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Numerical Modeling of 3D Electrowetting Droplet Actuation and Cooling of a Hotspot

Mun Mun Nahar, Govindraj Shreyas Bindiganavale, Jagath Nikapitiya and Hyejin Moon

University of Texas at Arlington

UNIVERSITY OF TEXAS ARLINGTON

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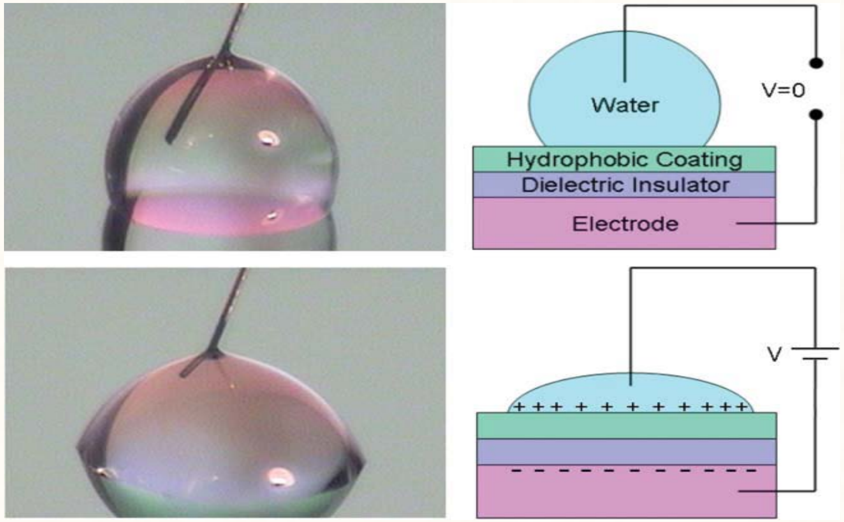
What is EWOD?

- A micro-scale fluidic phenomena that can be used to manipulate liquid droplets

- Manipulation of liquid by modifying the surface properties by applying voltage

Charge Accumulation → Solid-Liquid Interfacial Tension Decrease → Contact Angle Change



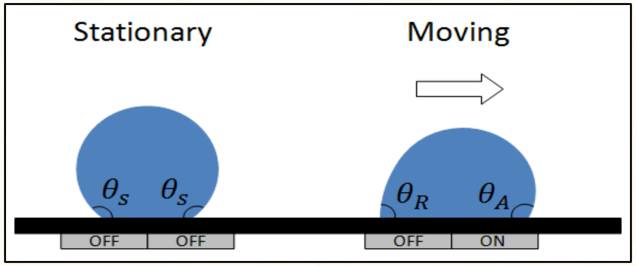
Top: A water drop placed on a hydrophobic surface with a high contact angle. **Bottom:** Electrowetting of the surface. [Ref. Shamai et al.]

Lippman-young equation:

$$\cos\theta(V) = \cos\theta(0) + \frac{C_d}{2\gamma}V^2$$

What is EWOD actuation?

Open configuration

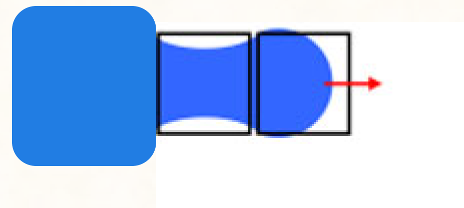


- By Creating asymmetric contact angle around meniscus, net pressure difference can be created and droplet can move [2]

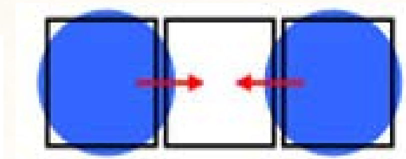
Basic operations

Top view

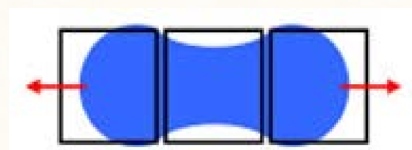
Droplet generation



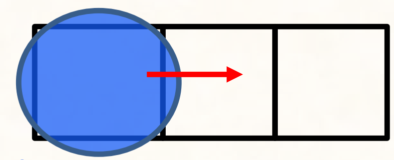
Droplet Merging



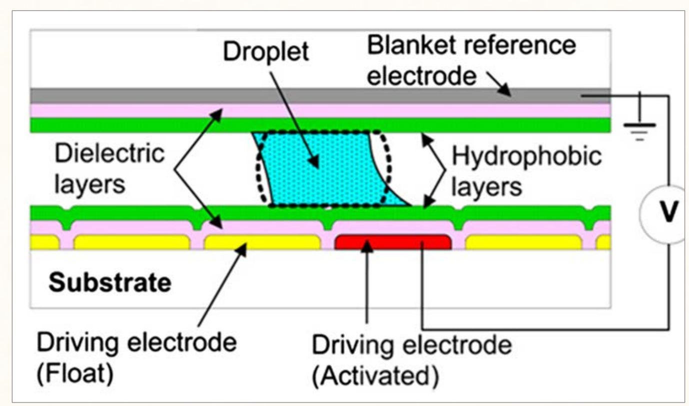
Droplet Splitting



Droplet Transport



Cross-sectional view



Ref. Hsien-Hua et al.

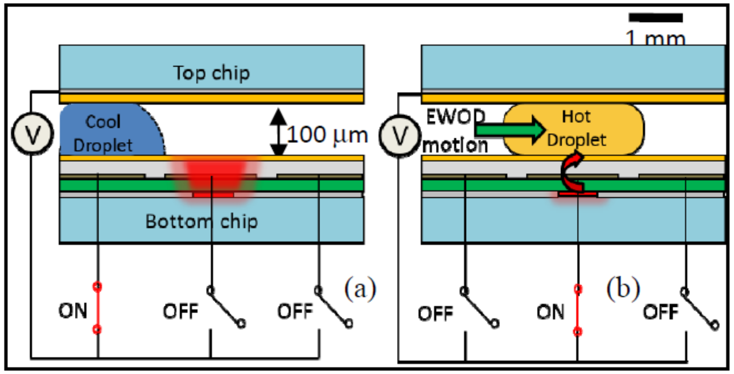
- **Parallel plate EWOD device**
  - Less sample volume
  - Less contamination
  - Faster reaction
  - Flexible
  - Portable

Objectives & Motivation

- **Objectives**
  - Modeling coupled physics:

  Droplet motion + Cooling of a hotspot
  (Fluid flow) (Heat transfer)

  - Comparing results from numerical modeling with experiments



Cross-section of DMF Cooling Chip

- **Motivation**
- Understanding the physics
  - Overcome challenges in experiments
    - Parametric study of geometric dimensions
      - Complicated EWOD fabrication
- Easy approximate temperature measurement
- Parametric study for optimum heat transfer performance

Model Description

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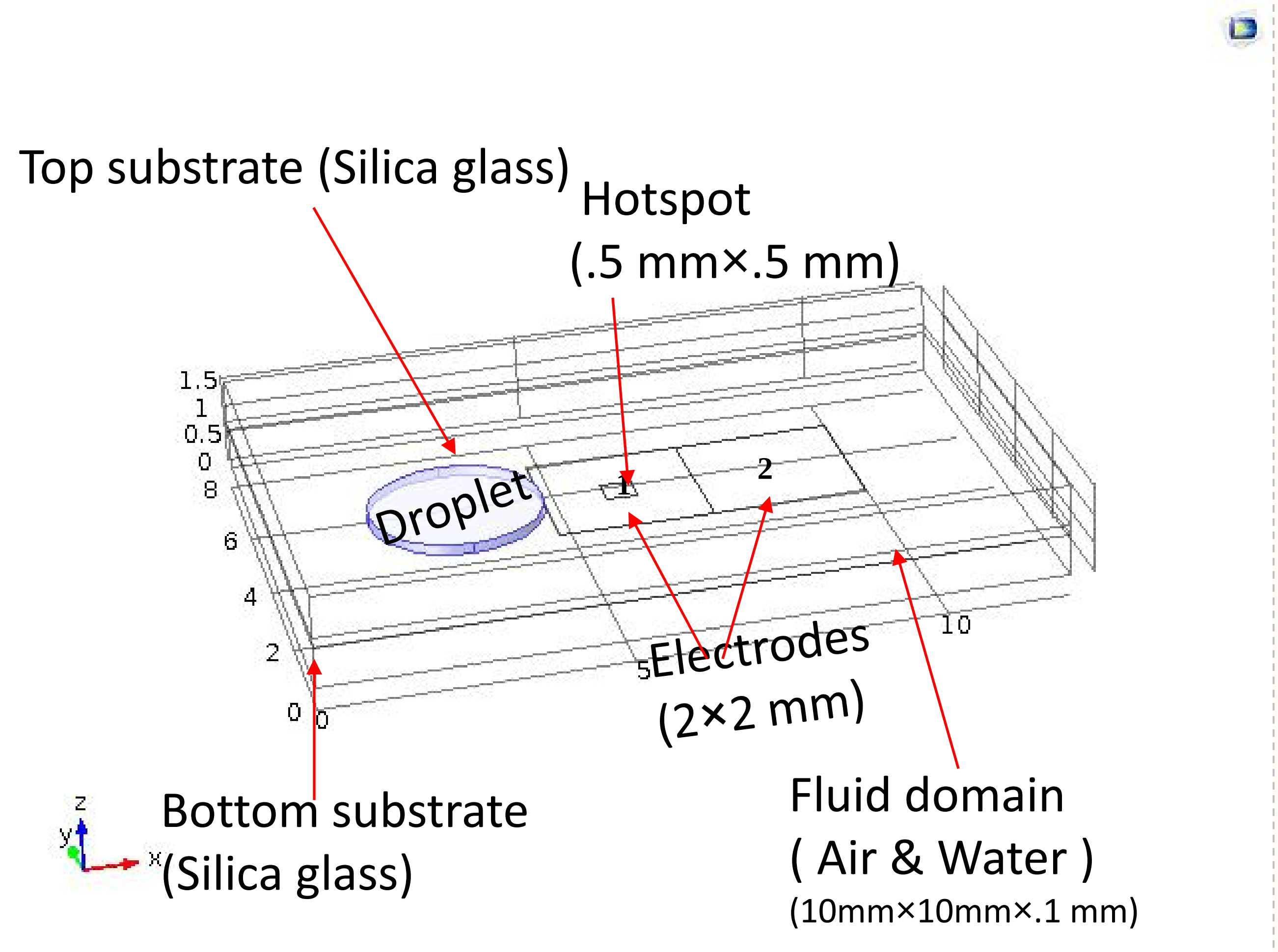


Geometry for numerical modeling

Numerical Formulations

- **Governing equations:**
  - Incompressible, constant properties flow
- **Navier-stokes equations:**

$$\nabla.\boldsymbol{u} = 0$$

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}.\nabla\boldsymbol{u}\right) + \nabla p - \underbrace{\mu\nabla^2\boldsymbol{u}}_{\text{shear and air drag}} = \underbrace{F_{st}}_{\text{actuating force}}$$

$$\mathbf{F_{st}} = \sigma k \delta(\phi)\nabla\phi$$

k=curvature of the interface
σ=surface tension.
δ=Dirac delta function (only non-zero at the interface
Φ=Phase field variable

- **Energy equation:**

$$\rho Cp.\mathbf{u}.\nabla T + \rho Cp.\partial T/\partial t = \nabla.(K\boldsymbol{\nabla} T)$$

C_p=Specific heat capacity
ρ=Density
K=Thermal conductivity

Simulation Setup

- Use of Two-phase flow, Level Set and Two-phase flow, Phase field interface for interface tracking
- **Advection equation for interface tracking:**

$$\frac{\partial \phi}{\partial t} + \boldsymbol{u}.\nabla\phi = \nabla.\frac{\Upsilon\lambda}{\epsilon^2}\nabla\psi$$

(For phase-field method)

γ is the mobility (m3·s/kg), λ is the mixing energy density (N) and ε (m) is the interface thickness parameter and ψ is referred to as the phase field help variable

- Use of Heat Transfer in Fluids interface and coupled to two-phase flow interface

- **Material Properties:**

$K=(K_{water}-K_{air})\times\phi_{water}+K_{air}$

$C_p=(C_{water}-C_{air})\times\phi_{water}+C_{air}$

$\rho=(\rho_{water}-\rho_{air})\times\phi_{water}+\rho_{air}$

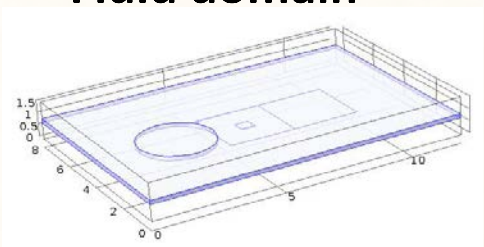
K=Thermal conductivity
C_p = Specific heat capacity
ρ = Density

Simulation Setup

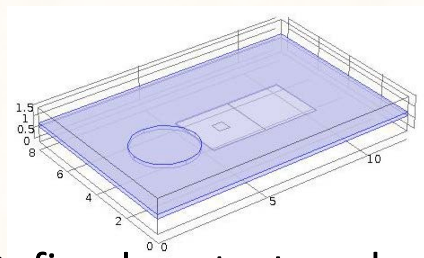
▪Boundary Conditions

Fluid flow

Fluid domain

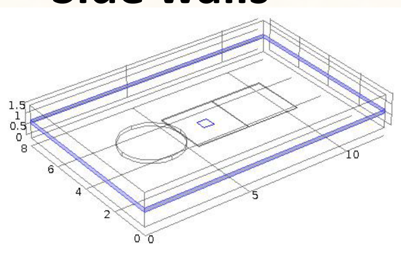


Top and bottom surface



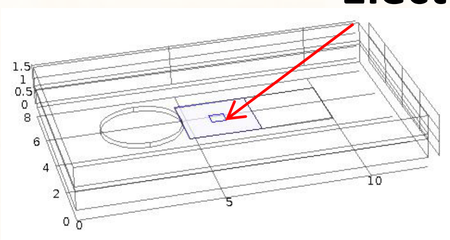
Defined contact angle corresponding to zero voltage (Wetted wall or Navier slip condition

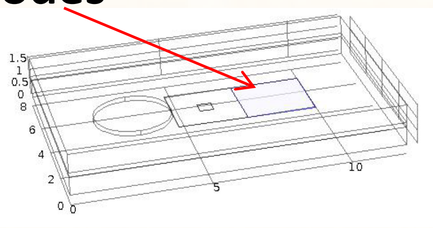
Side walls



No slip condition

Electrodes





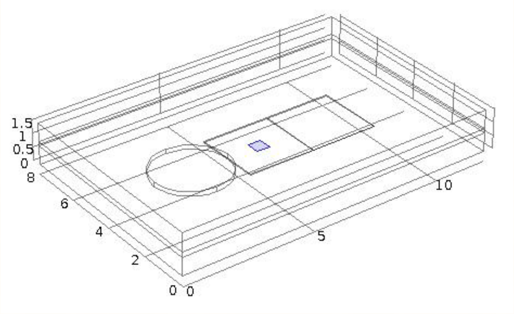
- Defined contact angle corresponding to voltage V(t) (From Young-Lippmann equation) (Wetted wall or Navier slip condition)

Simulation Setup

▪**Boundary Conditions**

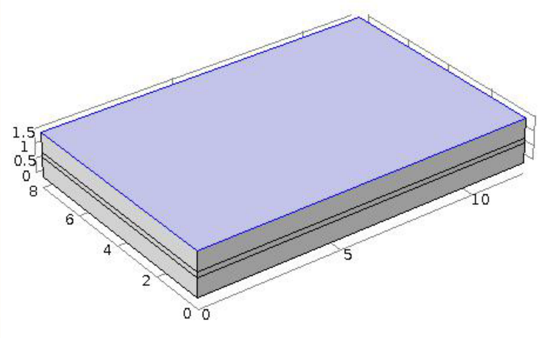
Heat Transfer

Hotspot



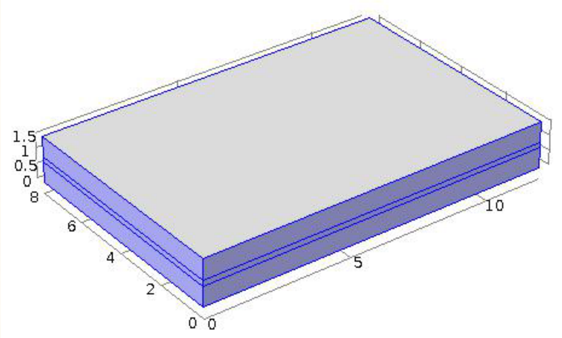
Constant heat flux (Boundary heat source)

Top surface



Convection to air

Other boundaries



Insulated

Simulation Setup

- **Geometrical dimensions**

Parameter name	**Dimension (mm)**
Electrode dimension	2×2
Channel height	0.1
Hotspot dimension	0.5×0.5
Top & bottom plate thickness	0.7

- **Simulation Parameters**

Name	**Value**
Surface tension, σ	.072 [N/m]
Applied voltage, V_{ac}	150[V]
Initial contact angle,θ_o	118[degree]
Dielectric thickness, d	5[µm]
Heat Flux, q"	36.6[W/cm^2]
Dielectric constant, ε_r	2.5
Convection co-efficient, h_{air}	5[W/(m.K)]
Initial temperature, T	298.15 [K]

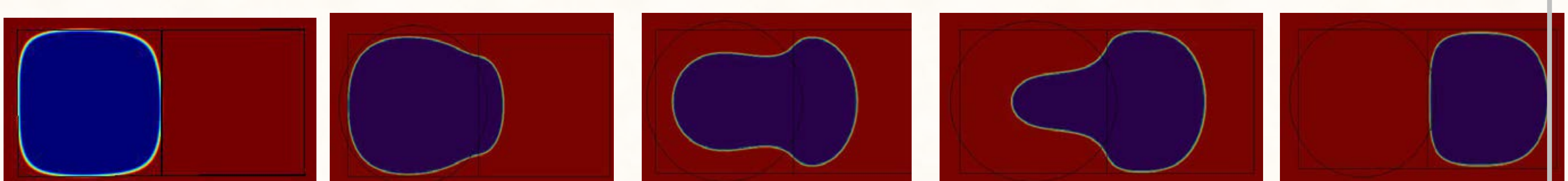
Results

Droplet profiles

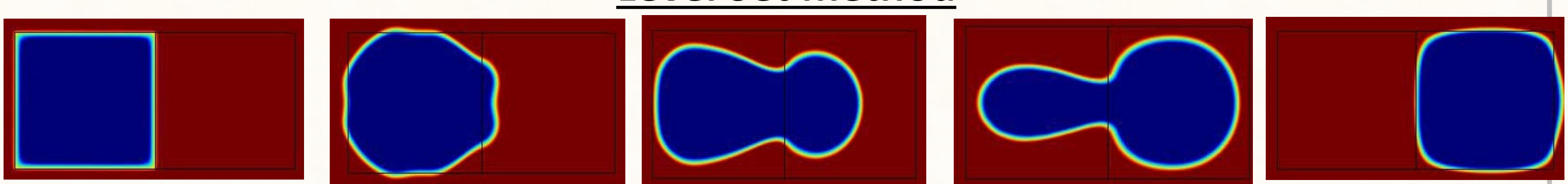
At t=0 ms | At t=20 ms | At t=40 ms | At t=60 ms | At t=100 ms

Experiment

Phase Field method



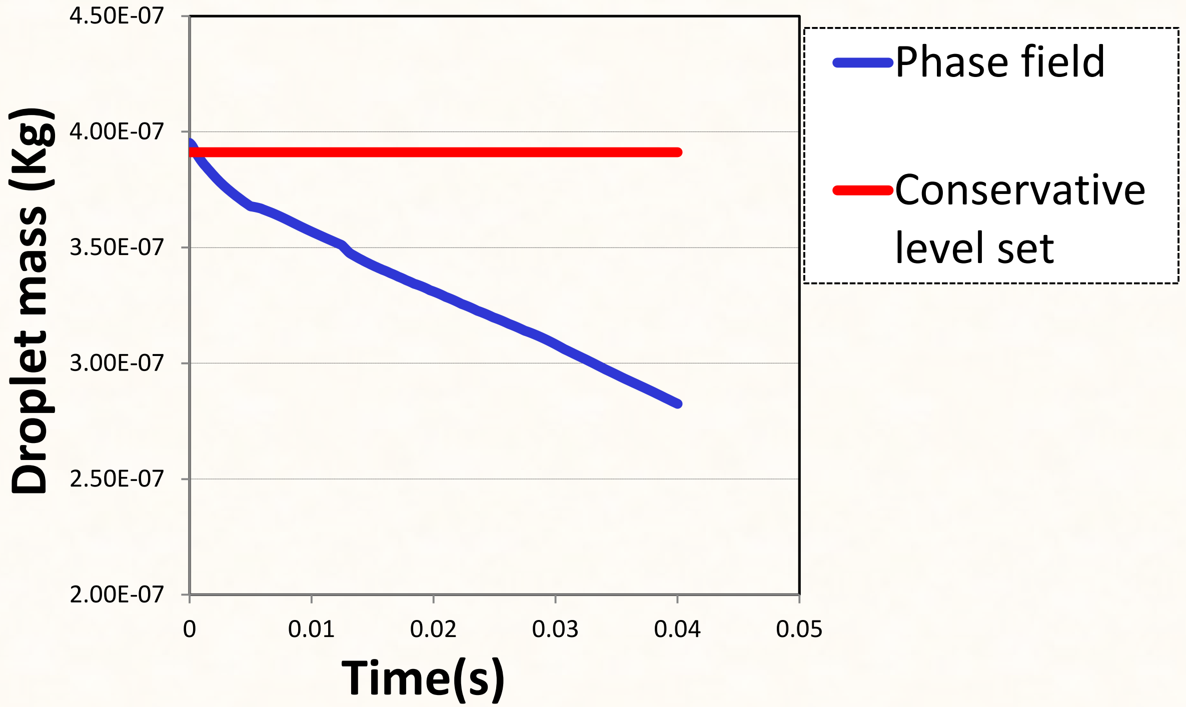
Level Set method



- Phase field method gives more accurate and smooth profile

Results

Mass conservation issues



- **Phase field:** 30% mass loss after 40 ms

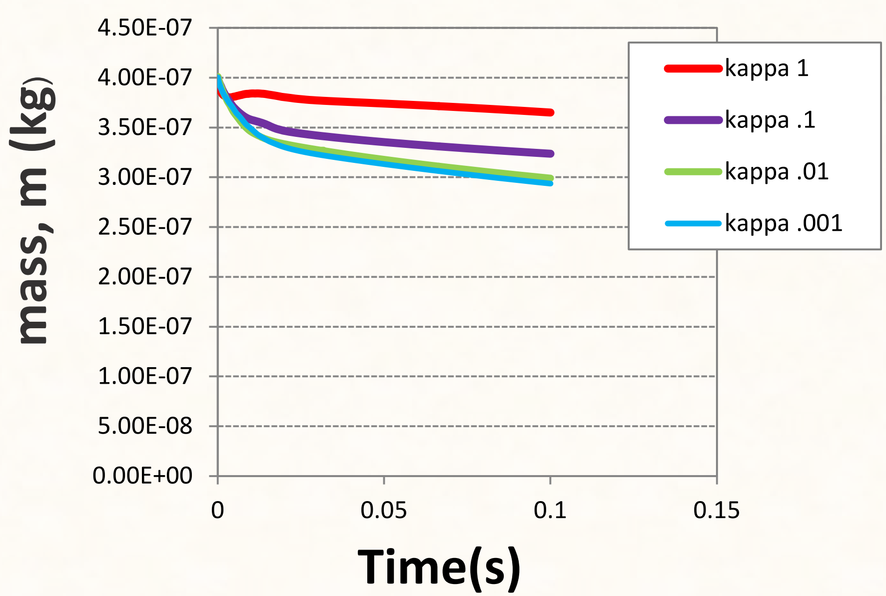
- **Conservative level set:** Guarantees mass conservation

- Mass conservation is affected by numerical tuning parameters such as:
  - Mobility tuning parameter
  - Interface thickness
  - Tuning parameter

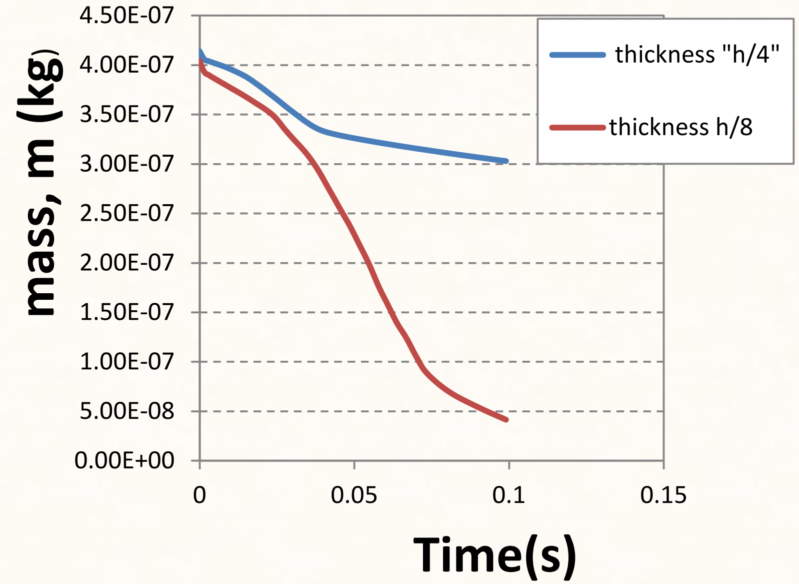
Results

Parametric study for phase field method

Mobility tuning parameter, χ



Interface thickness, ε



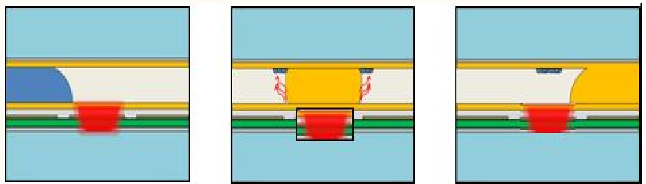
- Mass loss increases with decrease in value of mobility tuning parameter
- Mass loss increases with decrease in interface thickness

Results

Cooling curve of the hotspot

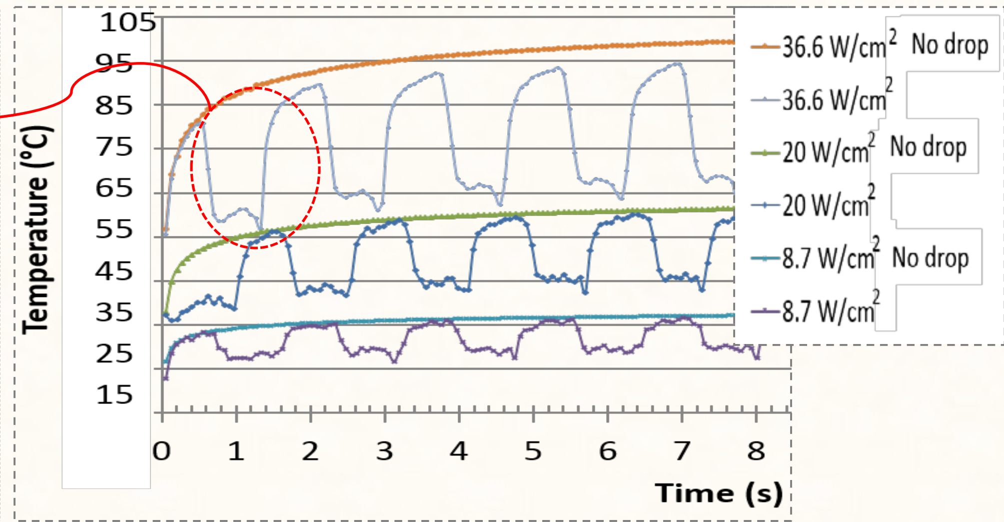
Convection | Conduction & evaporation | Convection

Simulation



Experiment

Entry | Dwell | Exit



Average surface temperature of hotspot

- Temperature drop from simulation: 18 °C
- Temperature drop in experiment: 20 °C

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Conclusions

- 3-Dimensional EWOD droplet motion has been successfully modelled using two methods of interface tracking of two-phase.
    - Two Issues:
        - Mass loss
        - Slight inaccuracy in results due to negligence of hysteresis angle, contact line friction and evaporation heat transfer
- Droplet motion results have been validated with the experiment
- Numerical modeling of cooling of a hotspot has been demonstrated by solving multiphysics problem
- Future study includes modeling heat transfer enhancement due to evaporation by an EWOD actuated droplet

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