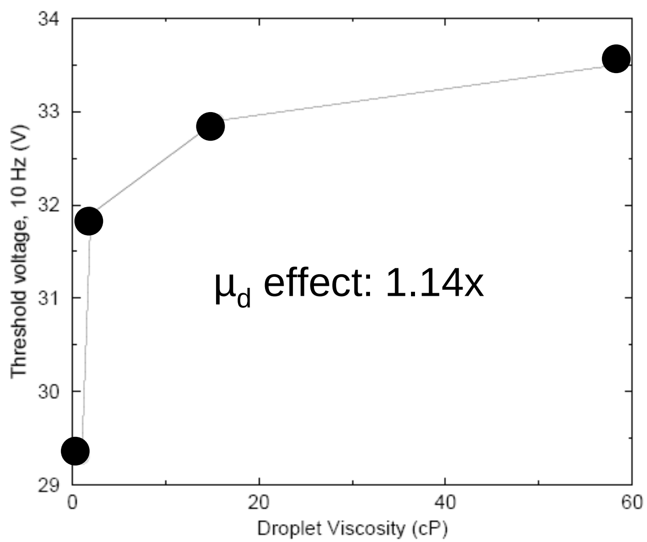


Figure 4.15: Effect of droplet viscosity on 10 Hz threshold voltage

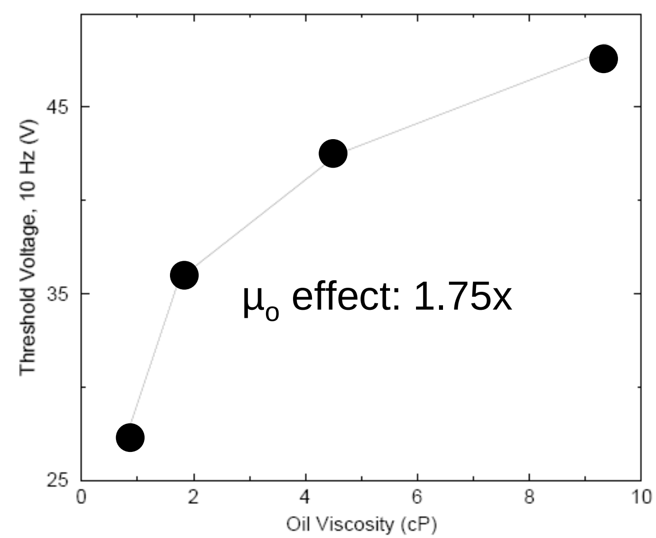


Figure 4.16: Effect of silicone oil viscosity on 10 Hz threshold voltage

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

- -Pollack

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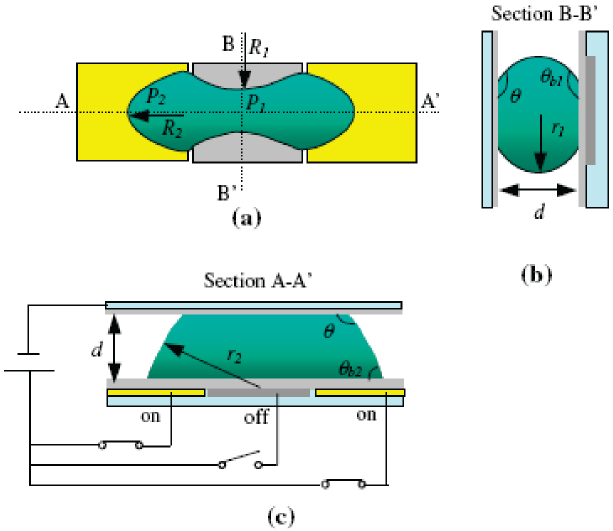
Static Splitting Model

(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:

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

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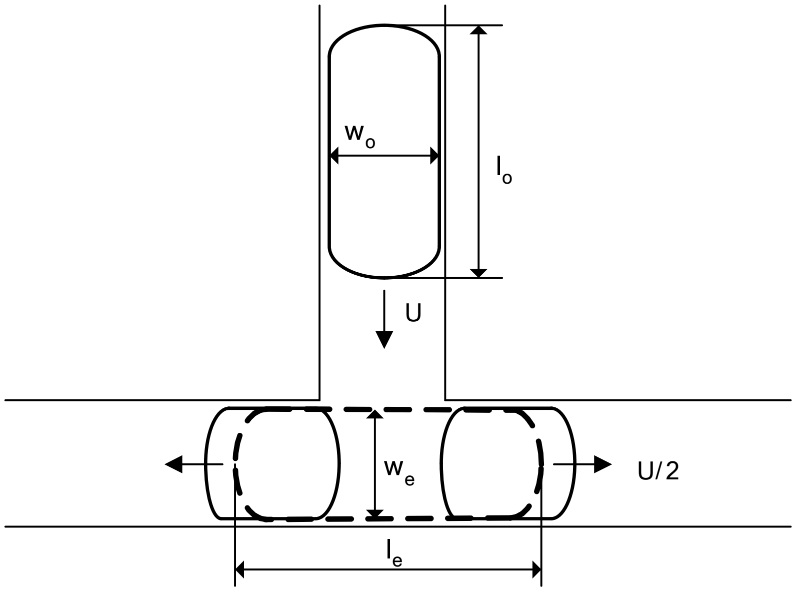
Dynamic Splitting Model

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



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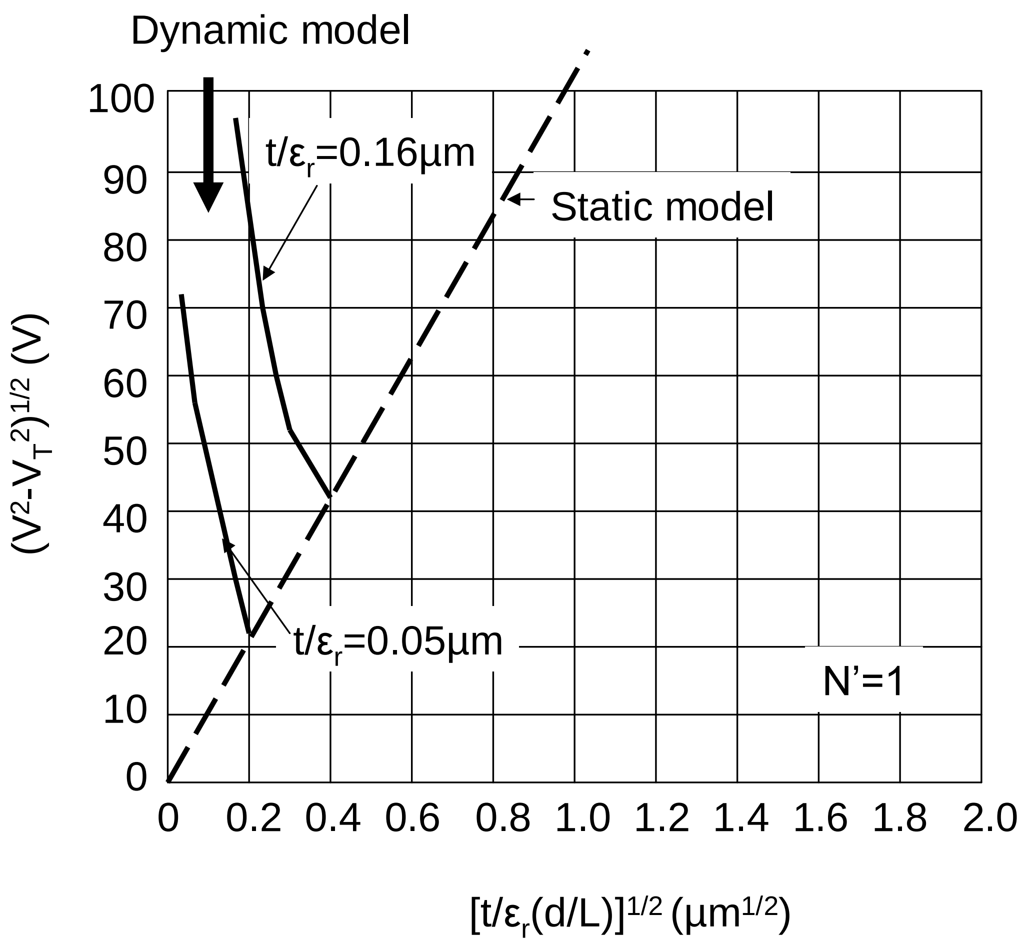
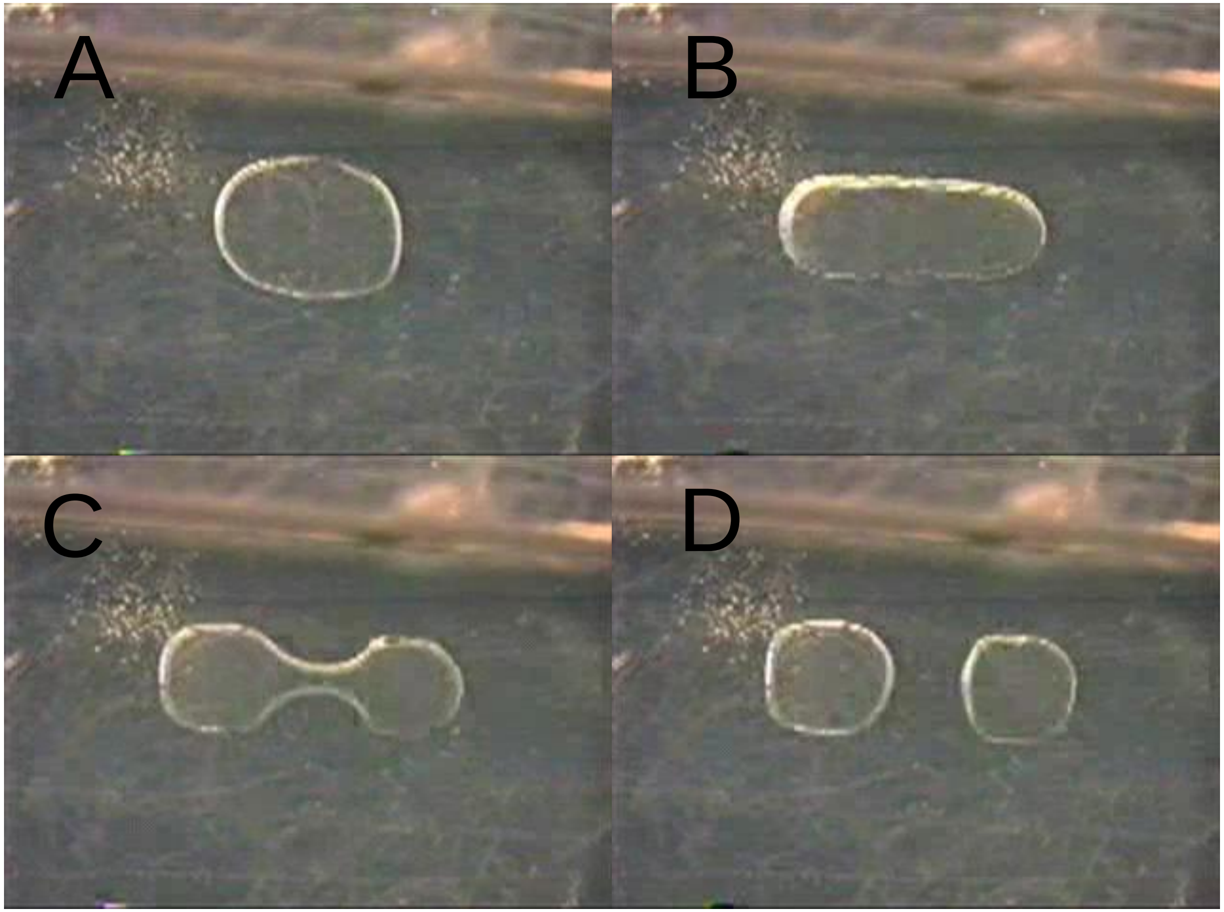
Splitting: Static vs. Dynamic Models



Splitting Model Comparison

- Static model:
  - splitting voltage increasing linearly with $[t/\varepsilon_r(d/L)]^{1/2}$ due to lower internal pressure at higher aspect ratio
- Dynamic model:
  - Splitting voltage decreases with $[t/\varepsilon_r(d/L)]^{1/2}$ due 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

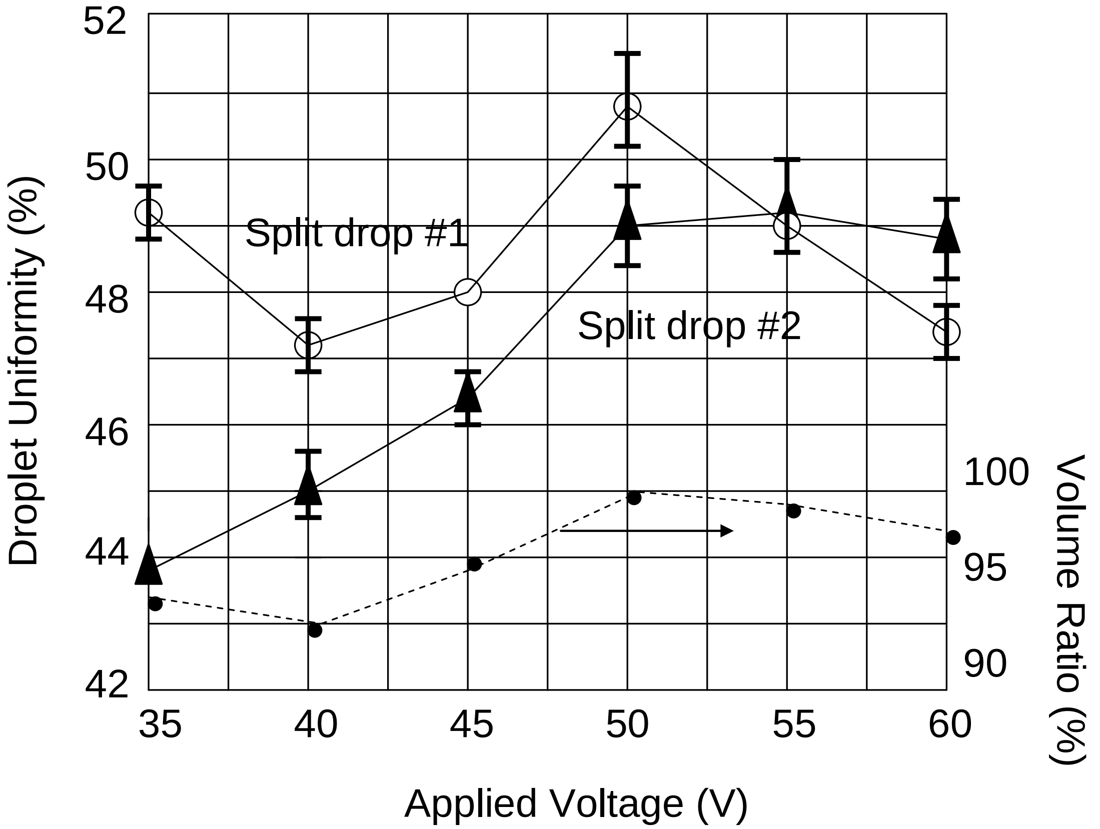


Variables in Uniform Droplet Splitting

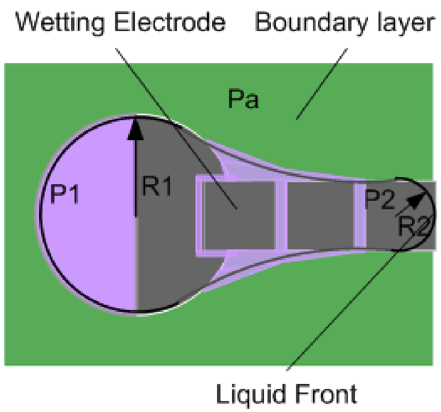
- Aspect ratio, d/L
- ζ_{lg}
- Electrode shape
- Time sequencing
- Initial droplet position
- Contact angle saturation
- Electrode voltages

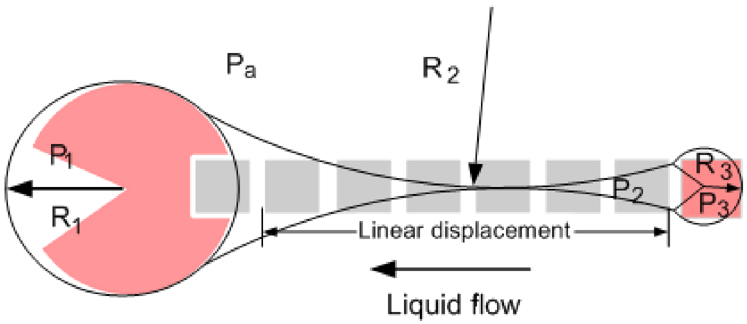
Best Splitting Conditions

$d/L=0.2$, $V_T=16V$
Insulator: Teflon/0.5µm parylene C
V_{sat} >50V



Dispensing





$$\frac{\varepsilon_0\varepsilon}{2\gamma_{LM}td}(V-V_T)^2 > \frac{1}{R_2}-\frac{1}{R_1}$$

$$P_2 > P_1 \Rightarrow \frac{1}{r_2}-\frac{1}{r_1} = \frac{\varepsilon_0\varepsilon}{2\gamma_{LM}td}V^2 > \frac{1}{R_1}-\frac{1}{R_2}$$

$$\Rightarrow \frac{\varepsilon_0\varepsilon}{2\gamma_{LM}t}V^2 > \frac{d}{R_1}+\frac{2d}{(N^2+1)R_3}$$

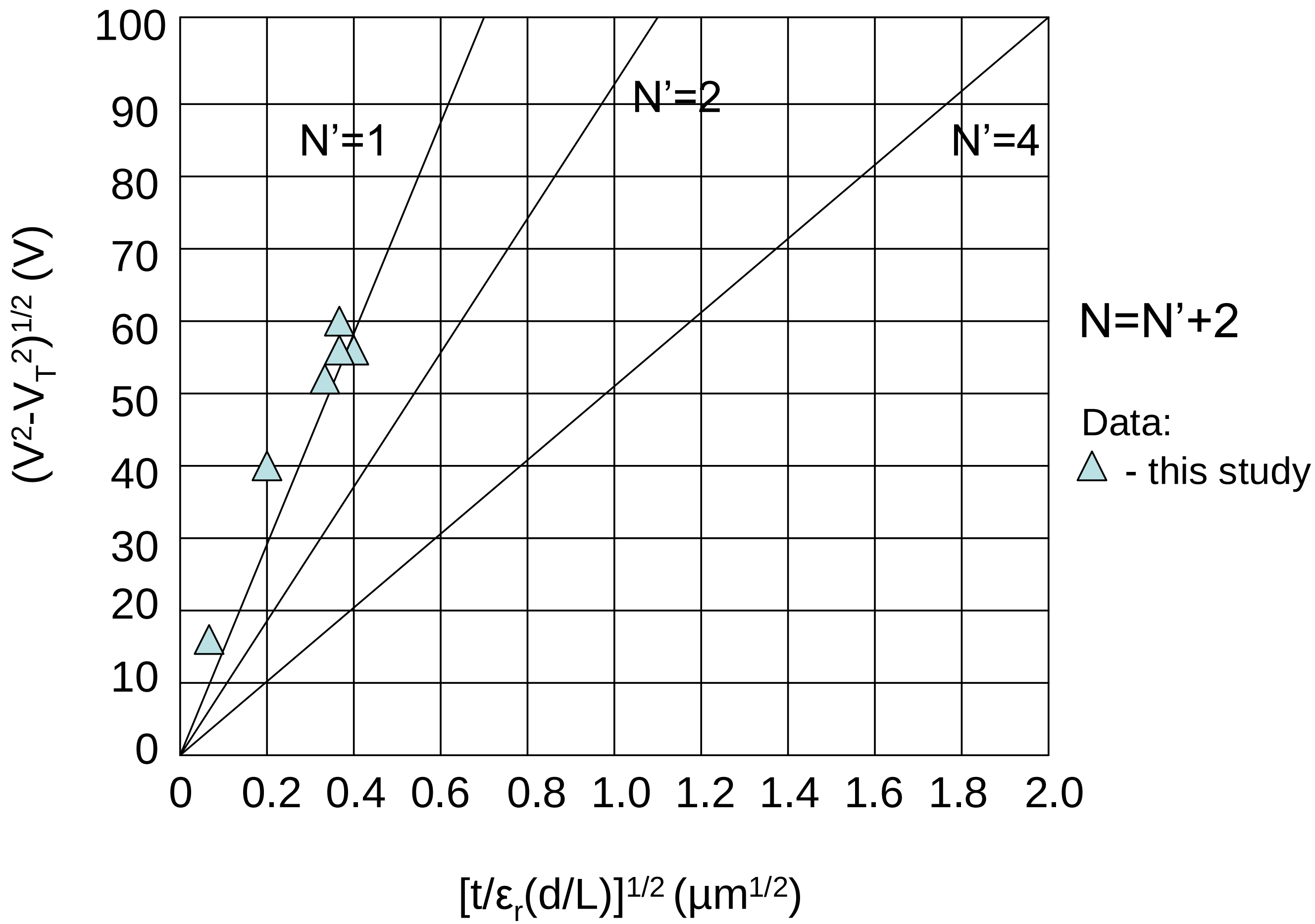
(Ren, 2003)

- If R1=2mm, R2=250μm, d=200μ, then V_{min} =45V
- If R2=250μm, d=100μm V_{max}=50V, then $R1_{max}$=2.3mm

- 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

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



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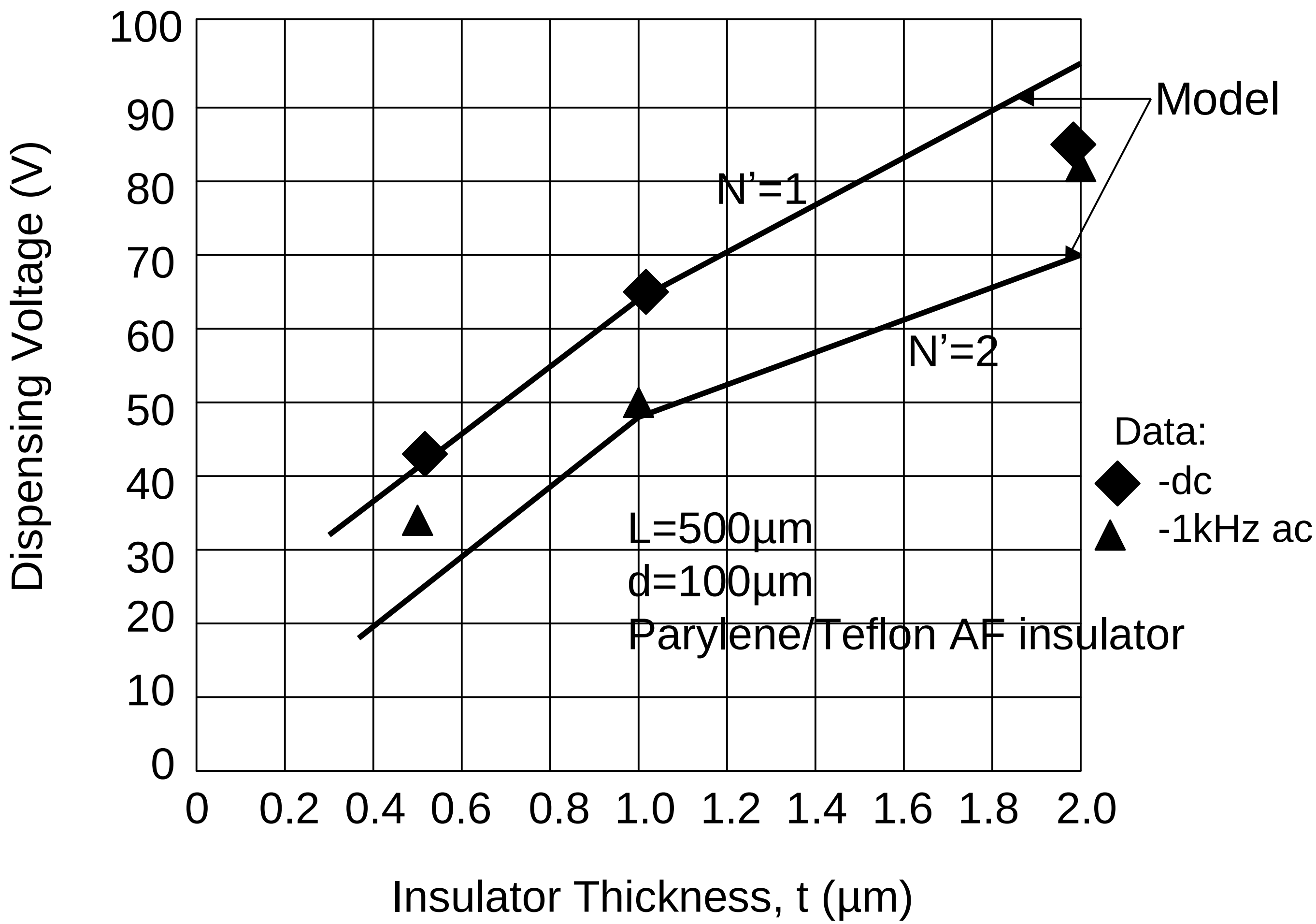
Dispensing in Oil



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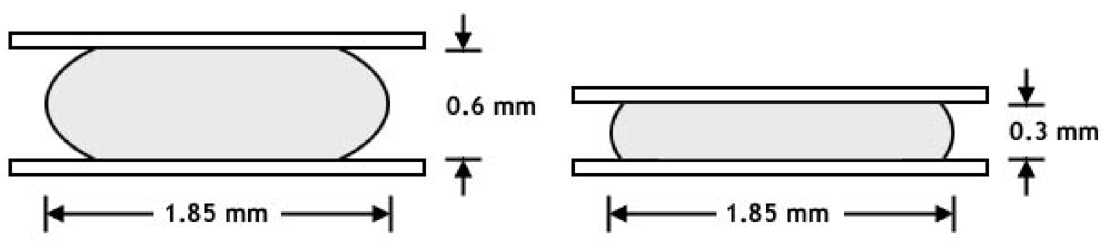
Mixing

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

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

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

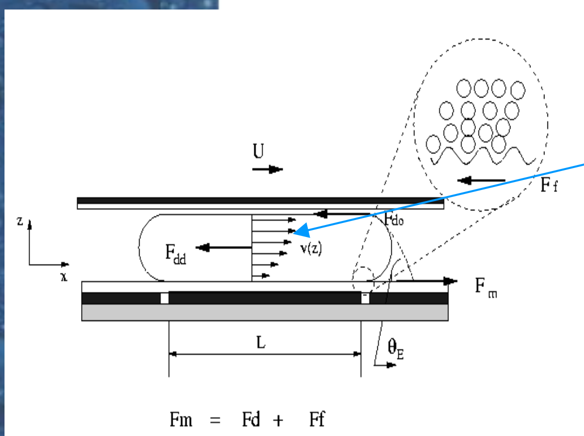


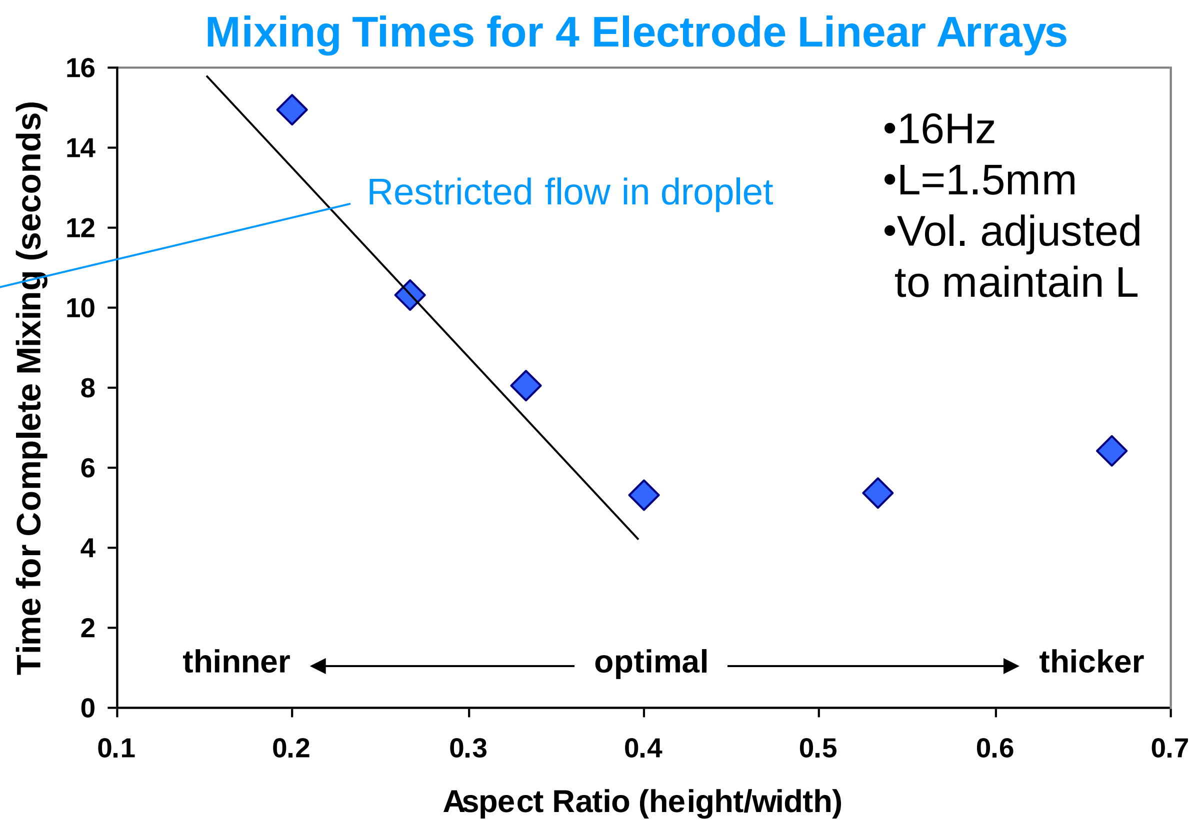
- Song et al.: mixing by chaotic advection:

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

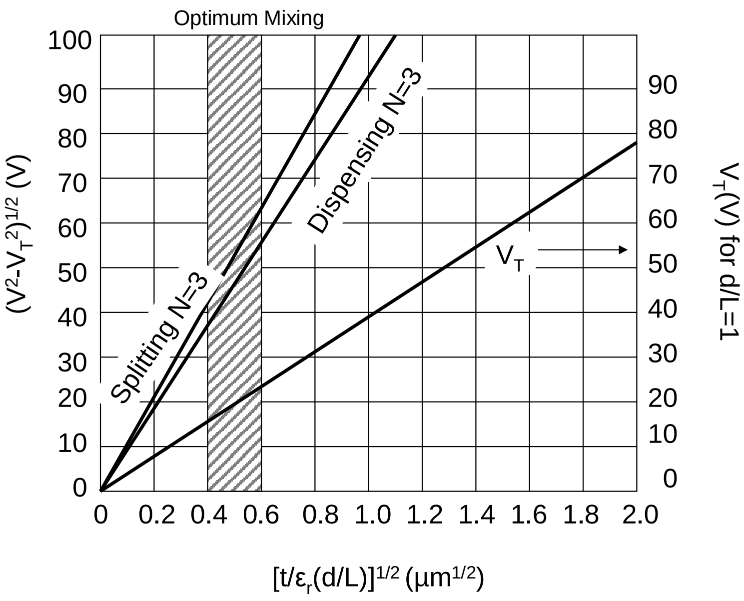
Mixing

(Paik-2003)

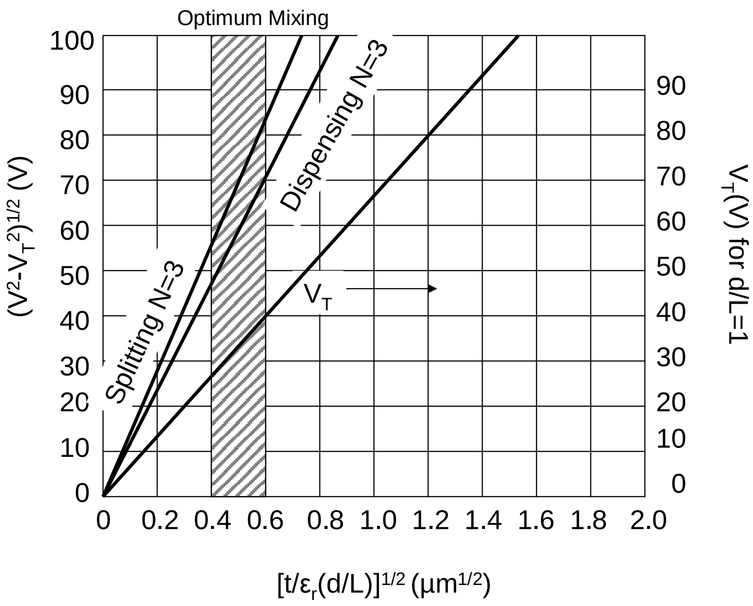




Combined Scaling



Silicone Oil



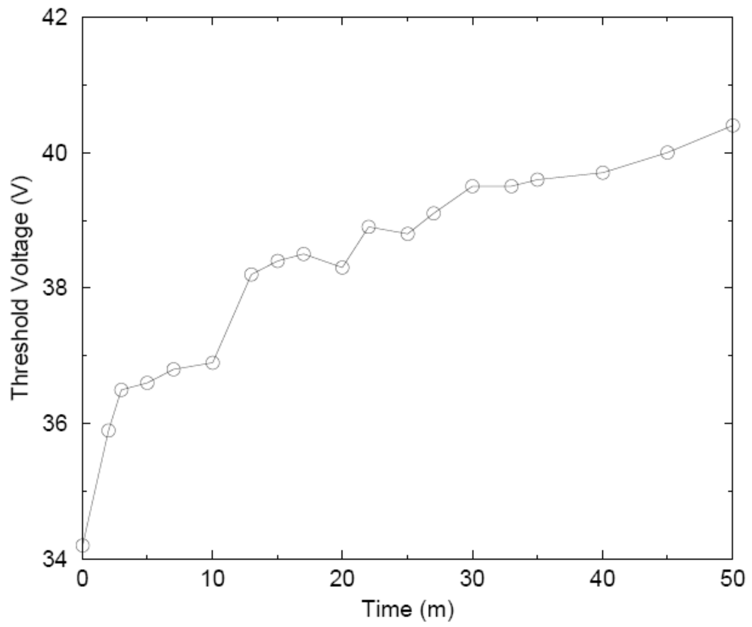
Air

Scaling EWD Actuators

- Scaling variables: electrode size (L); aspect ratio (d/L), insulator thickness (t/ε_r), electrode gap (d)
  - Maximum droplet velocity ➔ d/L~1
  - Low dispensing voltage ➔ $t/\varepsilon_r(d/L)$ small
  - Optimum mixing rate ➔ d/L ~0.4
  - Low threshold voltage ➔ d/L>0.2, t/ε_r small
  - Low splitting voltage ➔ $t/\varepsilon_r(d/L)$ 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 ≥60V
Pollack

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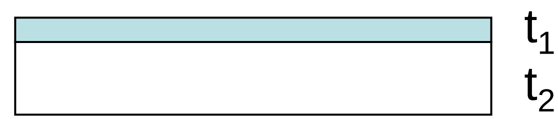
Contact Angle Saturation

Lippmann-Young Eq.:

$$V_{sat} = \{2\gamma_{lg}/\varepsilon_o\varepsilon_1[t_1 + t_2\ (\varepsilon_1/\varepsilon_2)][\cos\theta(V_{sat}) - \cos\theta(0)]\}^{1/2}$$

where

$$t/\varepsilon_r = t_1/\varepsilon_1 + t_2/\varepsilon_2$$



Pollack’s actuator:

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

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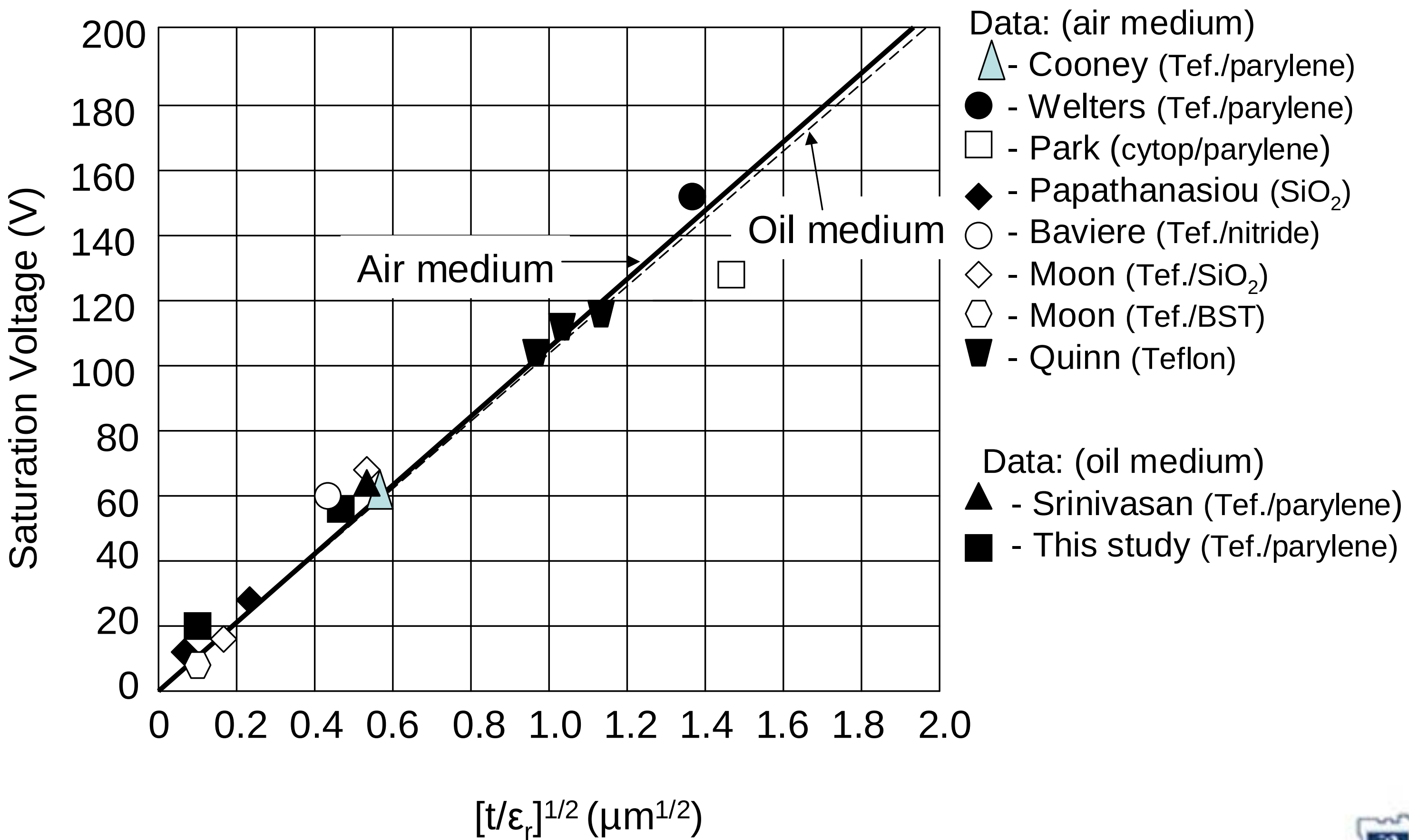
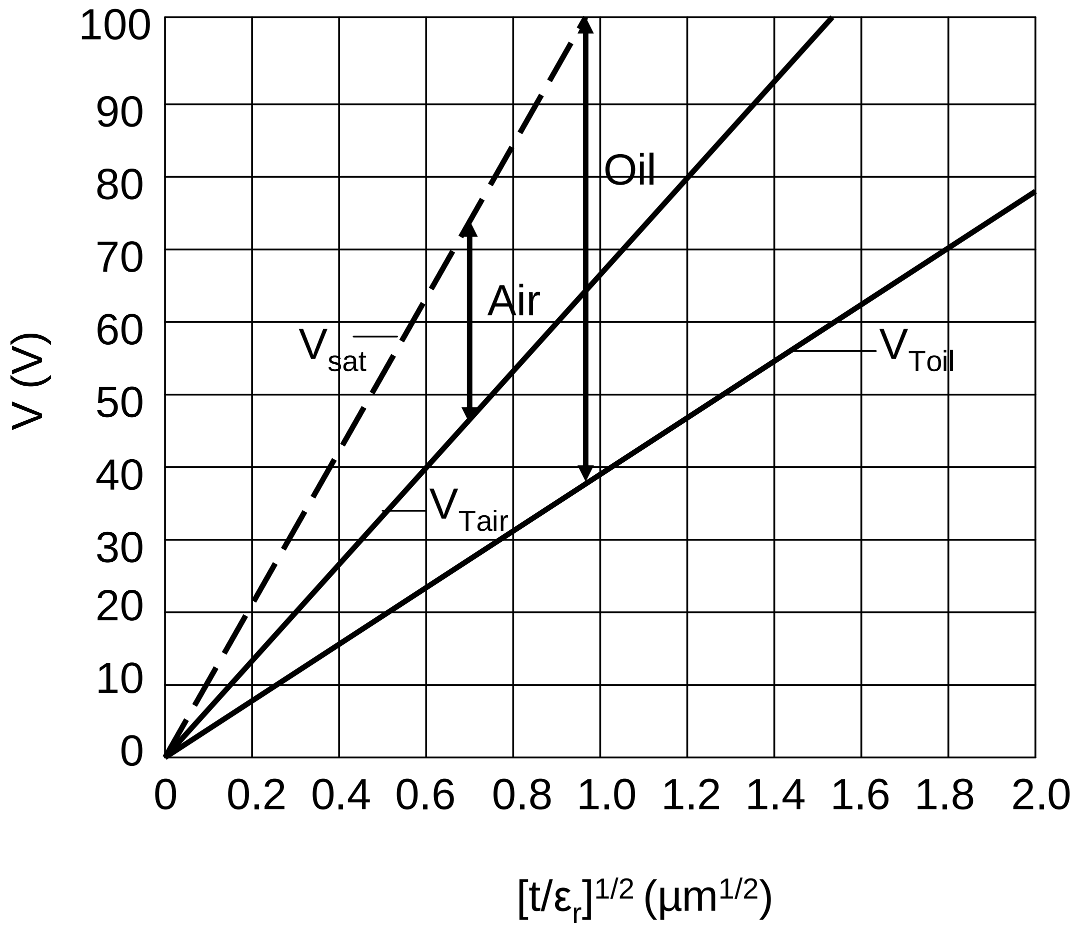
Contact Angle Saturation

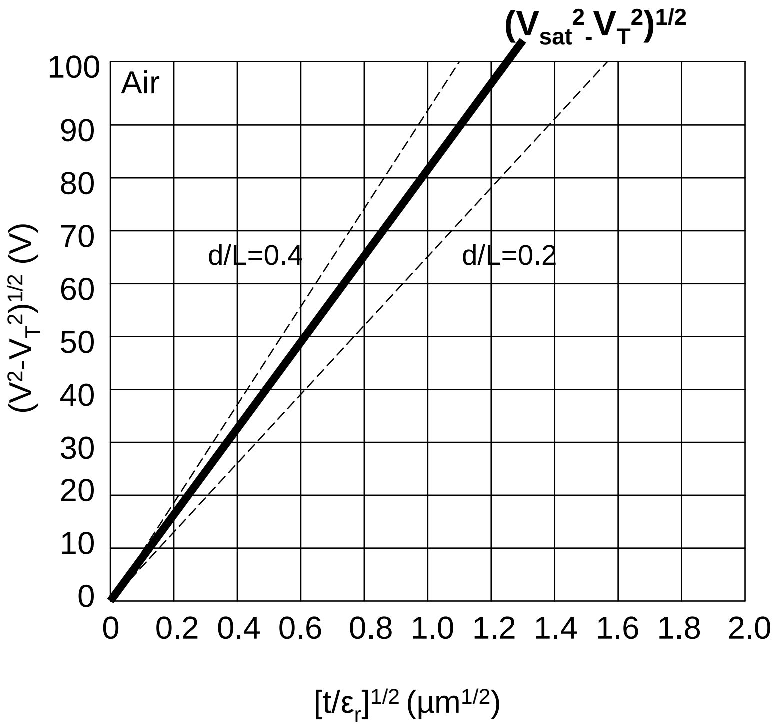
$$V_{sat} = \{2\gamma_{lg}/\varepsilon_o\varepsilon_1[t_1 + t_2(\varepsilon_1/\varepsilon_2)][\cos\theta(V_{sat}) - \cos\theta(0)]\}^{1/2}$$



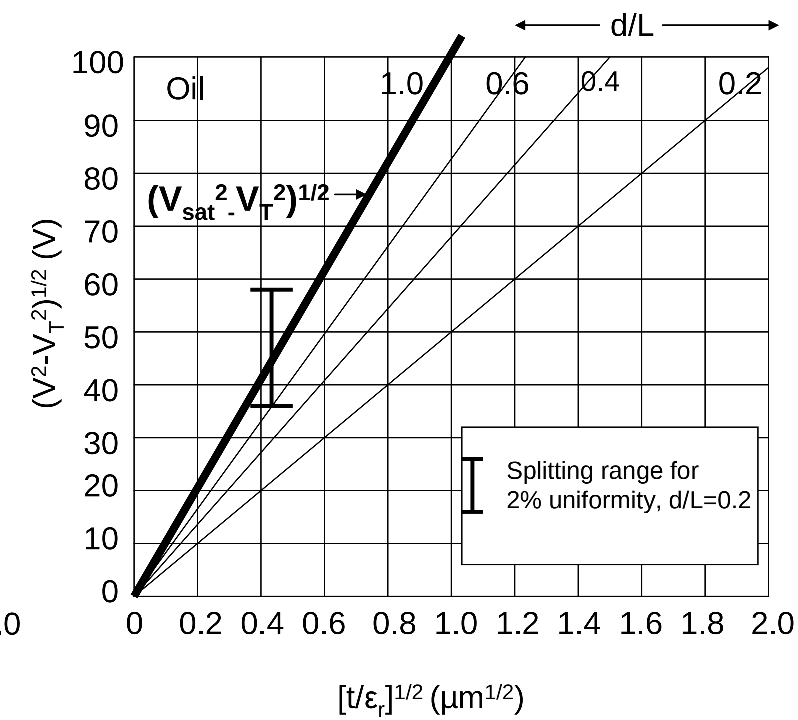
Safe Operating Ranges



Reliable 3-Electrode Splitting in Silicone Oil and Air



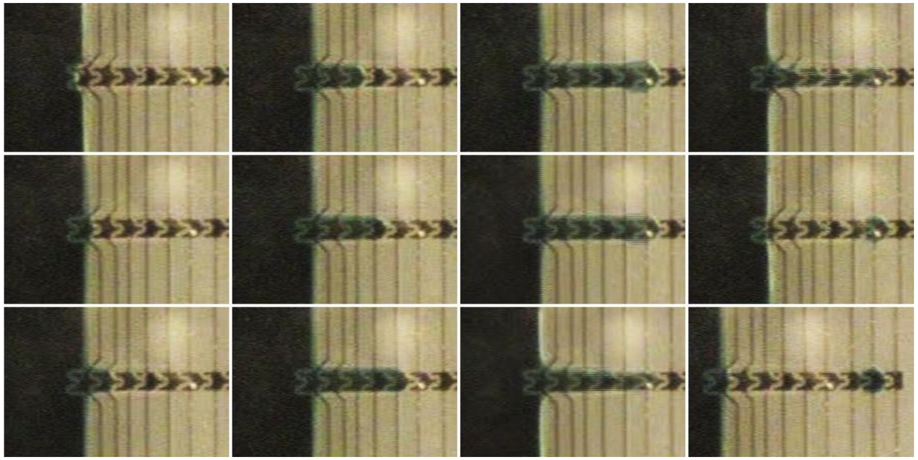
Air



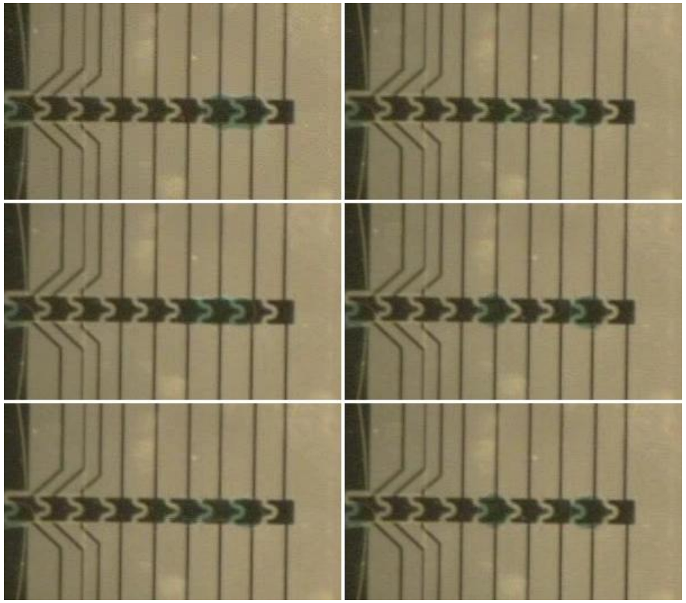
Oil

Picoliter Droplet Scaling

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

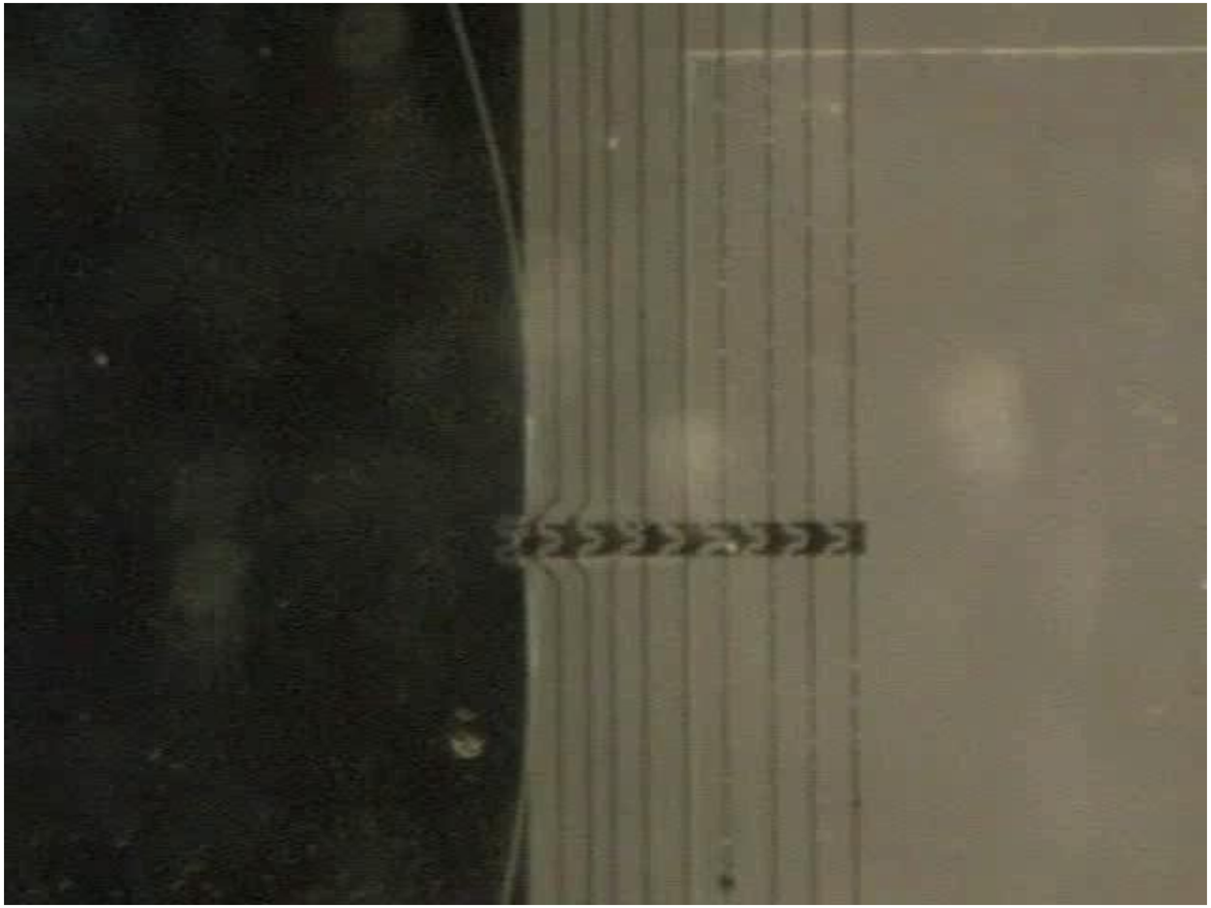


Dispensing and actuating 35pL droplet (40µm electrodes, 9.4um gasket height, 70V, 2µm parylene



Splitting ~100pL droplets (60µm electrode, 7.5µm gasket, 2um 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 $[t/\varepsilon_r(d/L)]^{1/2}$
  - With $t/\varepsilon_r(d/L)$ 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

Acknowledgements

- NSF
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