Electric Field Assisted Formation of Polymeric Hollow Microstructures

Vivek

Under the guidance of

Prof. Prof. Arnab Atta

And

Prof. Rabibrata Mukherjee

Department of Chemical Engineering

IIT Kharagpur

COMSOL CONFERENCE
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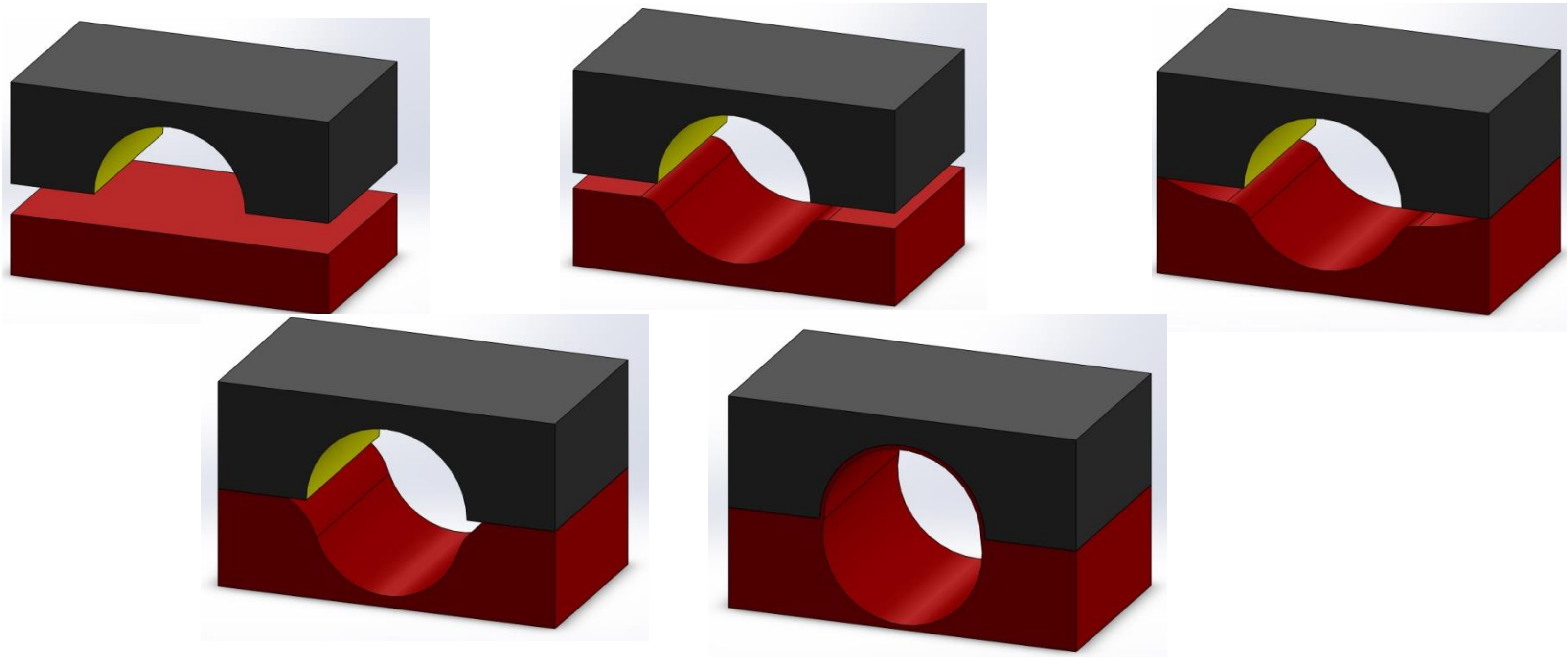
Electrohydrodynamic Instability Patterning

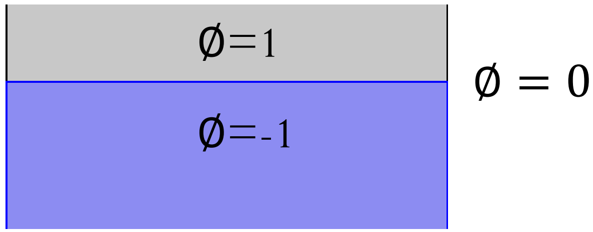


- This process patterns polymers by Non-uniform electric fields and patterned electrode
- The sequence is shown above with a **black** coloured **electrode** and **red polymer** film
- The spatial heterogeneity of electrostatic field is induced by the **patterned top electrode**
- The polymer liquid grows upwards under the protrusion of the top electrode due to the higher voltage causing a greater force, depleting the liquid under the cavity
- When the polymer reaches the top mask Capillary force becomes dominant causing the polymer to coat the top mask forming a hollow microstructure

Simulation Methodology By Using Comsol Multyphysics 4.4

- Process is modelled using the Laminar Phase Field and Electrostatics modules in COMSOL Multiphysics 4.4
- Laminar Phase field module describes the motion of the fluid using Incompressible Navier-Stokes and tracks the interface using Phase Field parameter

$$\emptyset = \left\{ \begin{array}{cr} 1 & \text{at fluid 1} \\ 0 & \text{at interphase} \\ -1 & \text{at fluid 2} \end{array} \right\}$$



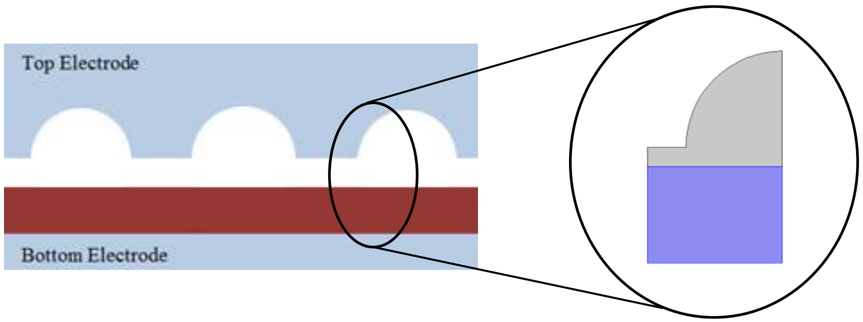
- $\rho = \rho_1 + (\rho_2 - \rho_1)V_f$
- $\epsilon = \epsilon_1 + (\epsilon_2 - \epsilon_1)V_f$ where $V_f = \frac{(1+\emptyset)}{2}$
- Electrostatics module solves the Laplace equation

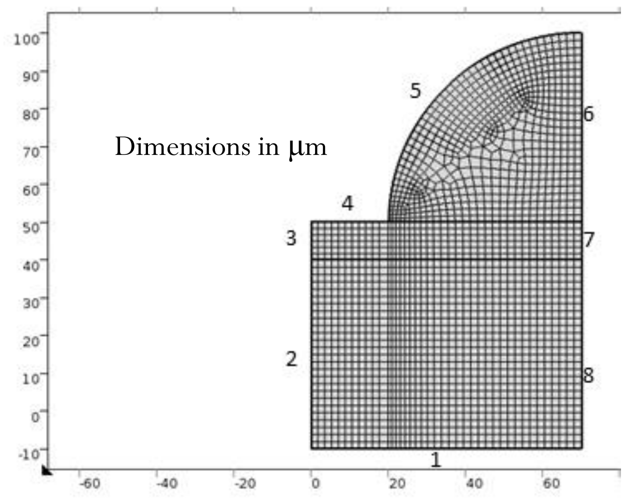
$$\nabla\epsilon\nabla\mathbf{V} = 0$$

- Calculated electric field is used to find interfacial electrostatic force

$$\mathbf{F} = \rho_f\mathbf{E} - \frac{1}{2}\mathbf{E}.\mathbf{E}\nabla\epsilon + \nabla\left(\frac{1}{2}\mathbf{E}.\mathbf{E}\frac{\partial\epsilon}{\partial\rho}\rho\right)$$

Geometry and Boundary Conditions



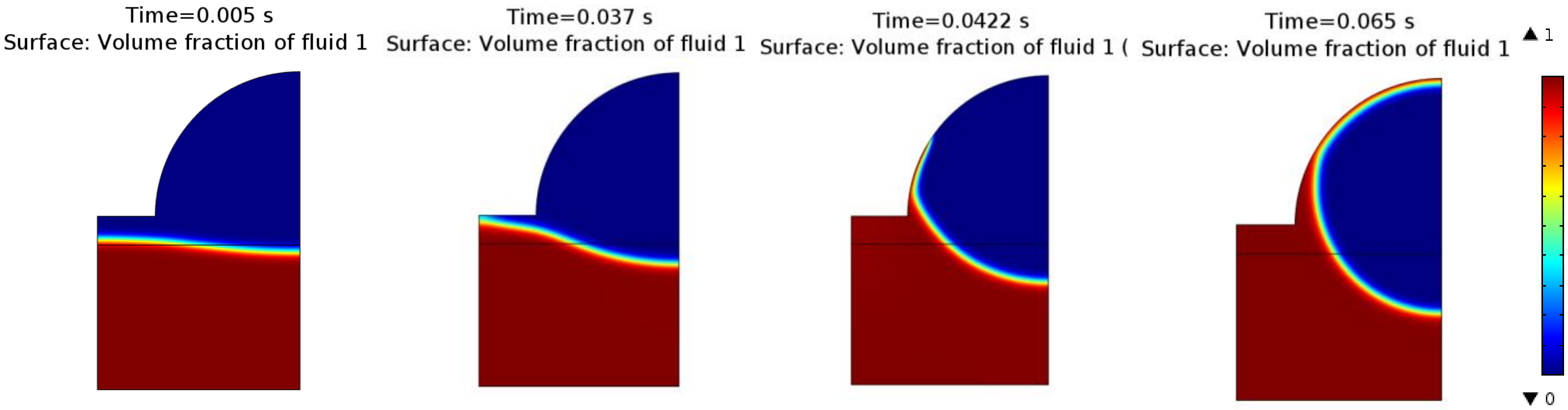


Assumptions:

- 2D **non-axisymmetric** model is developed representing an infinitely long microchannel in third dimension
- The polymer is considered to be Newtonian and the upper fluid is air
- The incompressible Navier–Stokes equations are introduced to describe the flow
- Both fluids are considered to have a uniform dielectric constant
- Polymer has zero free charge in the bulk
- At the interface due to the change in dielectric free charges are present

No	Boundary Conditions (Flow/E-field)
1	No Slip Wall/ 0V
2	Slip Wall/Symmetry for V
3	Slip Wall/Symmetry for V
4	Slip Wall/250V
5	Wetted Wall 20º/250V
6	Symmetry
7	Symmetry
8	Symmetry
9	Initial Interface

Simulation Results

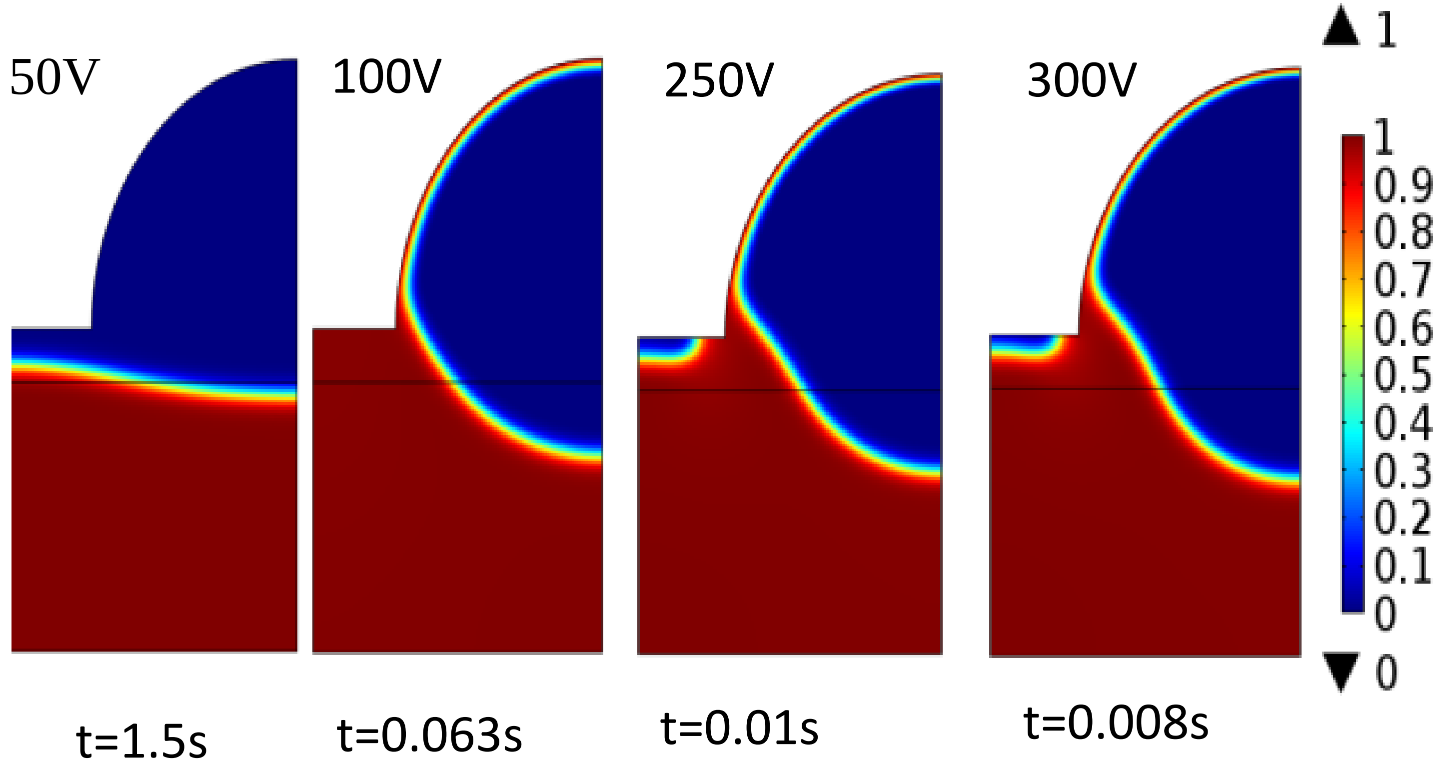


Voltage= 200V , Contact angle between top electrode and polymer = 20° (Red represents polymer and blue represents air)

- Polymer liquid grows upward under protrusion of top electrode due to localised higher voltage
- Growing polymer touches the protrusive surface of top electrode
- Then it flows along the inner surface into the cavity because of capillary action
- The liquid converges at the top, achieving self-encapsulation of the hollow microstructure

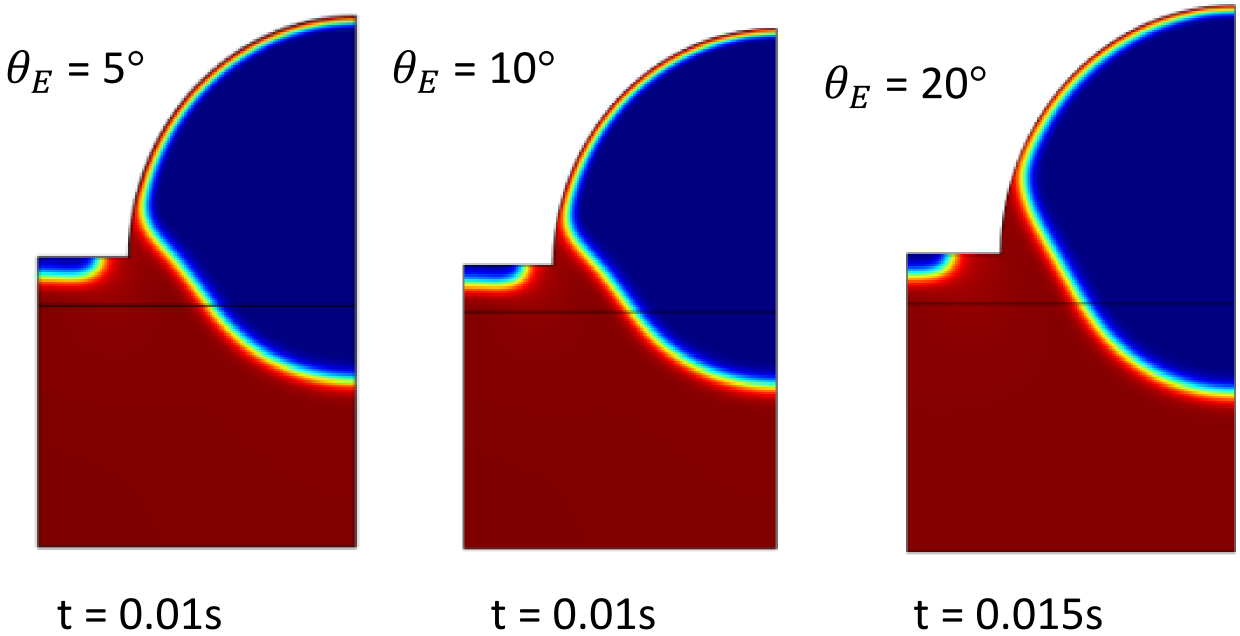
Wettable upper electrode surface

- **Variation in Voltage:**



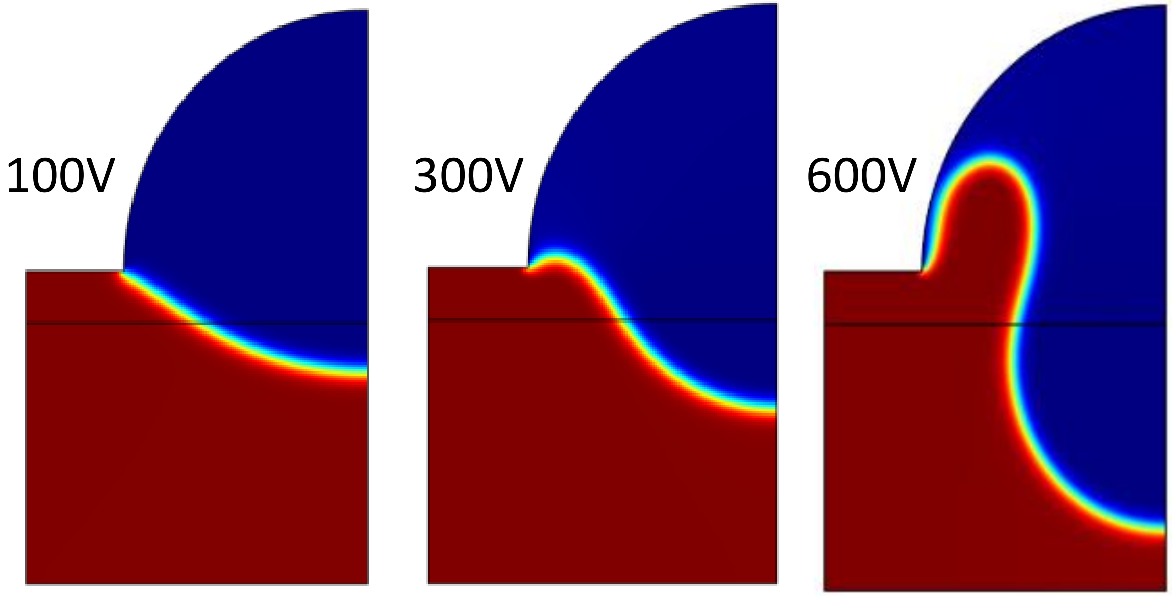
Simulations were done till 1.5s for a range of voltages while keeping the contact angle between the polymer and the upper electrode material at $\boldsymbol{\theta_E} = \mathbf{10°}$ to study the minimum time required for pattern transfer.

Variation in Contact angle with DC Voltage



- Keeping voltage constant at **250V** and varying the contact angle we get that the changing the contact angle doesn't have a significant impact as the difference in the times is in milliseconds.
- So, its alleged that varying the contact angle will not have much effect on fabrication process, while changing the voltage will have a greater impact.

Variation in Voltage for Nonwettable upper electrode surface



Nonwettable upper electrode surface was taken and simulations were done till 1.5s for a range of voltages while keeping the contact angle between the polymer and the upper electrode material at $\boldsymbol{\theta_E = 170°}$.

The hydrophobic electrode surface stops the capillary flow which can be used to get patterned depressions having various microfluidic applications.

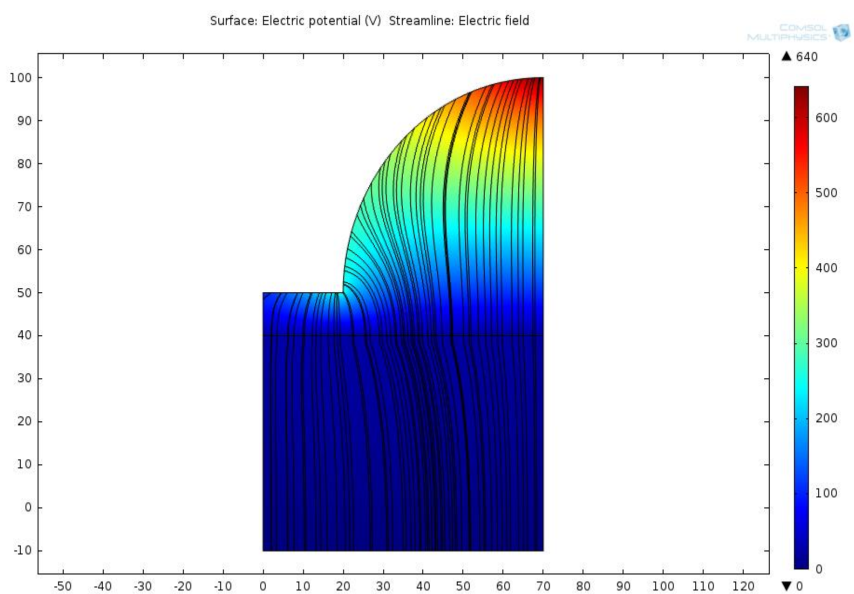
Spatial gradient in applied DC Voltage

The need of giving strength at specific points gives the idea of Voltage gradient.

$V = V_0 + m * x$ $\quad$ V_0 is 50V and 100V $\theta_E = 20°$

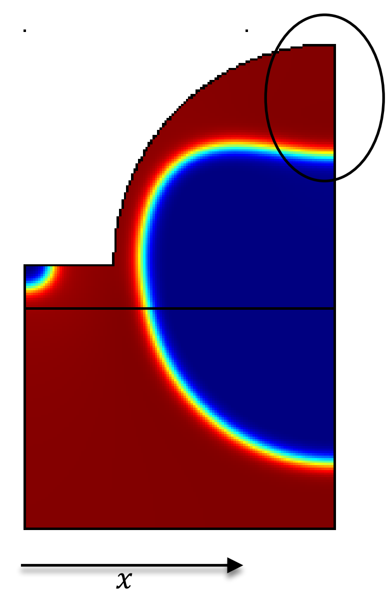
M= $5.71 * 10^6 \; ^V/_m$, $6.71 * 10^6 \; ^V/_m$ and $7.71 * 10^6 \; ^V/_m$

- The thickness of the polymer increases spatially with x replicating the spatial gradient of the applied voltage
- A hollow structure can be made having desired thicknesses at desired locations giving this technique superior than the conventional one

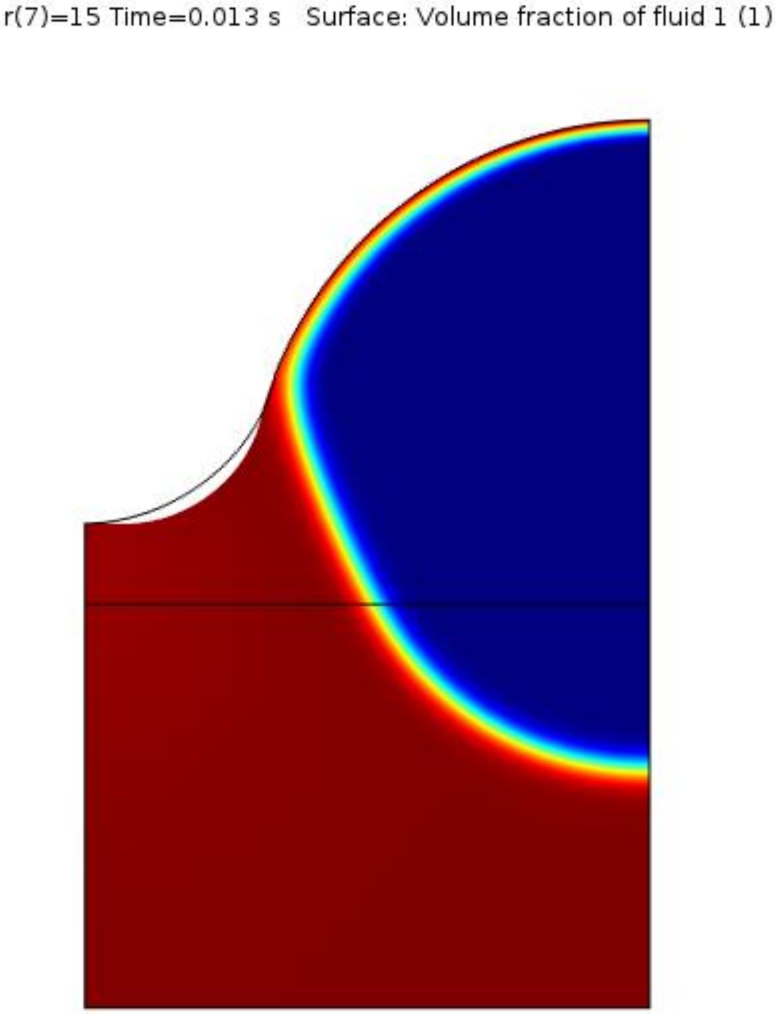


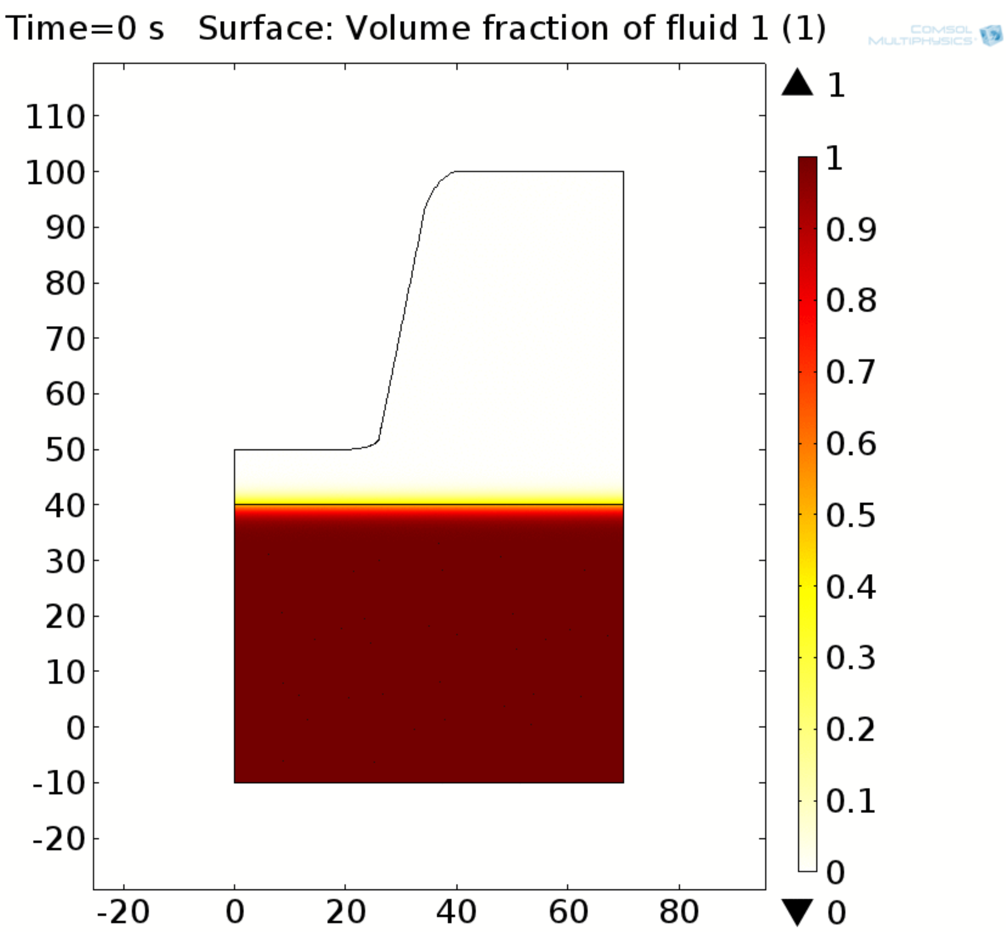
$V_0 = 100V$

$m = 7.71 * 10^6 \; ^V/_m$

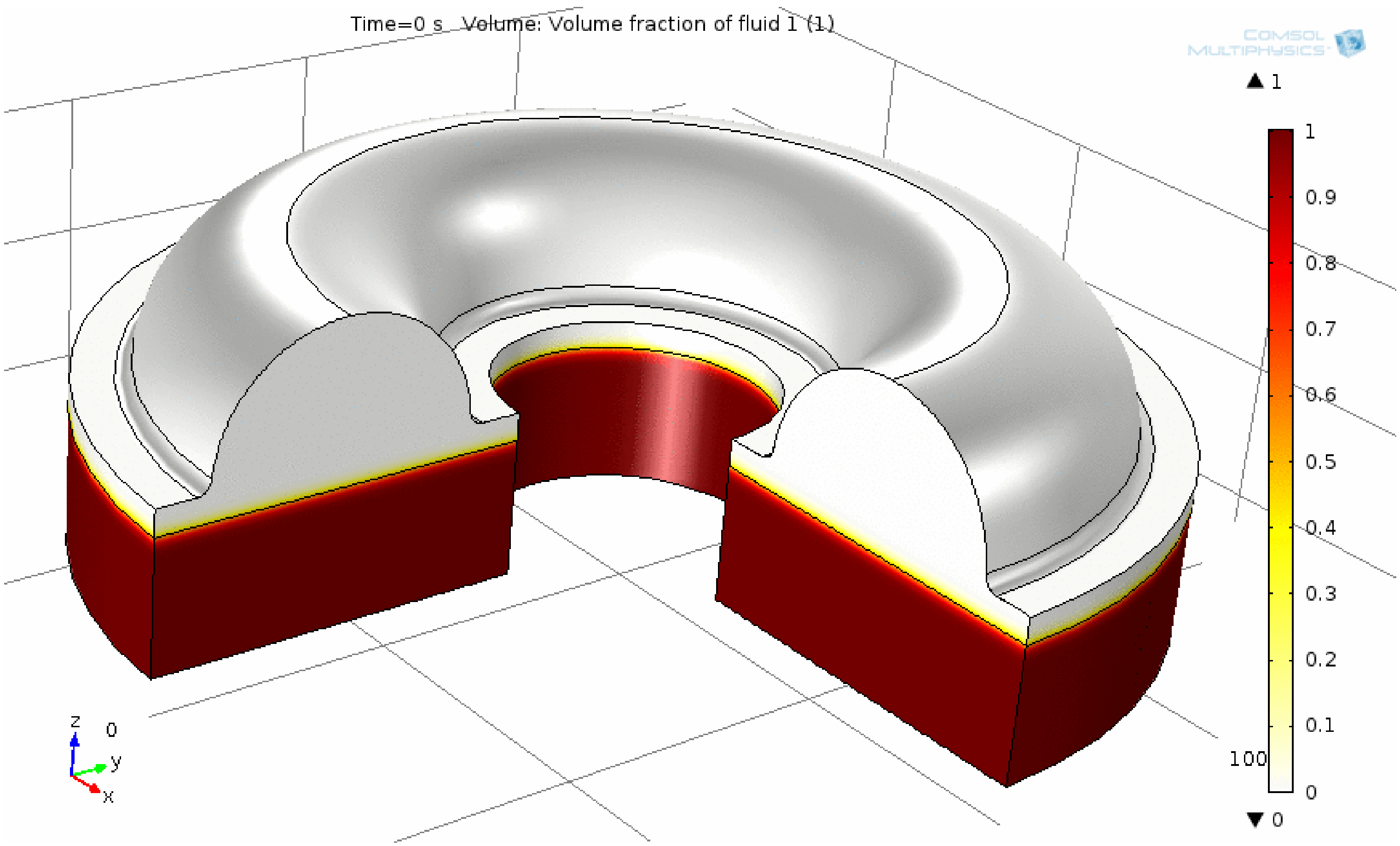


Future Work


r(7)=15 Time=0.013 s   Surface: Volume fraction of fluid 1 (1)


Time=0 s   Surface: Volume fraction of fluid 1 (1)
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-20
0
20
40
60
80
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
0

3D Extension of Model



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viii. COMSOL documentation