Experimental Investigation on the Behavior of Ferromagnetic Fluid Droplet in a Magnetic Field

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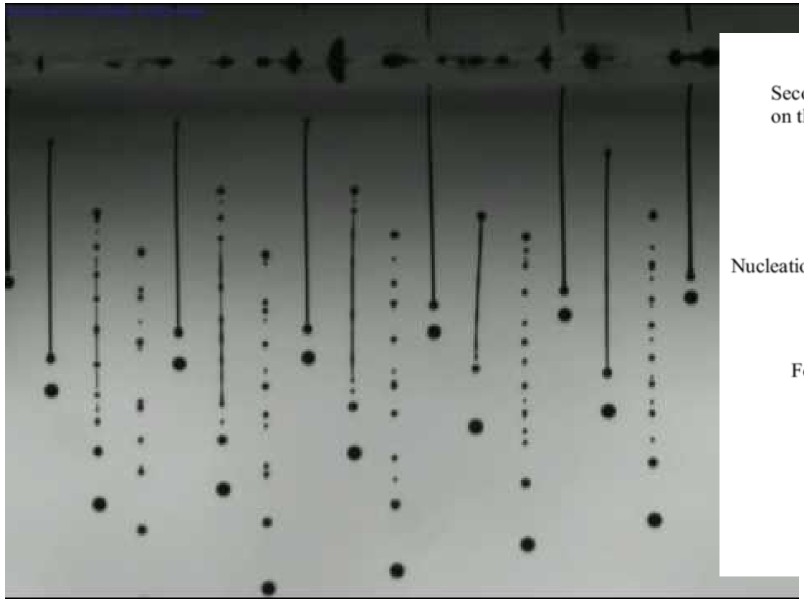
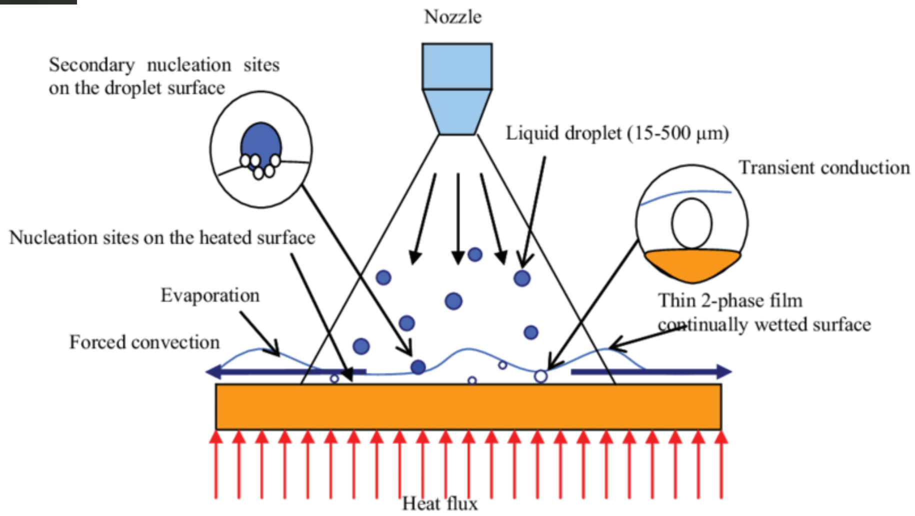
Background

Self-cleaning
Surface



Ink jetting



Spray Cooling

Background

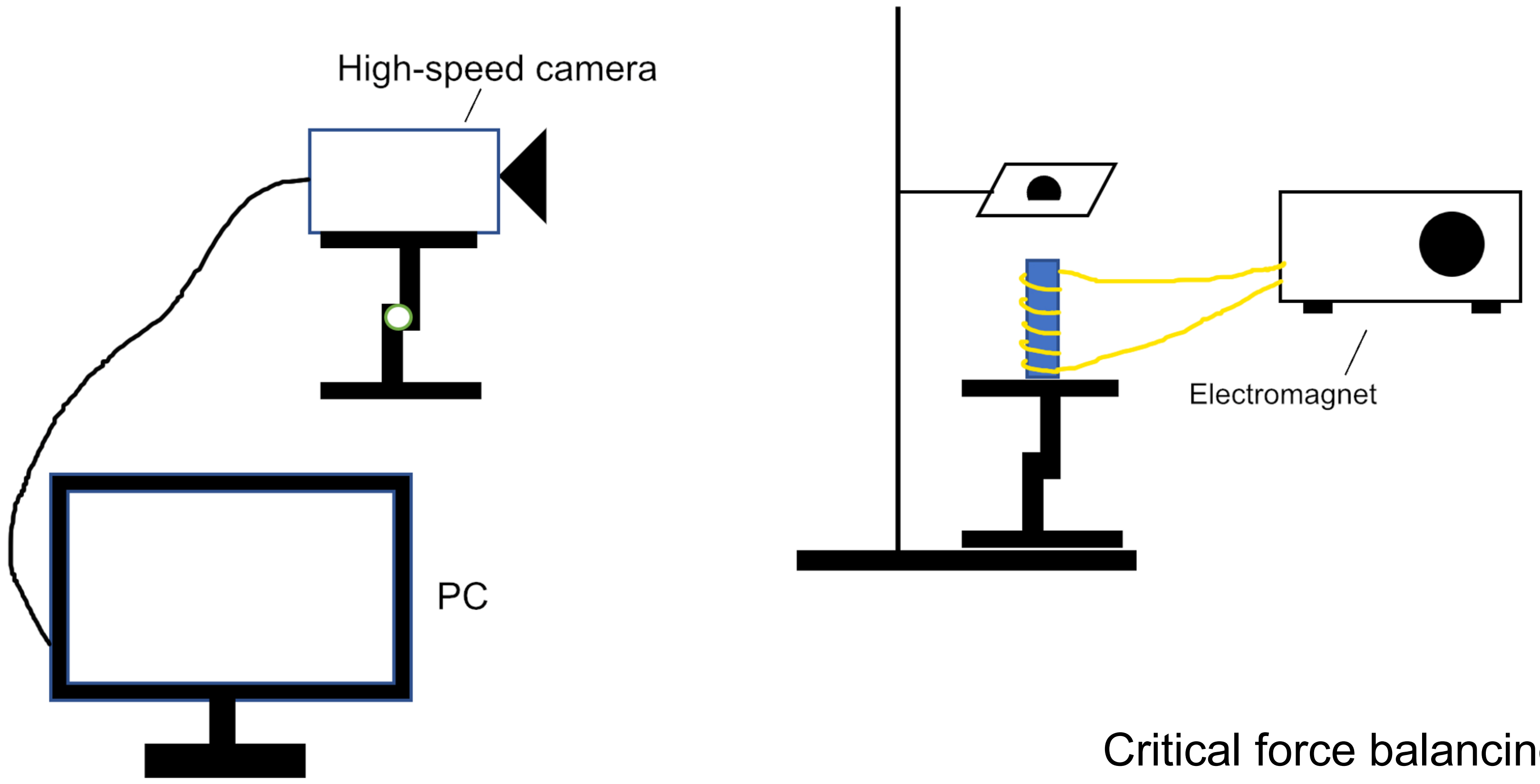
International Space Station

Background

Zero-G Cooperation

Acoustic Levitation

Schematic



Critical force balancing points:

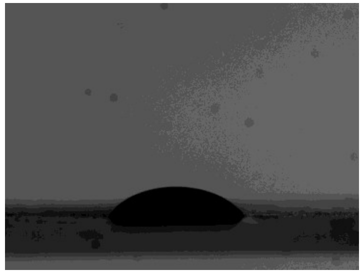
- $F_{mag} = G + F_{int}$
- $F_{mag} = G$

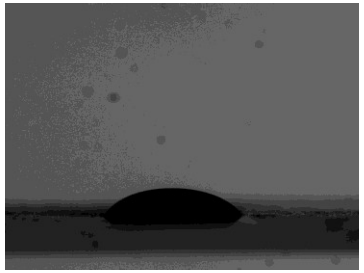
Objectives

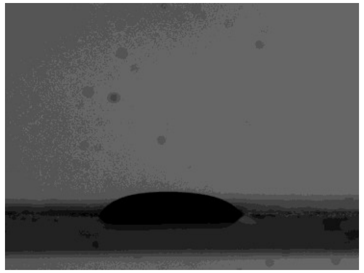
- Balancing gravity with magnetic force, studying the changes in h/d ratio & contact angles during the processing of lifting;
- Studying the effects of factors, e.g. fluid density, fluid viscosity, surface wettability to the lifting process;
- Tracking the streamlines inside the droplets;
- Studying the evaporating process of droplets floating in the air.

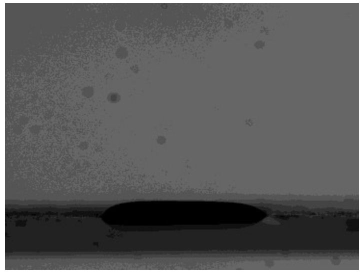
Results

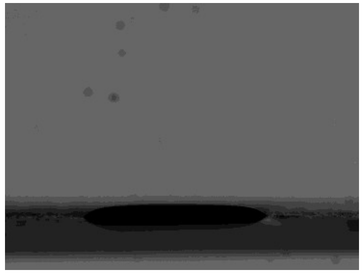
Magnetic field direction: Downside


3.83mT

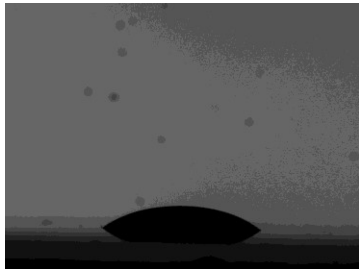

57.35mT

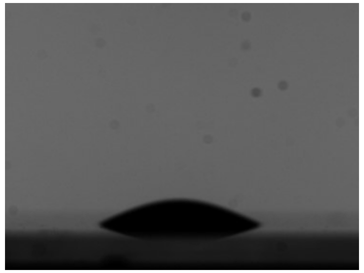

116.31mT

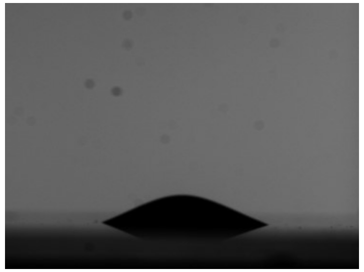

246.62mT

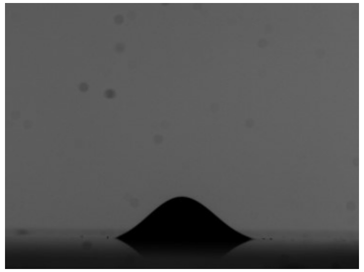

294.31mT

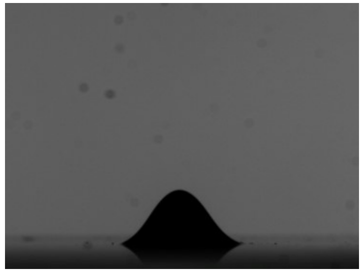
Magnetic field direction: Upside


3.05mT

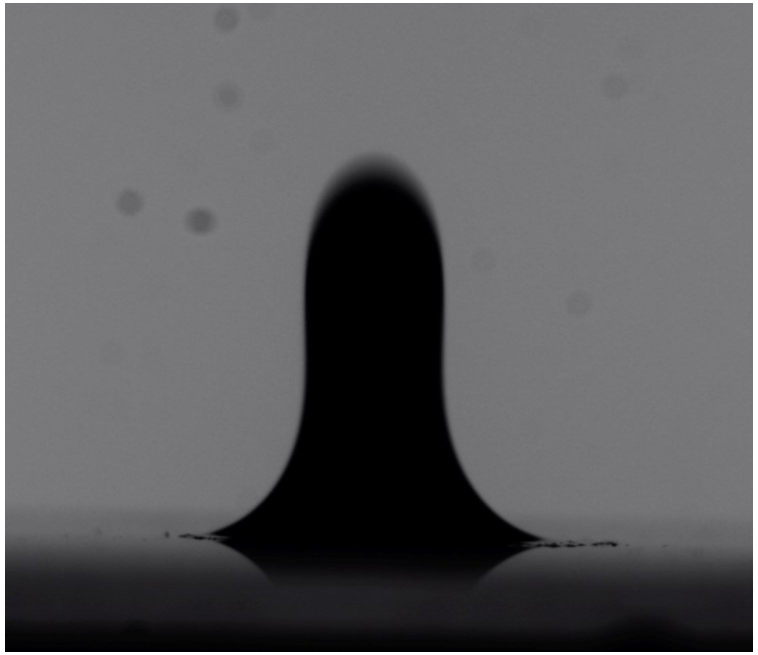

20.95mT


280.7mT


439.1mT


543.3mT

Predictions



- It will be easier to lift droplets on hydrophobic surfaces, and there will be less liquid left on the hydrophobic surface than on Hydrophilic ones;

- Droplets of higher viscosities are harder to be lifted, and the higher the viscosity, the less amount of liquid will be left on the surface;

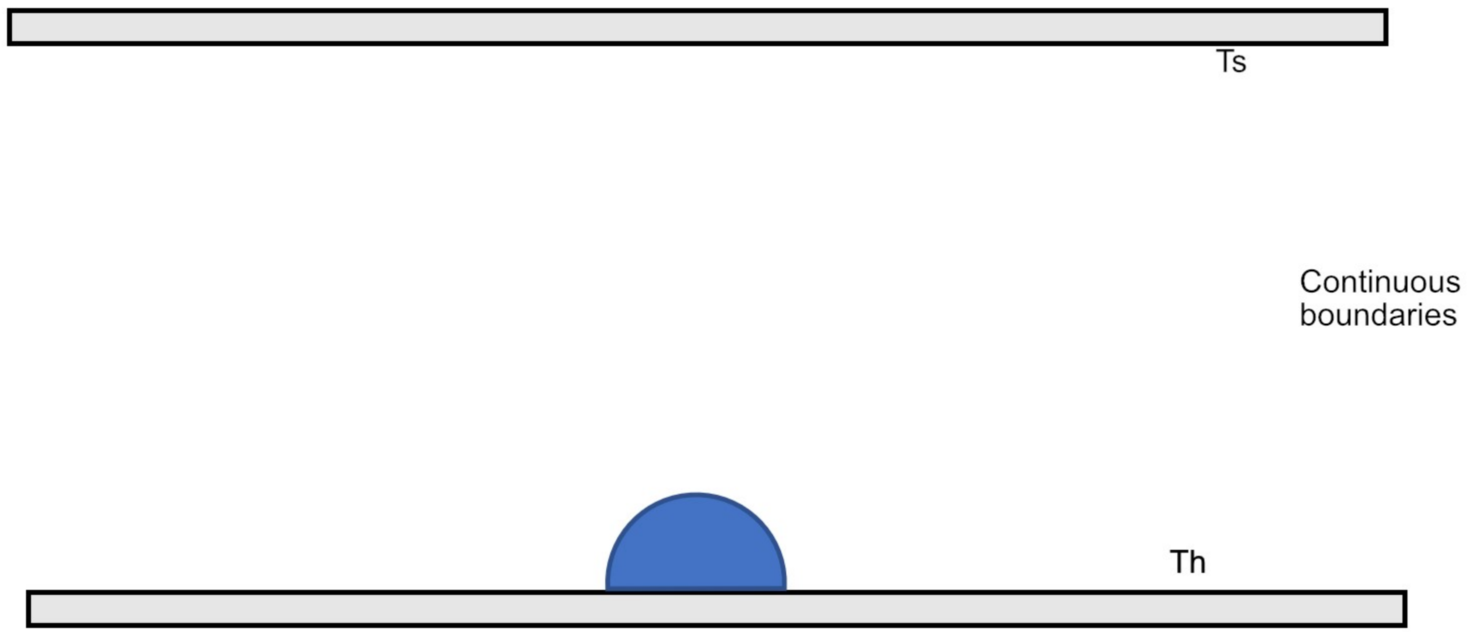
Work plans & Difficulties

- Frame rate of the camera is to be increased;
- Surfaces of different wettability are to be prepared;
- More attention will be paid to the movement of contact line.

- It's hard to track the streamline inside the ferrofluid droplet, as the fluid is very dark and non-transparent;
- During the process of evaporation, the concentration of ferrofluid keeps increasing, so magnet field strength needs to be adjusted accordingly to minimize the vertical motion of the droplet.

Numerical Study on the Process of Droplet Evaporation

Simulation set up



Initial contact angel: 90°, Th=0.91*Tc, Ts=0.87*Tc;

A brief introduction of the binary-phase LBM model

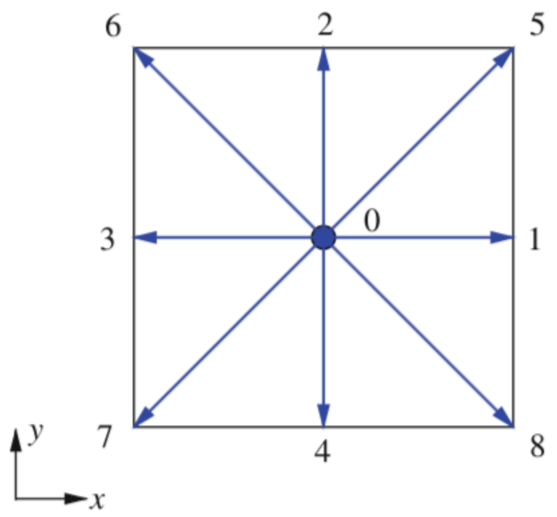
$$f_i^\sigma(x+e_i\Delta t, t+\Delta t) - f_i^\sigma(x,t) = -\frac{1}{\tau^\sigma}[f_i^\sigma(x,t) - f_i^{\sigma,eq}(x,t)]$$

$$\sigma = 1,2$$

$$f_i^{\sigma,eq} = \omega_i \rho^\sigma [1 + 3\frac{(e_i \cdot \mathrm{u}^{\sigma,eq})}{c^2} + \frac{9}{2}\frac{(e_i \cdot \mathrm{u}^{\sigma,eq})^2}{c^4} - \frac{3}{2}\frac{(\mathrm{u}^{\sigma,eq})^2}{c^2}]$$

$$\omega_i = \begin{cases} \frac{4}{9} & i=0 \\ \frac{1}{9} & i=1,2,3,4 \\ \frac{1}{36} & i=5,6,7,8 \end{cases}$$

$$\boldsymbol{e}_i = \begin{cases} (0,0) & i=0 \\ c\left(\cos\left[\frac{\pi}{2}(i-1)\right], \sin\left[\frac{\pi}{2}(i-1)\right]\right) & i=1,2,3,4 \\ \sqrt{2}c\left(\cos\left[\frac{\pi}{4}(2i-1)\right], \sin\left[\frac{\pi}{4}(2i-1)\right]\right) & i=5,6,7,8 \end{cases}$$



$$\rho^\sigma(x,t) = \sum_i m^\sigma f_i^\sigma(x,t)$$

$$\rho^\sigma(x,t)\mathrm{u}^\sigma(x,t) = m^\sigma \sum_i f_i^\sigma(x,t) e_i$$

$$\mathrm{u}^{eq} = \frac{\Sigma_\sigma \frac{\rho^\sigma \mathrm{u}^\sigma}{\tau^\sigma}}{\Sigma_\sigma \frac{\rho^\sigma}{\tau^\sigma}}$$

$$\nu^\sigma = \frac{2\tau^\sigma - 1}{6}\frac{(\Delta x)^2}{\Delta t} = \frac{2\tau^\sigma - 1}{6} c^2 \Delta t$$

Key Equations

$$f_{\sigma,i}(\boldsymbol{x}+\boldsymbol{e}_i\delta t, t+\delta t) - f_{\sigma,i}(\boldsymbol{x},t) = \frac{1}{\tau_\sigma}(f^{eq}_{\sigma,i}(\boldsymbol{x},t) - f_{\sigma,i}(\boldsymbol{x},t))$$

$$g_{\sigma,i}(\boldsymbol{x}+\boldsymbol{e}_i\delta t, t+\delta t) - g_{\sigma,i}(\boldsymbol{x},t) = \frac{1}{\tau_{\sigma,T}}(g^{eq}_{i}(\boldsymbol{x},t) - g_{\sigma,i}(\boldsymbol{x},t)) + \delta t\omega_i\varphi_\sigma$$

Lattice Boltzmann Density and temperature distribution function

$$\varphi_\sigma = T_\sigma[1 - \frac{1}{\rho_\sigma c_{v,\sigma}}\left(\frac{\partial p_\sigma}{\partial T_\sigma}\right)_{\rho_\sigma}]\nabla \cdot \mathbf{U}_\sigma + \frac{1}{\rho_\sigma c_{v,\sigma}}\nabla \cdot (\lambda_\sigma \nabla T)$$

The phase change term

Key Equations

$$\psi_\sigma(\boldsymbol{x}) = \sqrt{\frac{p_\sigma - c_s^2 \rho_\sigma}{3 g_\sigma}}$$

Pseudo-potential

$$\boldsymbol{F}_\sigma = \boldsymbol{F}_{\sigma,\sigma} + \boldsymbol{F}_{\sigma,\sigma'} + \boldsymbol{F}_{\sigma,s} + \boldsymbol{F}_{\sigma,g}$$

$$\boldsymbol{F}_{\sigma,\sigma}(\boldsymbol{x}) = -\beta\psi_\sigma(\boldsymbol{x})\sum_{\boldsymbol{x}'} G_\sigma \psi_\sigma(\boldsymbol{x},\boldsymbol{x}') + \frac{(1-\beta)}{2}\sum_{\boldsymbol{x}'} G_\sigma \psi_\sigma^2(\boldsymbol{x},\boldsymbol{x}')$$

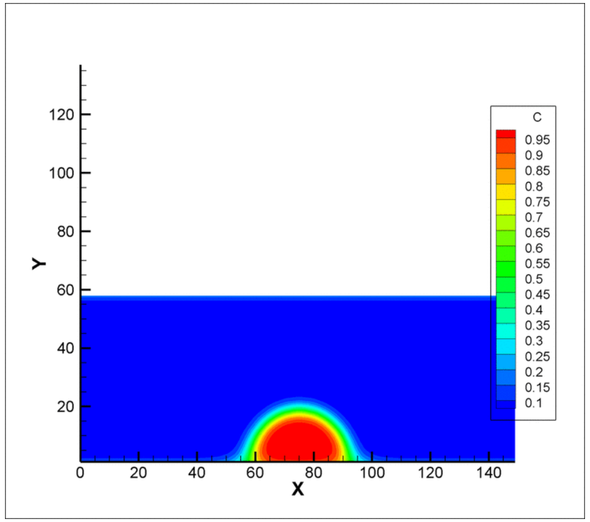
$$\boldsymbol{F}_{\sigma,\sigma'}(x) = -\psi_\sigma(\boldsymbol{x})\sum_{\boldsymbol{x}'} G_{\sigma'} \psi_{\sigma'}(\boldsymbol{x},\boldsymbol{x}')$$

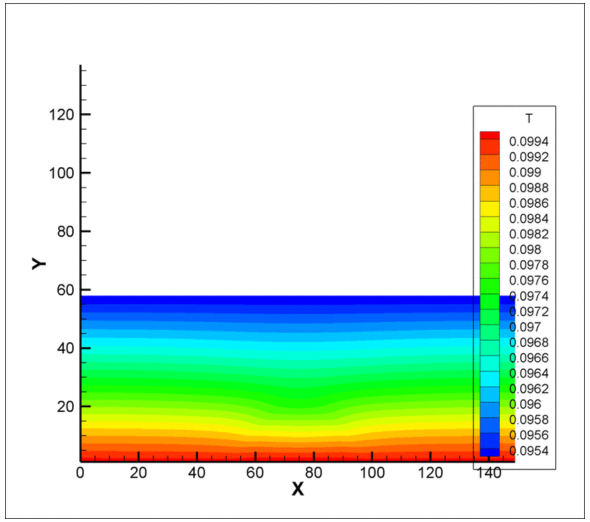
$$\boldsymbol{F}_{\sigma,s}(\boldsymbol{x}) = -\psi_\sigma(\boldsymbol{x})\sum_{\boldsymbol{x}'} G_s s(\boldsymbol{x},\boldsymbol{x}')$$

Force terms

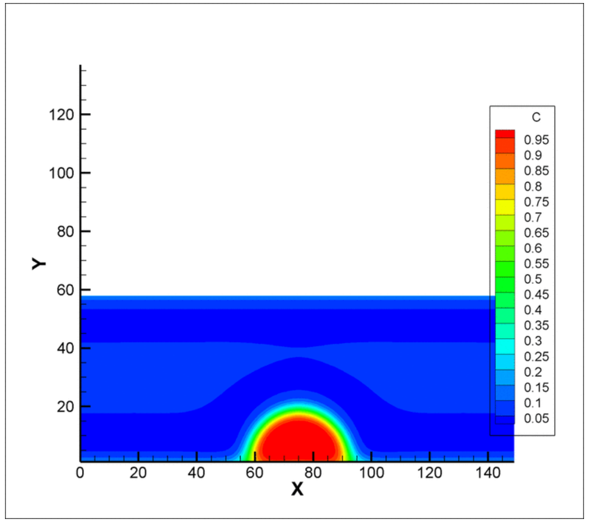
Results & Discussion

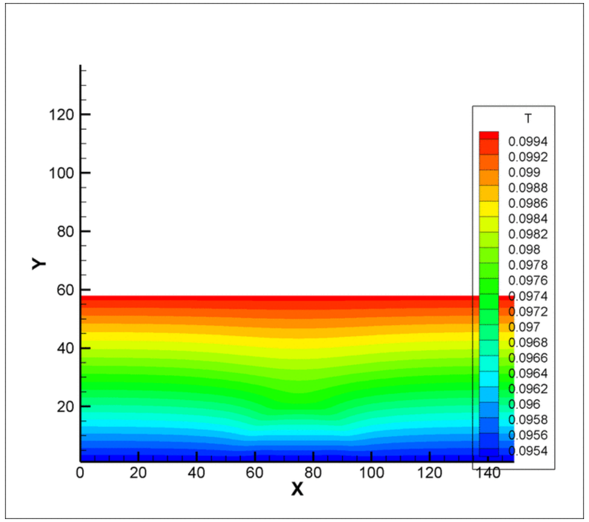
Heat Source: Bottom





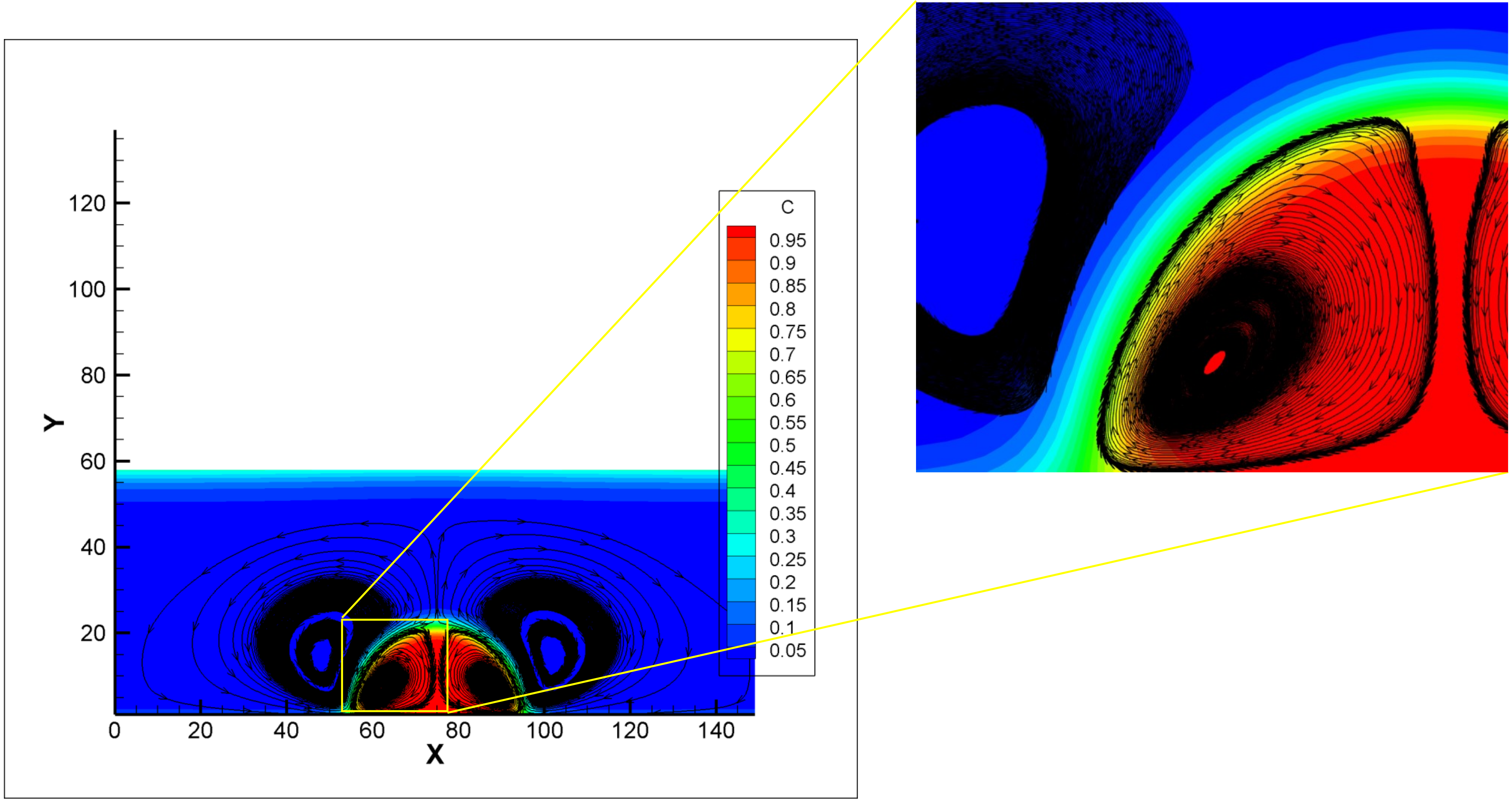
Heat Source: Top





Results & Discussion

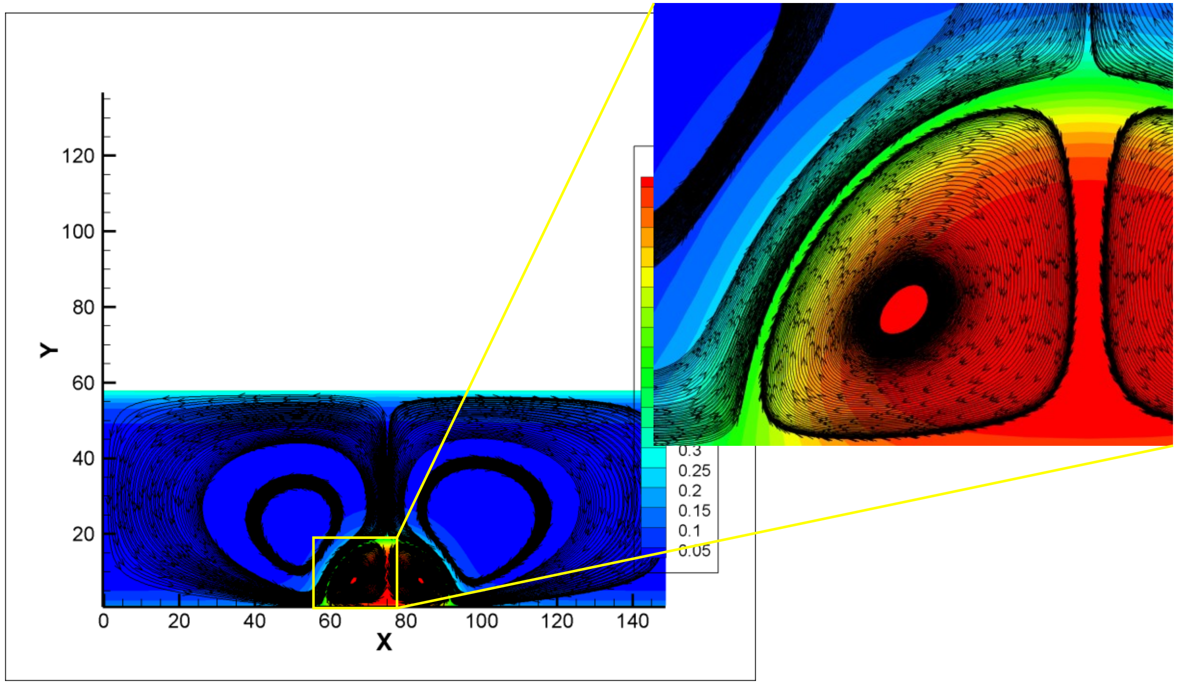
Constant temperature

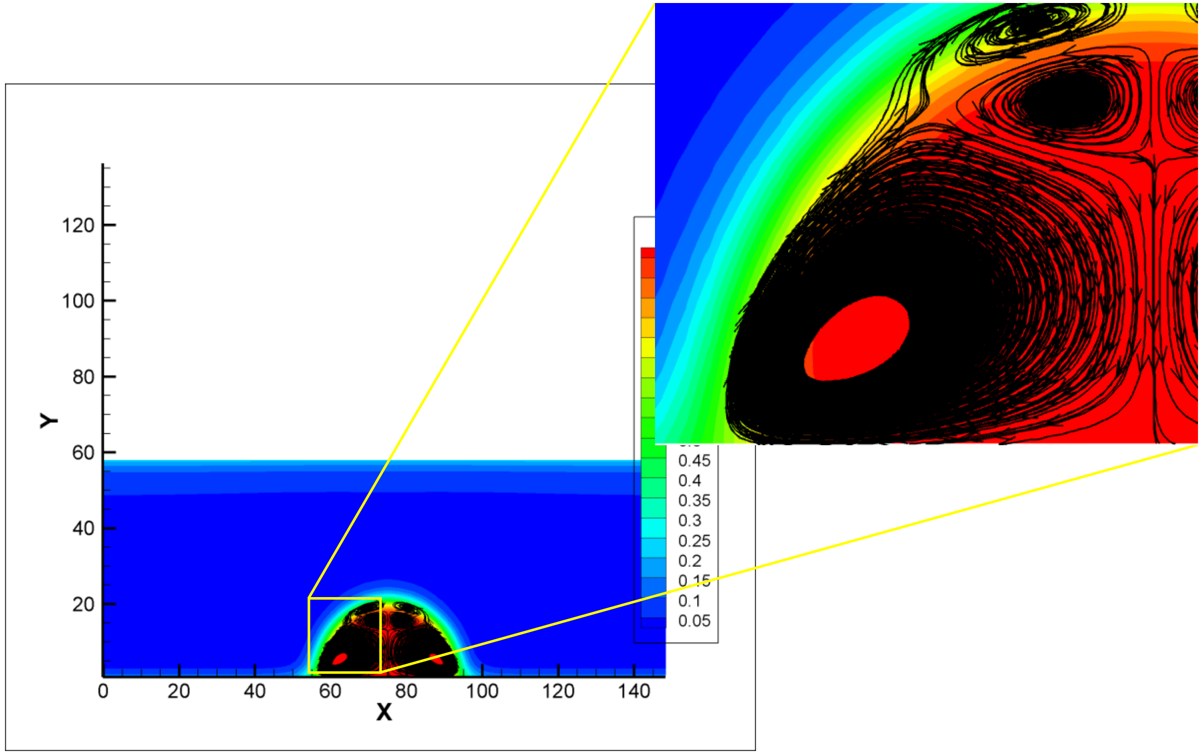


Results & Discussion

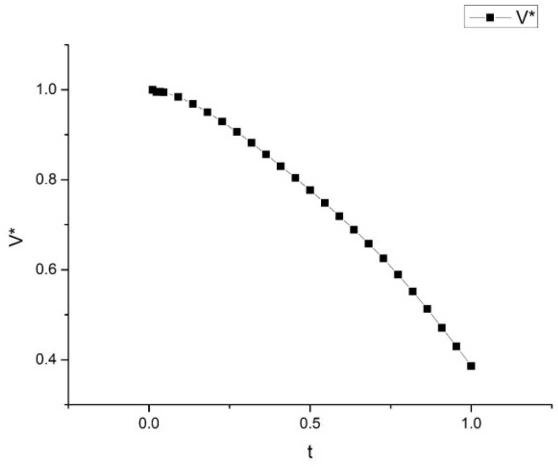
Heat source: Bottom

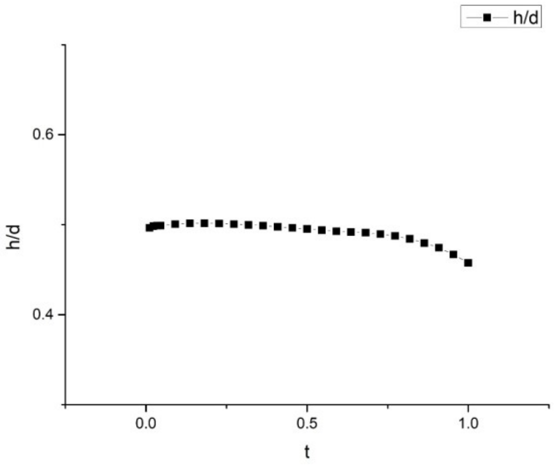
Heat source: Top

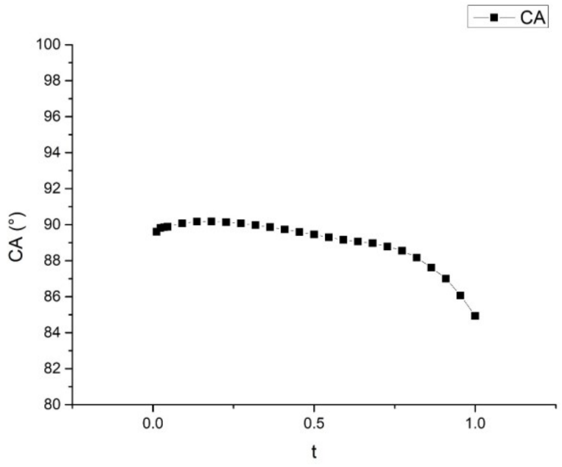




Results & Discussion







- When the evaporation process just started, the volume of the droplet expanded a little before starting to decrease. This is because the droplet is being heated up, and evaporation is yet to be the main factor;

- The h/d ratio and contact angle are both decreasing when the evaporation process is close to the end;

- When the droplet is expanding in the beginning, the h/d ratio and contact angle both increased.

Conclusions

- The streamline inside the droplet is affected by both Marangoni force and buoyance;
- The evaporation rate of droplet is increasing throughout the process, although the volume does expand when the process begins;
- The h/d ratio and contact angle decreases when the evaporating process is ending despites the interaction force coefficient remains unchanged.

Thank you for your attention