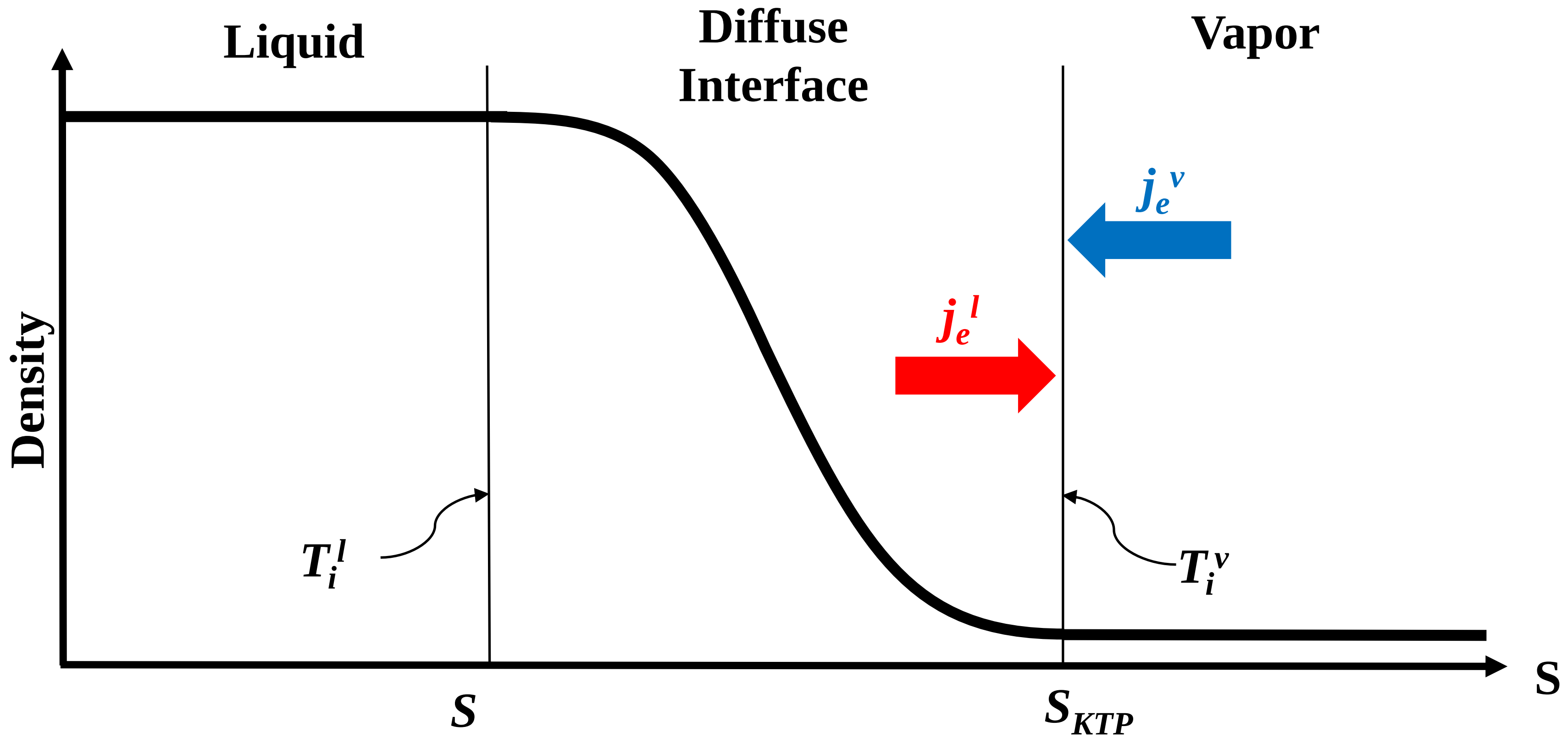
Testing simplified assumptions during liquid vapor phase change using data from International Space Station (ISS) experiments

Unmeelan Chakrabarti, Kishan Bellur, Jeffrey S Allen

Kinetic theory and phase change

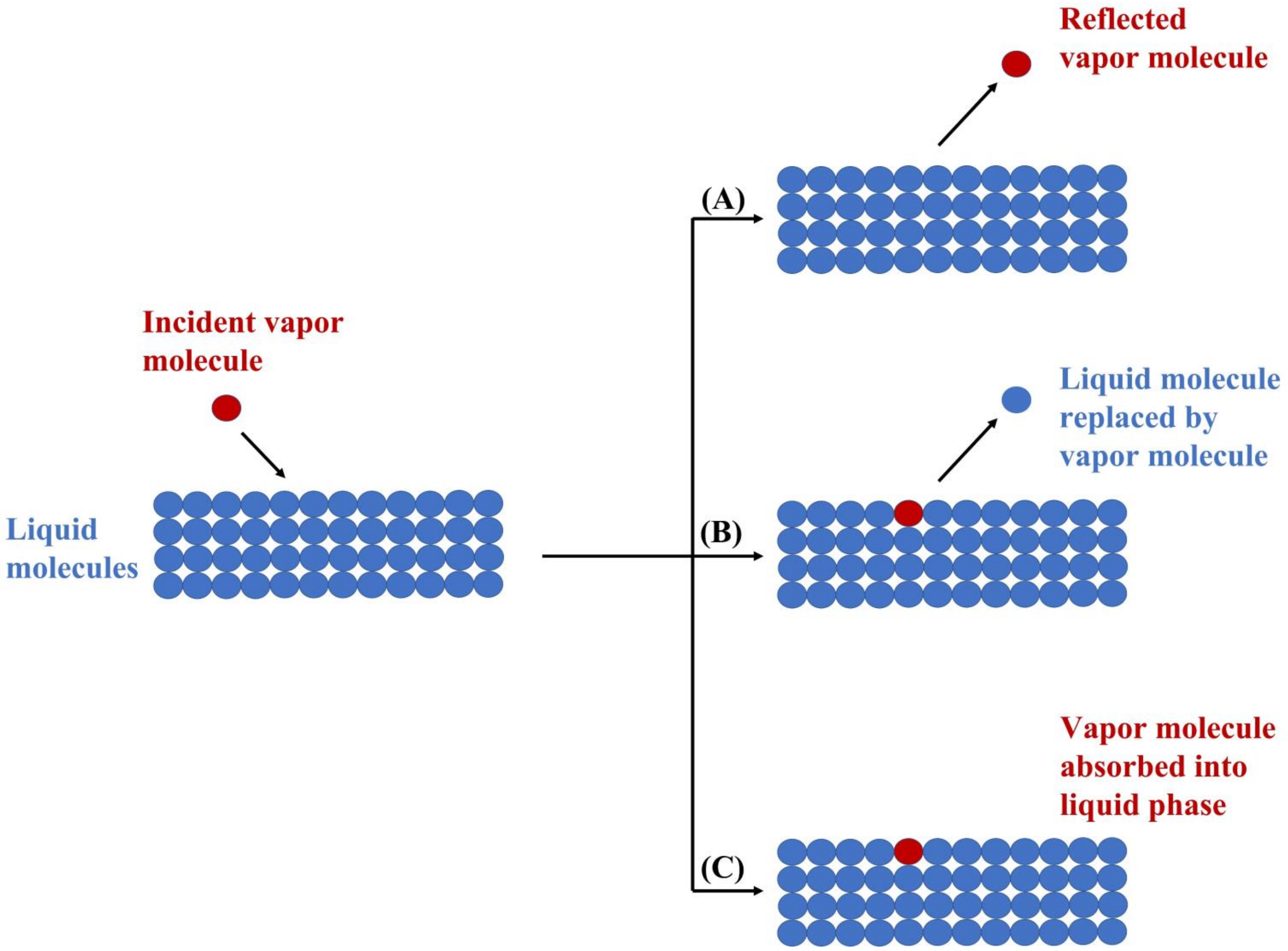


Phase change mass flux:

$$\dot{m}'' = \sqrt{\frac{k_B}{2\pi m}}\left[\rho_{sat}^{v}(T_i^l)\sqrt{T_i^l} - \rho_{sat}^{v}(T_i^l)\sqrt{T_i^l}\right]$$

evaporation condensation

Kinetic theory and phase change

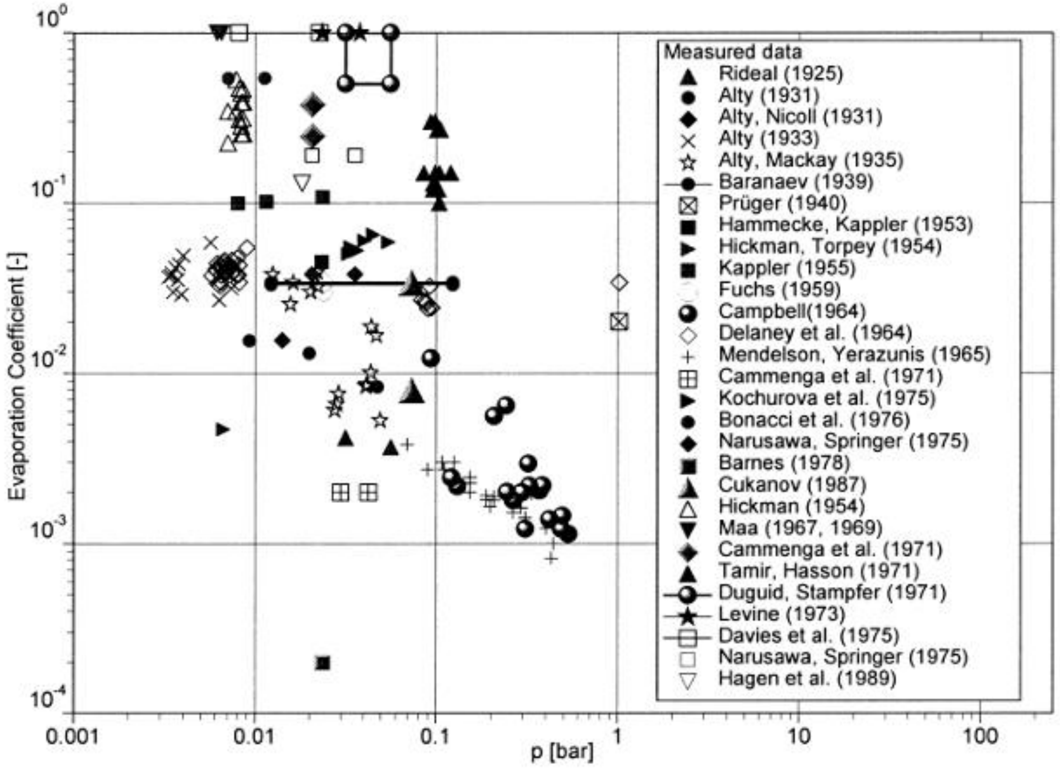


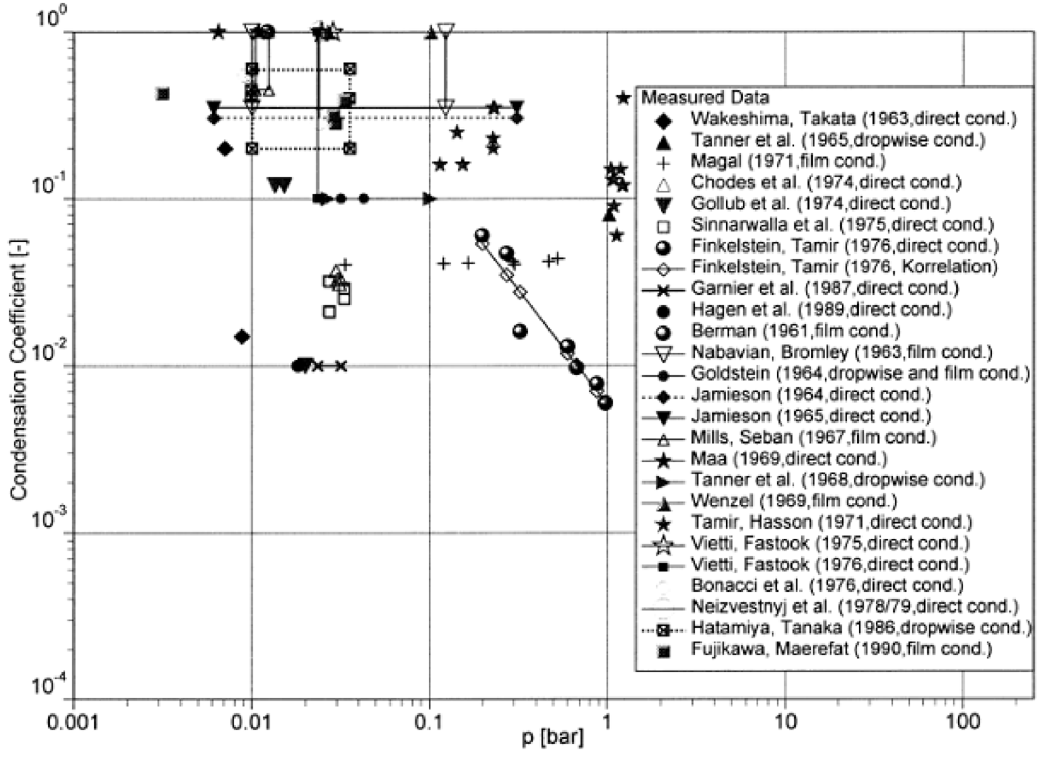
- Coefficients α_c and α_e are the fraction of molecules undergoing condensation and evaporation respectively.

- Phase change mass flux modified and rewritten in terms of saturation pressures using ideal gas laws:

$$\dot{m}'' = \left(\frac{2}{2-\alpha_c}\right)\sqrt{\frac{m}{2\pi k_B}}\left[\alpha_e \frac{P_s(T_i^l)}{\sqrt{T_i^l}} - \alpha_e \frac{P^v}{\sqrt{T_i^V}}\right]$$

Kinetic theory and phase change

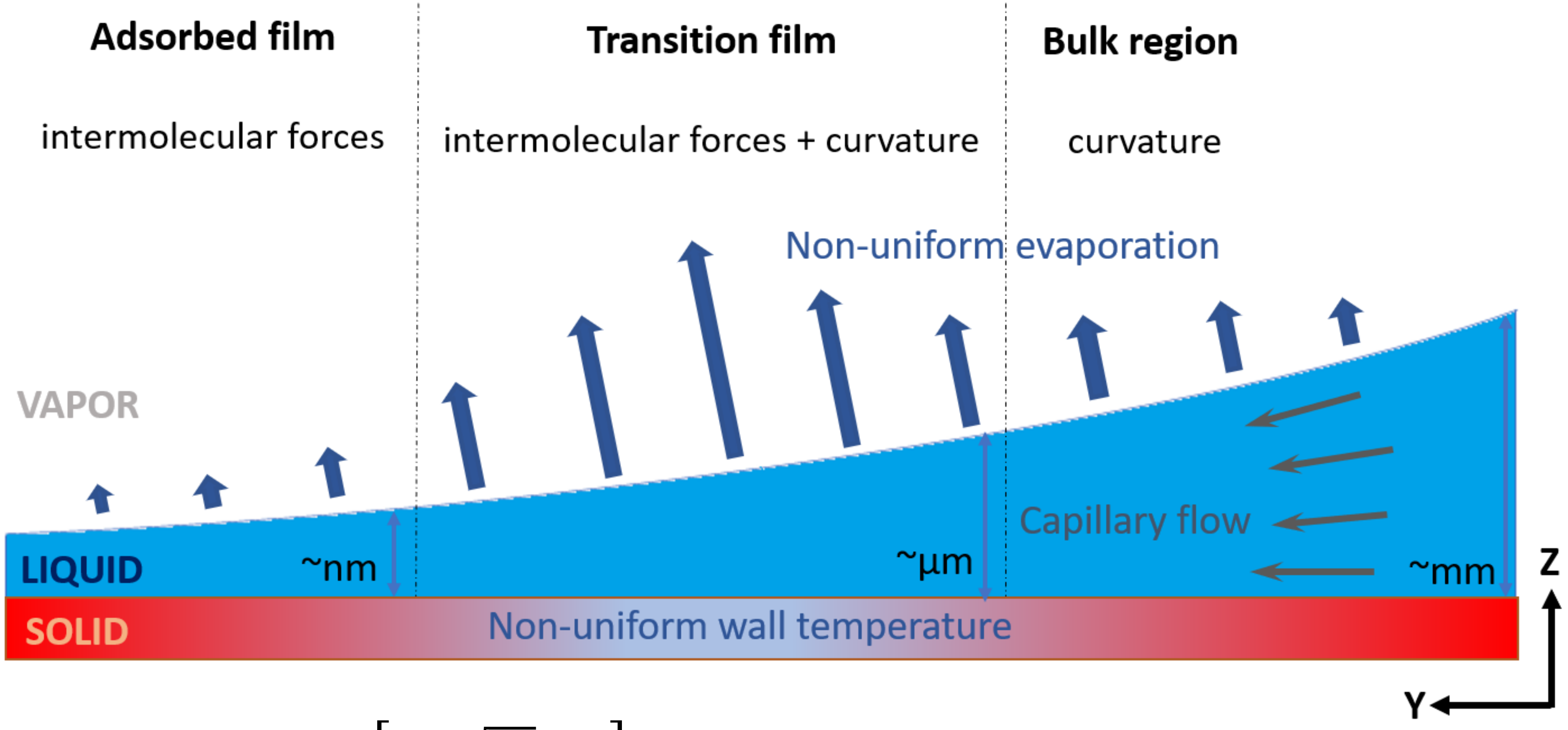




Simplified assumption: Equal evaporation and condensation coefficients ($\alpha_e = \alpha_c$)?

[1] Marek, R. et al. International Journal of Heat and Mass Transfer. 2001
[2] Robert . W. Schrage, PhD Dissertation. 1953

Modified equation for curved interfaces



$$\dot{m}'' = \left(\frac{2\alpha_c}{2-\alpha_c}\right)\frac{P_i^v}{\pi v_{mp}}\left[\beta W\sqrt{\frac{T_i^v}{T_i^l}} - 1\right]$$

$$\beta = \frac{\alpha_e}{\alpha_c}$$

$$W = \frac{P_s(T_i^l)}{P_i^v} = \frac{P_{sat}^v}{P} + \frac{\rho_{sat}^v h_{fg}}{P_i^v}\left(1 - \frac{T_i^v}{T_i^l}\right) + \left(\frac{T_i^v}{T_i^l}\right)\left(\frac{\rho_{sat}^v}{\rho^l}\right)\left(\frac{\Pi + P_c}{P_i^v}\right)$$

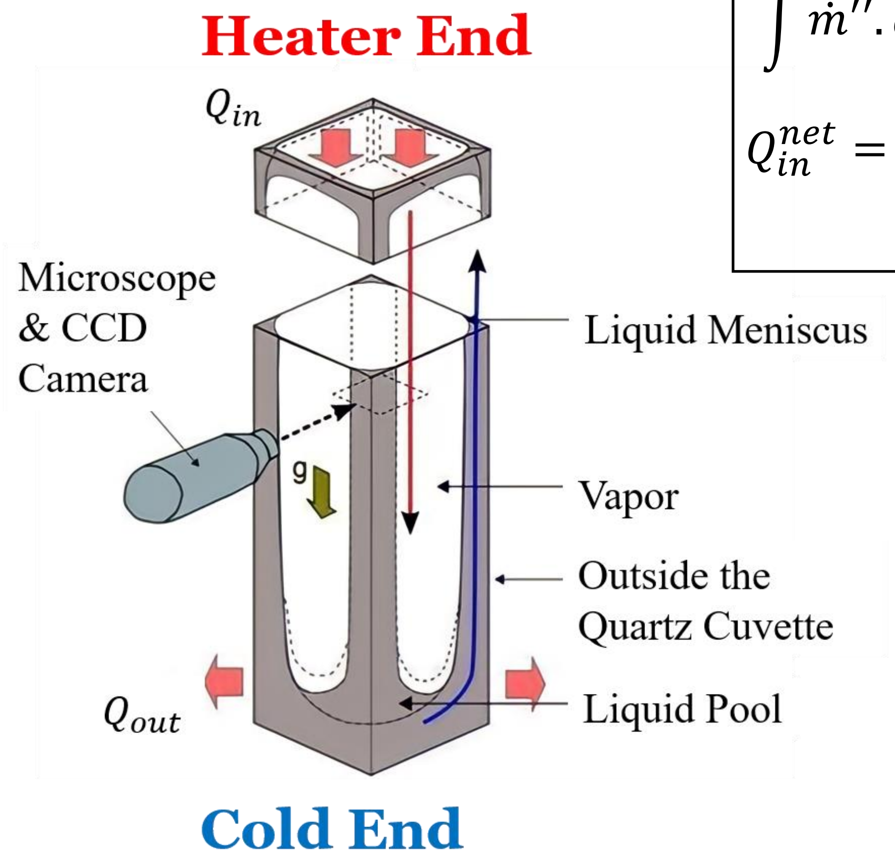
[3] *K. Bellur et al. Colloids and Surfaces. 2023*

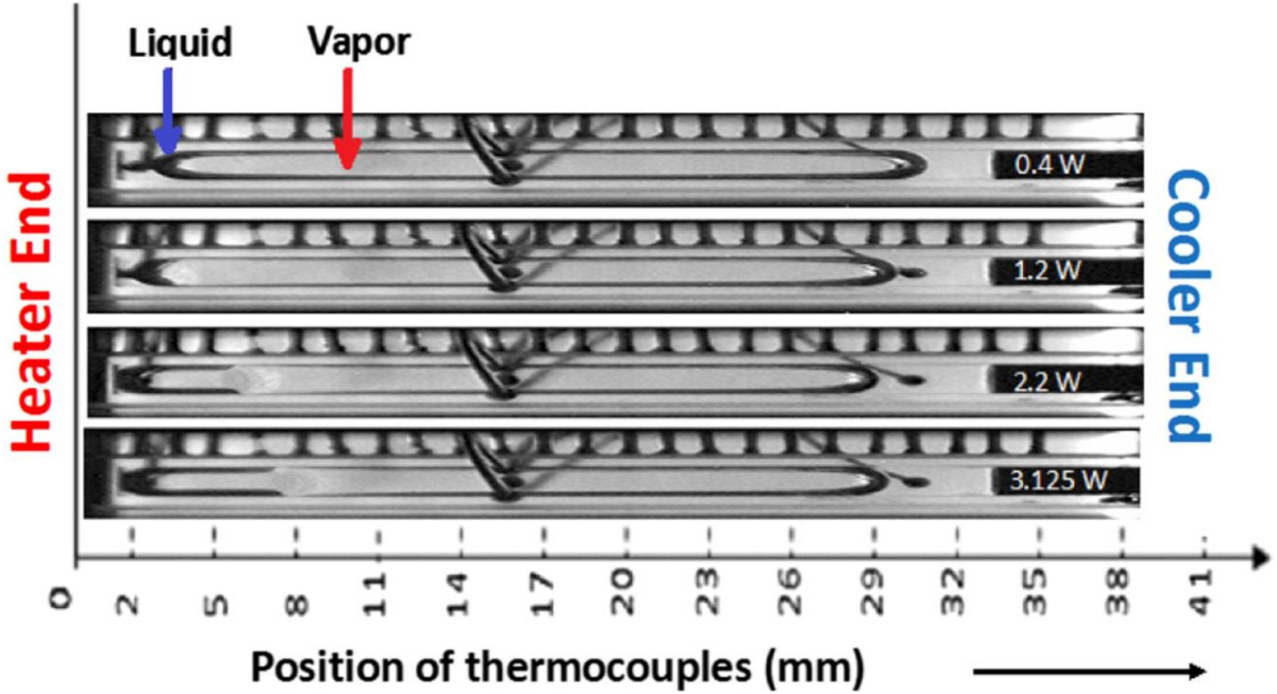
Constrained Vapor Bubble (CVB) experiments

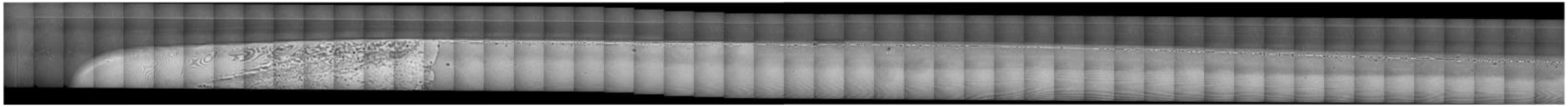
Unique constraints:

$$\int \dot{m}''.dA = 0$$

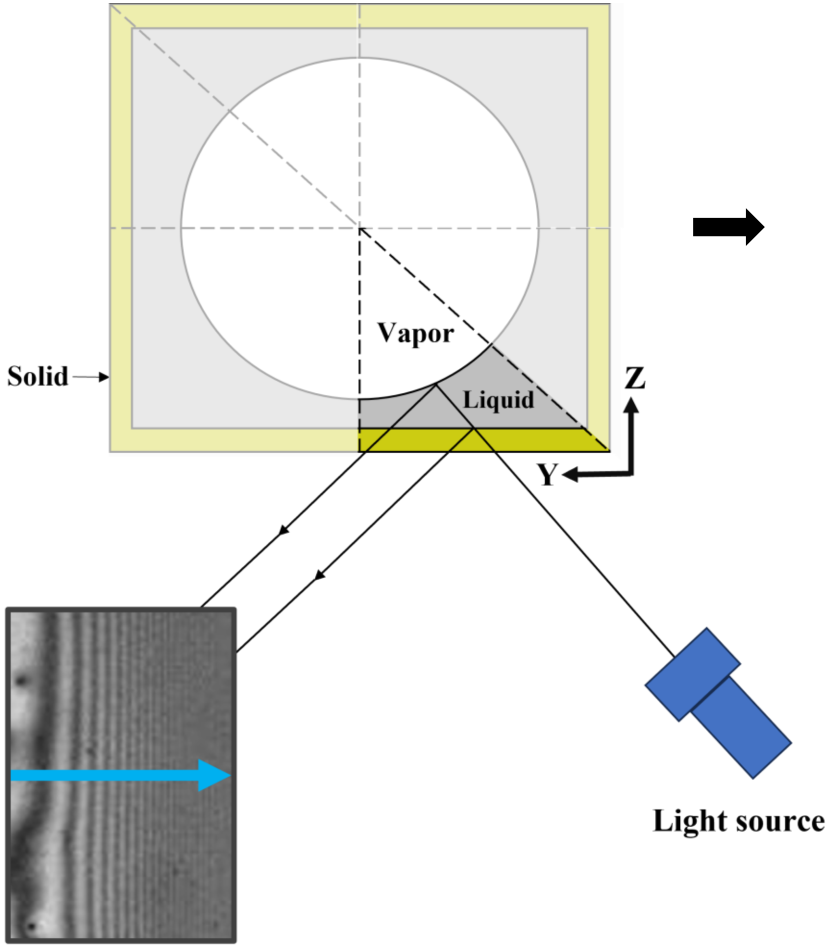
$$Q_{in}^{net} = hfg \int_{evap} \dot{m}''.dA$$

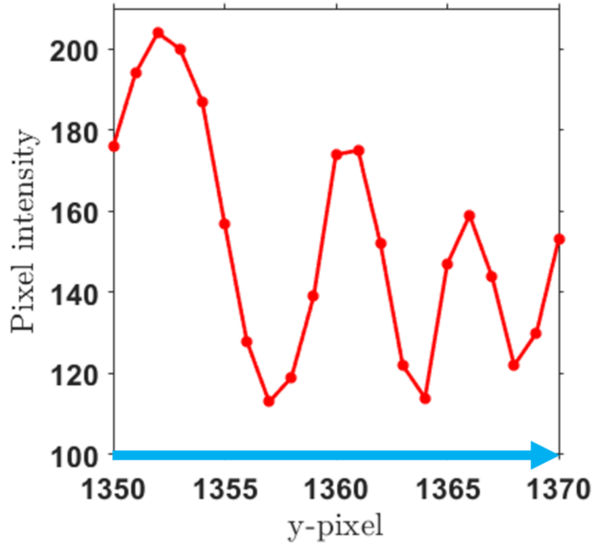


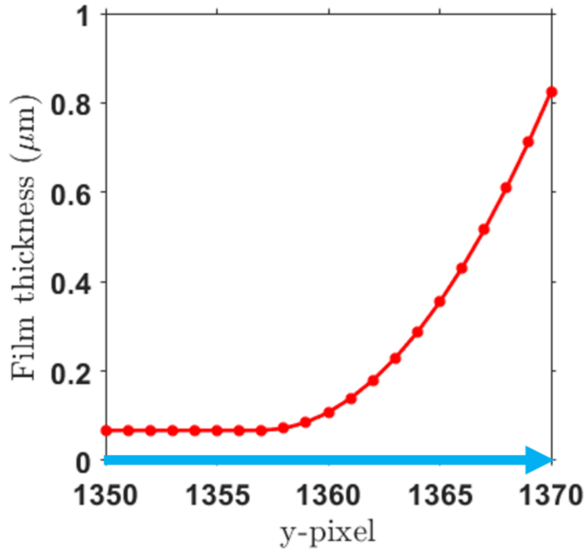


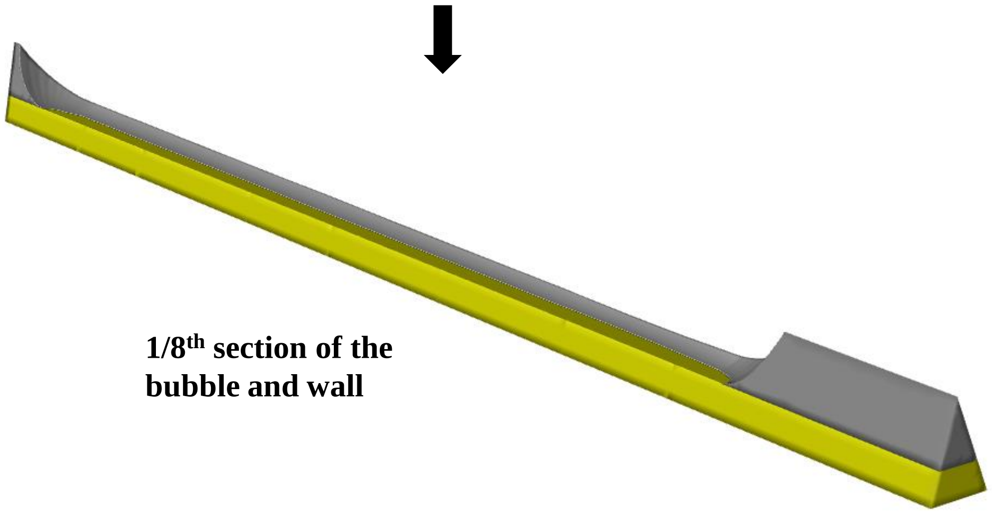


Interface Reconstruction





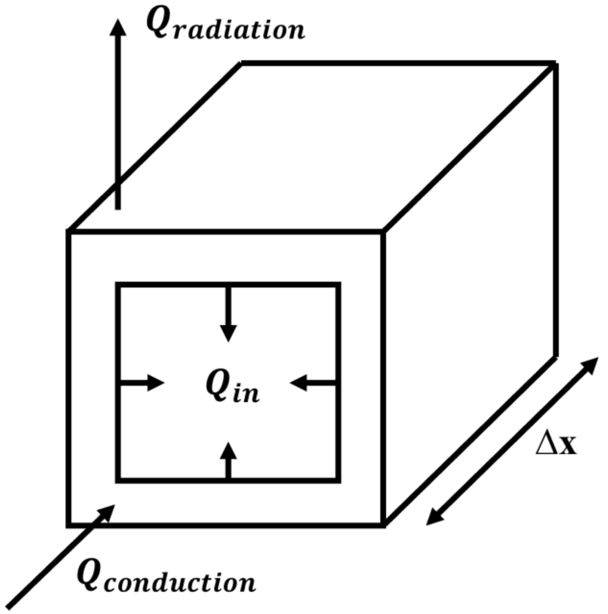


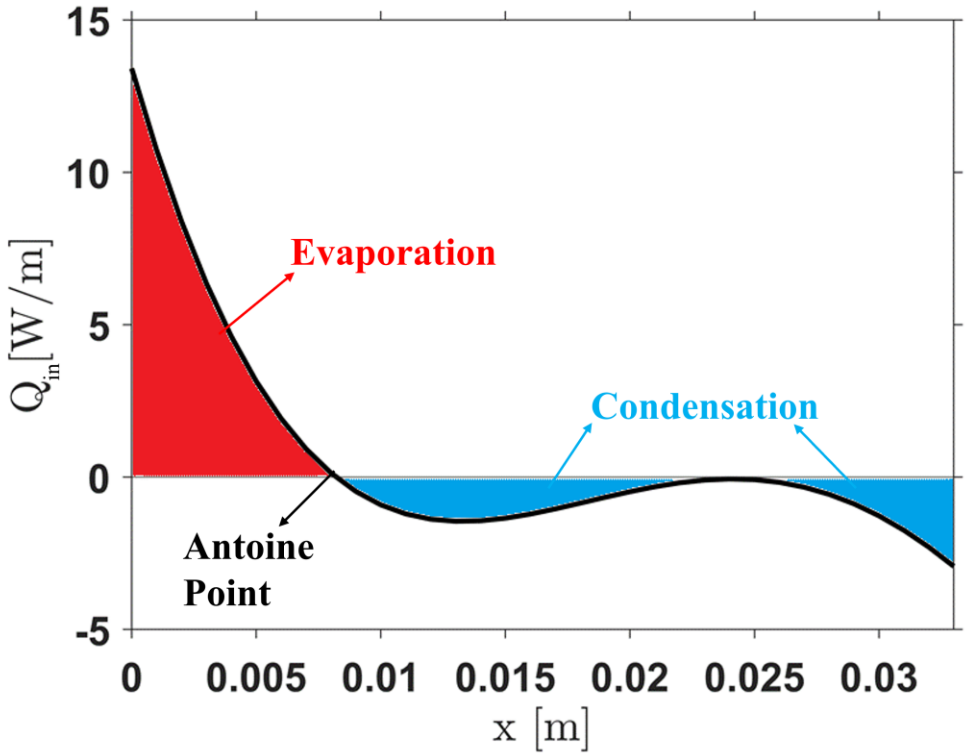


1/8th section of the bubble and wall

[5] *Chakrabarti et. al, Frontiers in Space Technologies 2023*

Heat balance

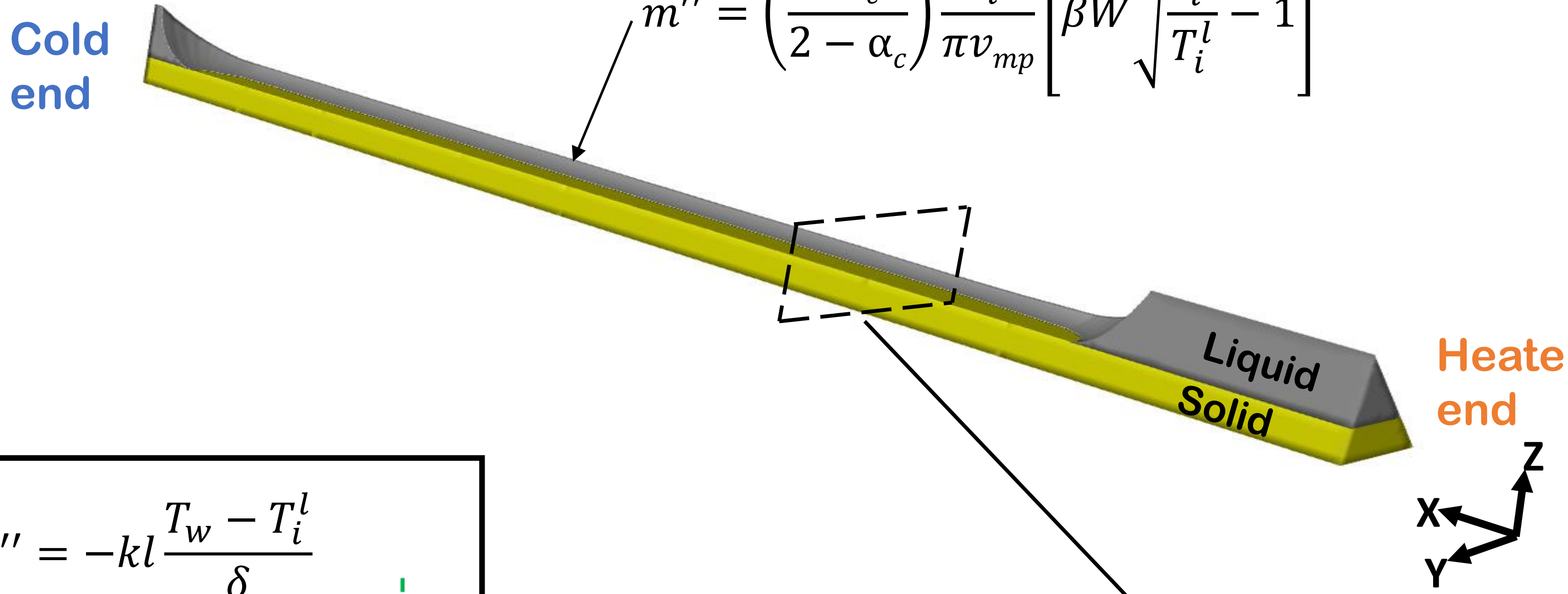




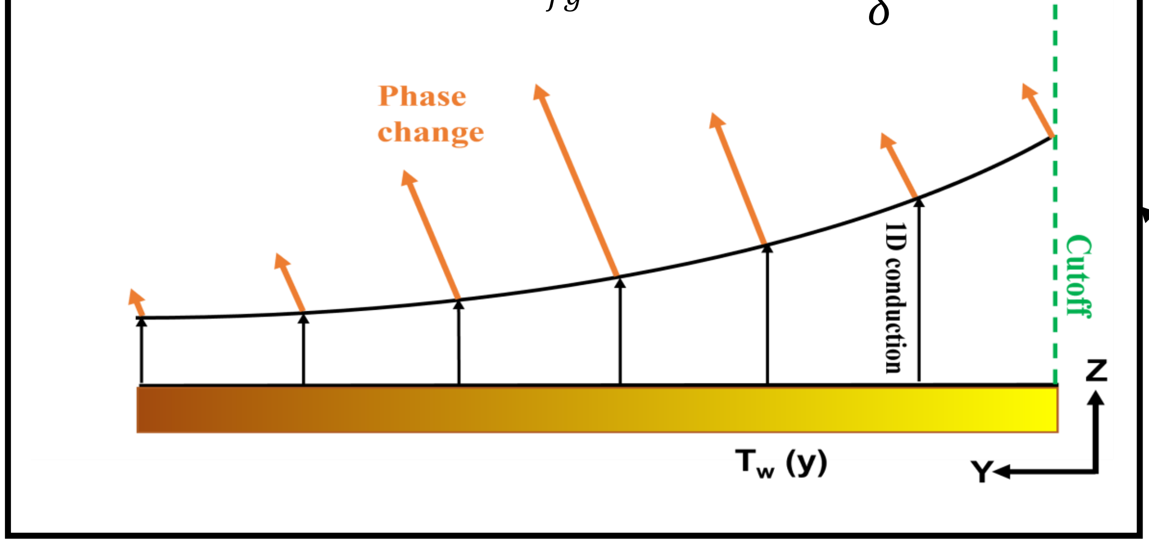
$$Q_{in}^{net} = \int_{evap} Q_{in} \,.\, dx = \int_{evap} [\sigma P_o \epsilon (T(x)^4 - T_\infty{}^4) - K A_c \frac{d^2T(x)}{dx^2}] \,.\, dx$$

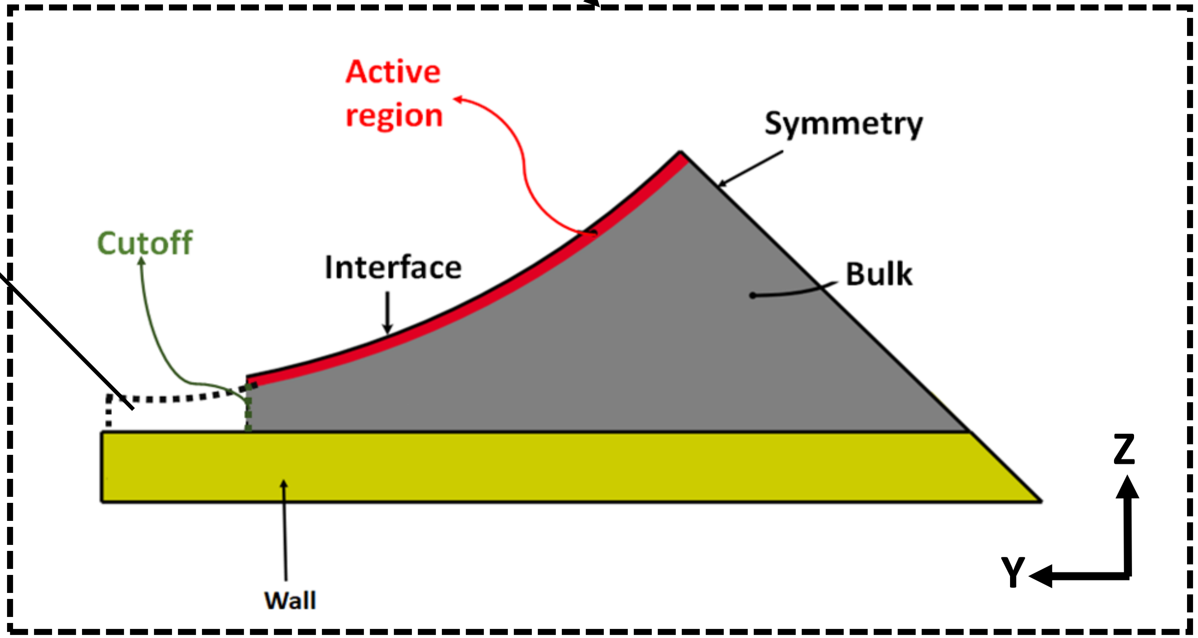
Multiscale model

$$\dot{m}'' = \left(\frac{2\alpha_c}{2-\alpha_c}\right)\frac{P_i^v}{\pi v_{mp}}\left[\beta W\sqrt{\frac{T_i^v}{T_i^l}} - 1\right]$$



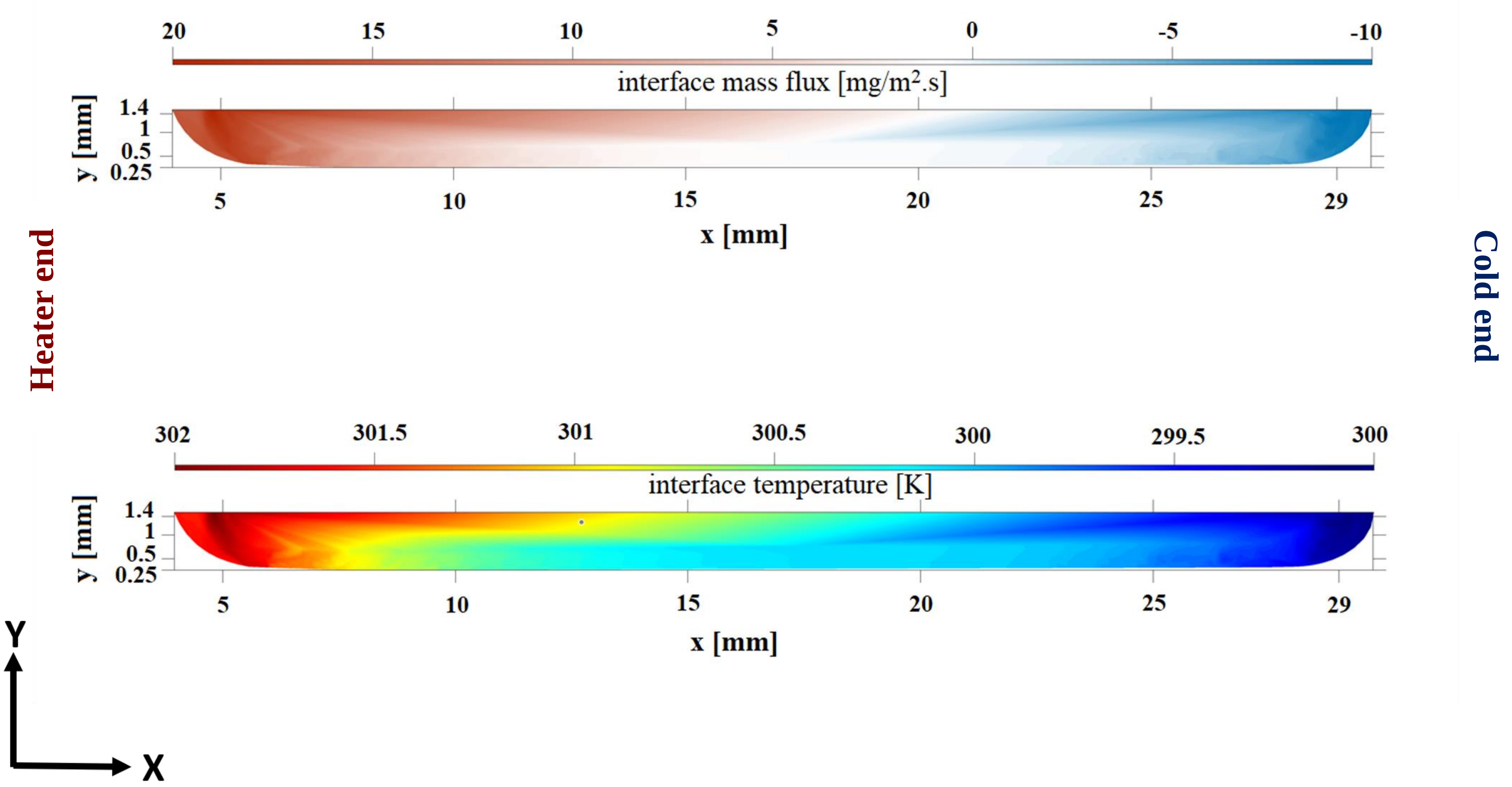
$$h_{fg}\dot{m}'' = -kl\frac{T_w - T_i^l}{\delta}$$





[5] *Chakrabarti et. al, Frontiers in Space Technologies 2023*

Surface non-uniformities



[5] *Chakrabarti et. al*, *Frontiers in Space Technologies 2023*

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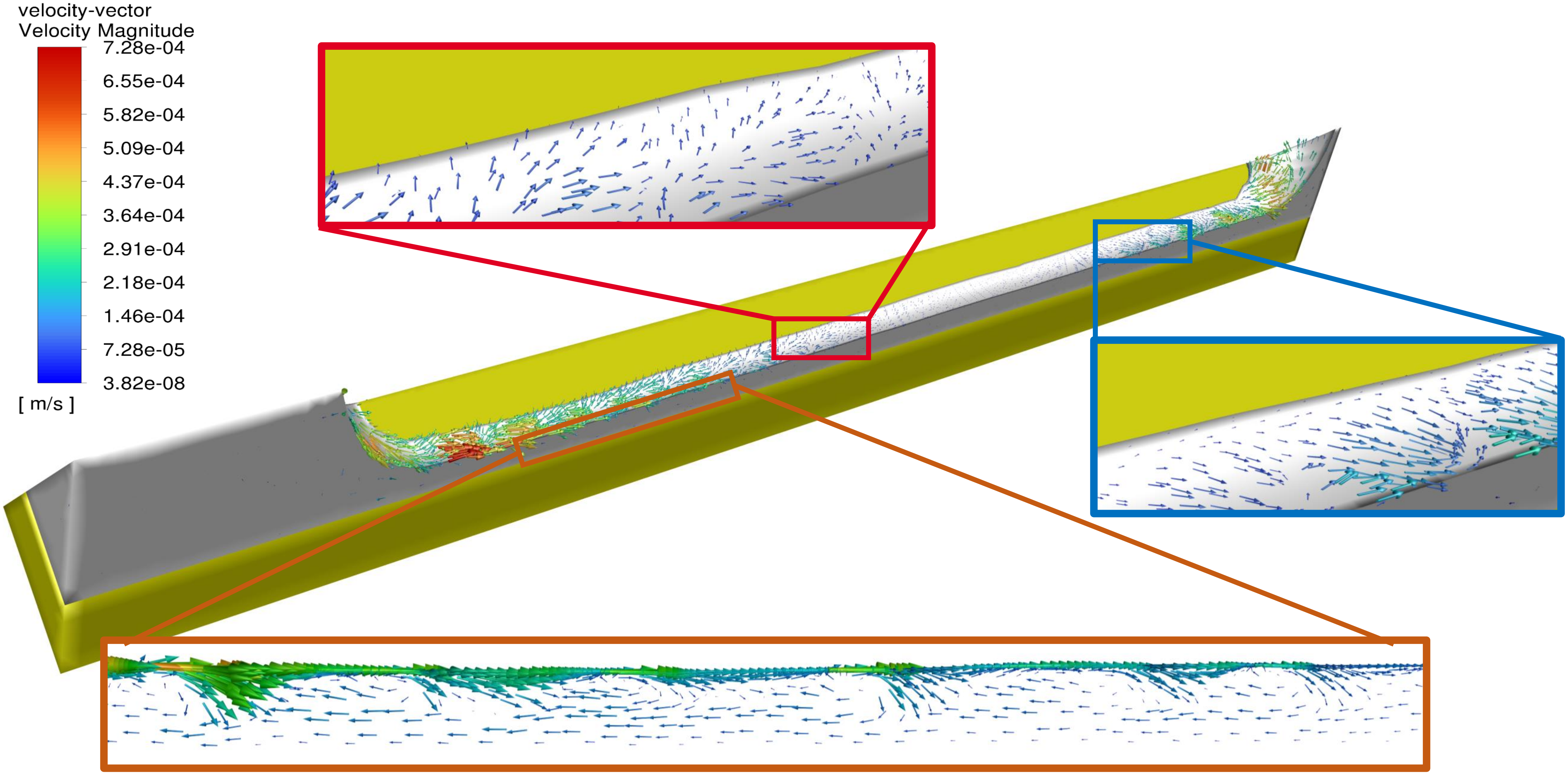

[5] Chakrabarti *et. al*, *Frontiers in Space Technologies 2023*

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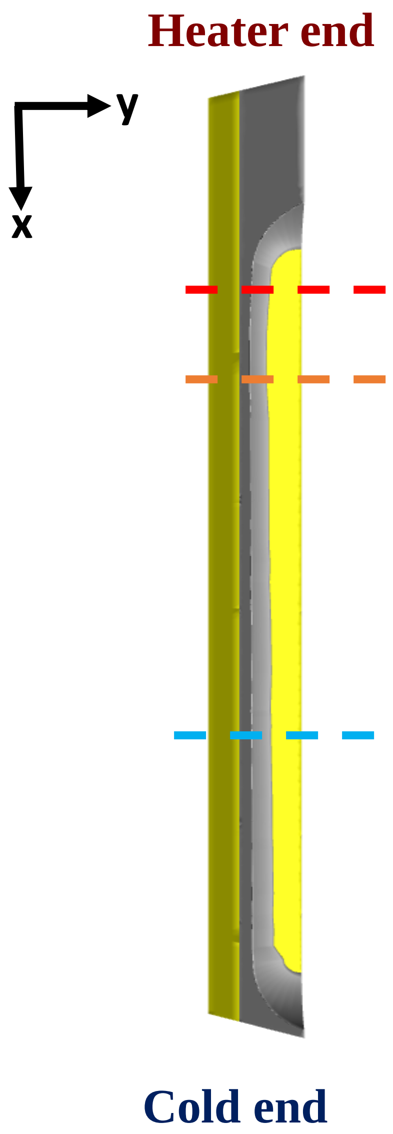

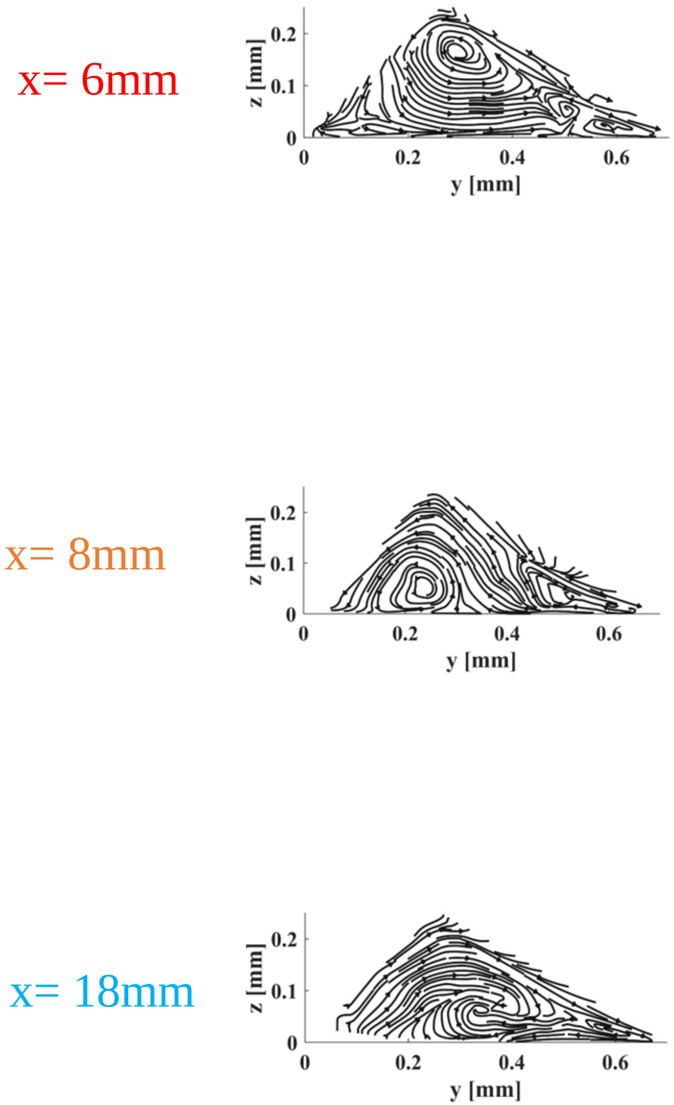

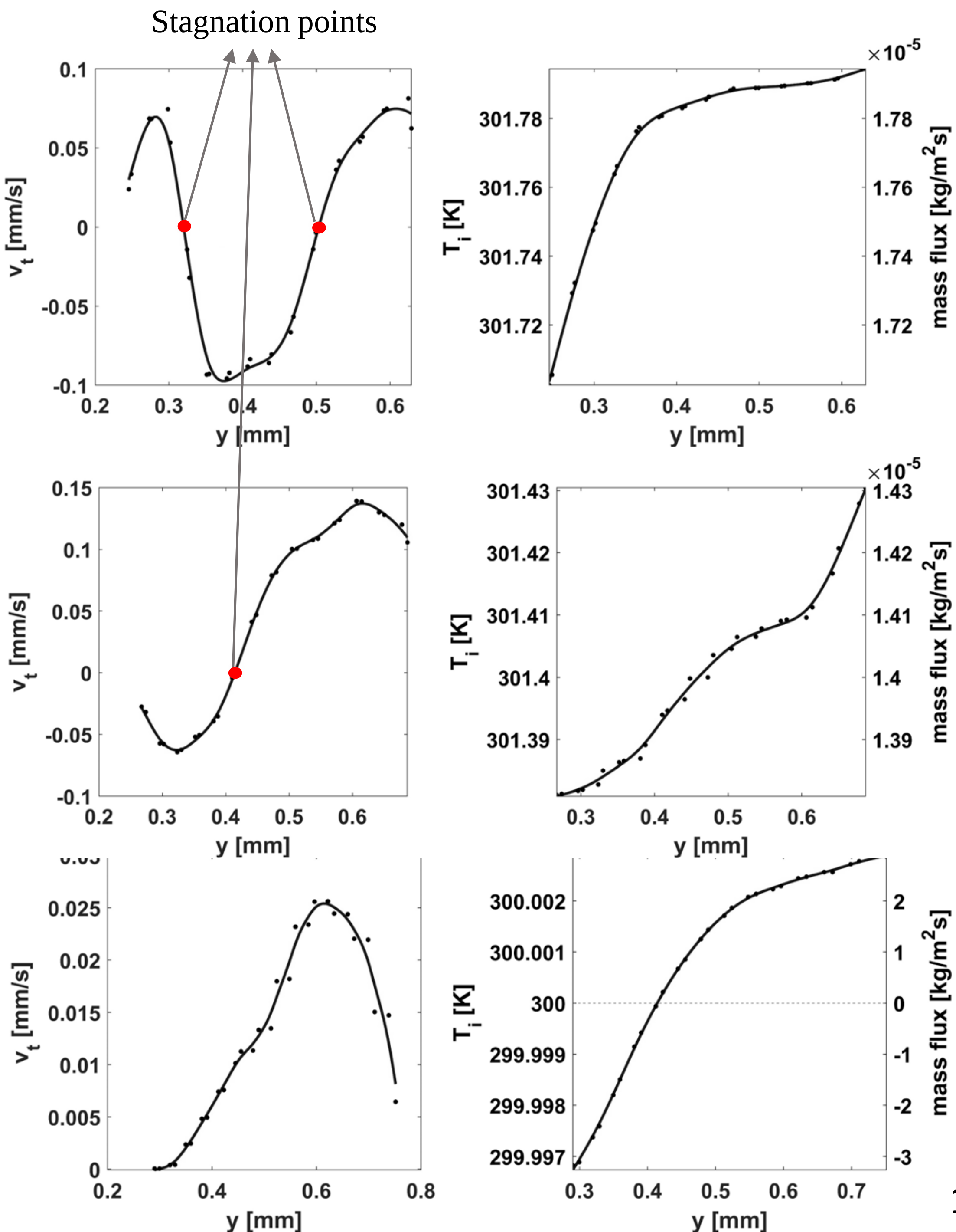

[5] Chakrabarti et. al, Frontiers in Space Technologies 2023

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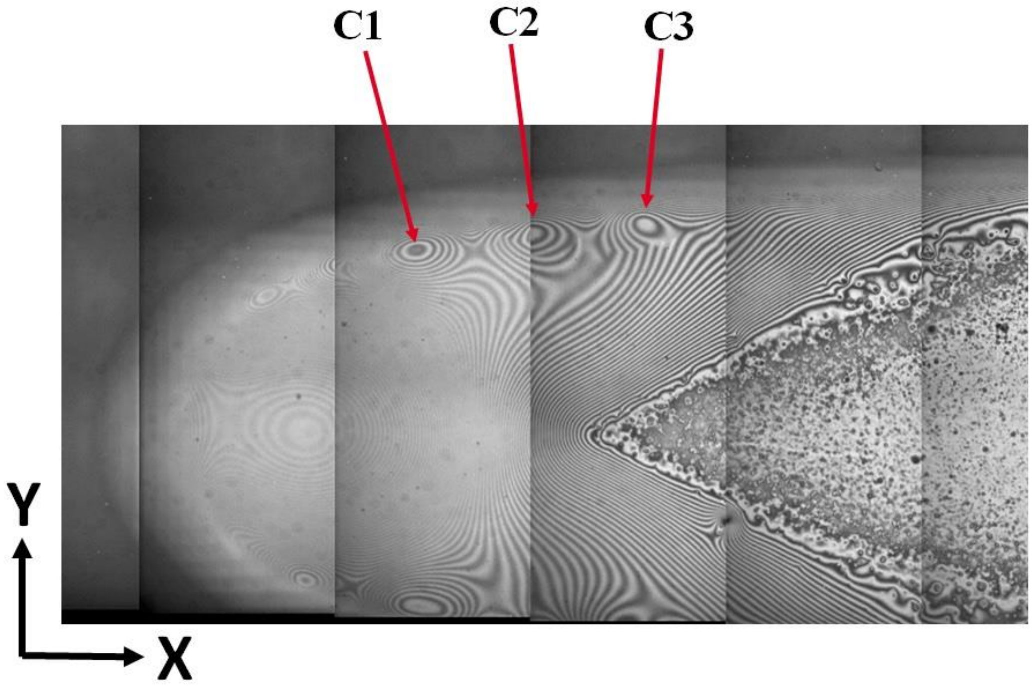

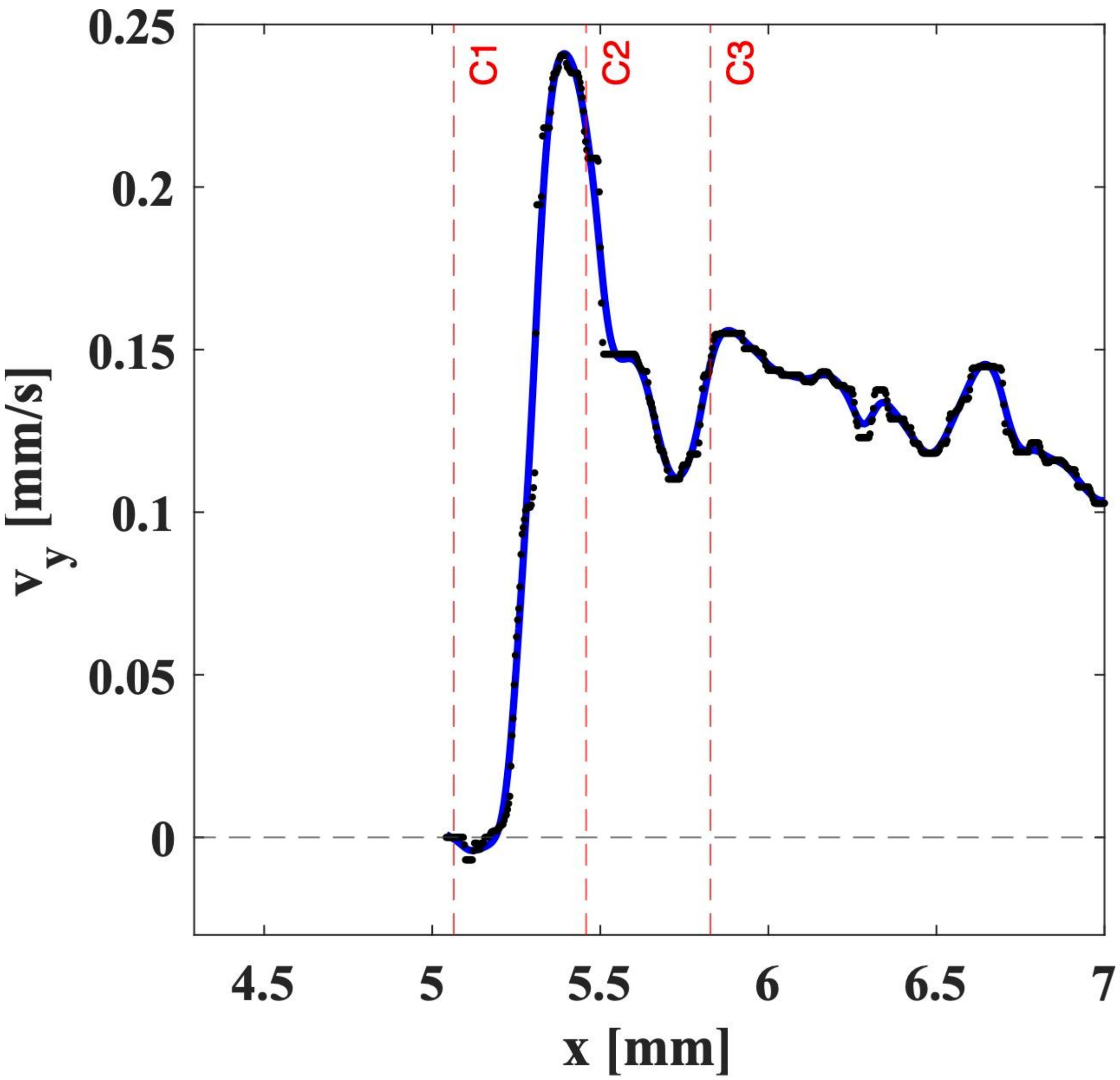

[5] Chakrabarti et. al, Frontiers in Space Technologies 2023

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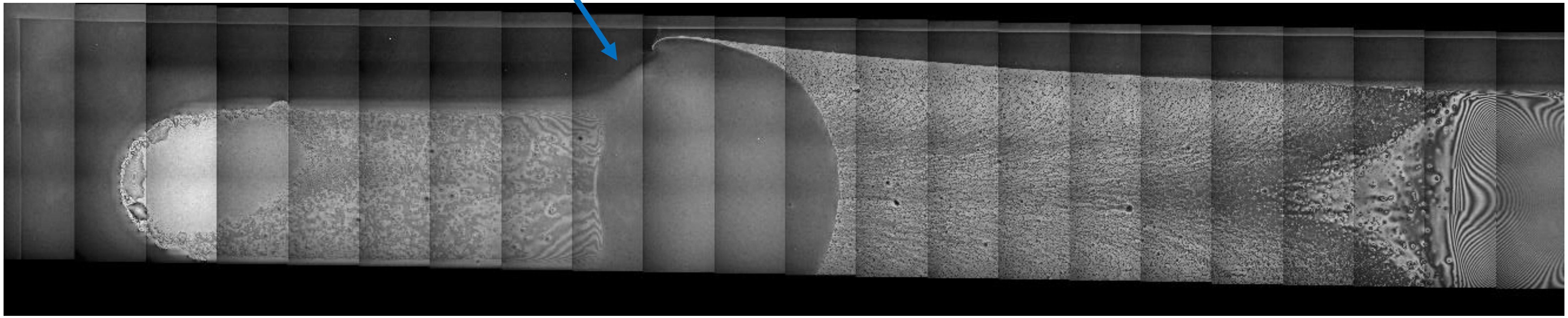


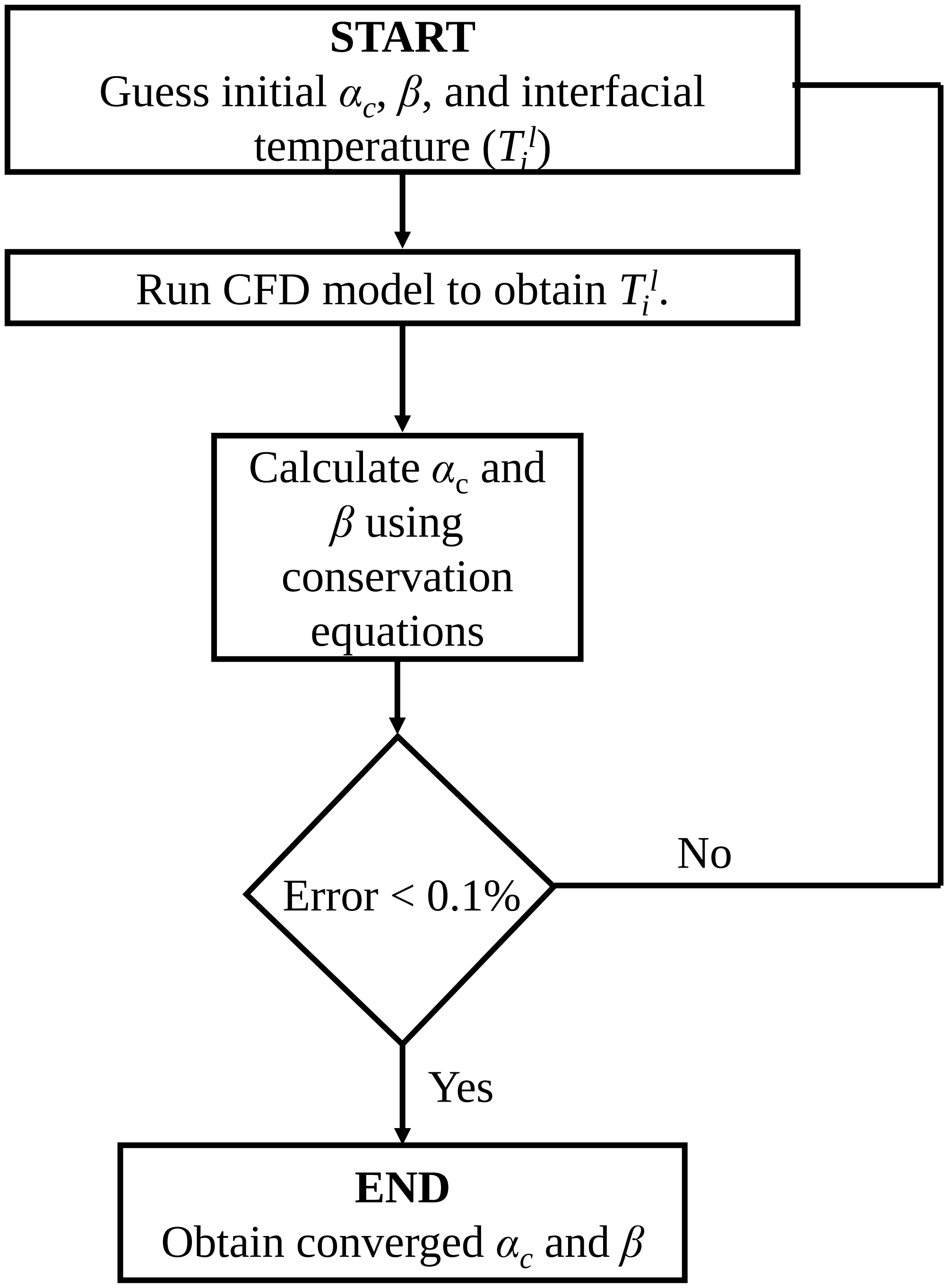
Calculation for α_c and β

$$\dot{m}'' = \left(\frac{2\alpha_c}{2-\alpha_c}\right)\frac{P_i^v}{\pi v_{mp}}\left[\beta W\sqrt{\frac{T_i^v}{T_i^l}} - 1\right]$$

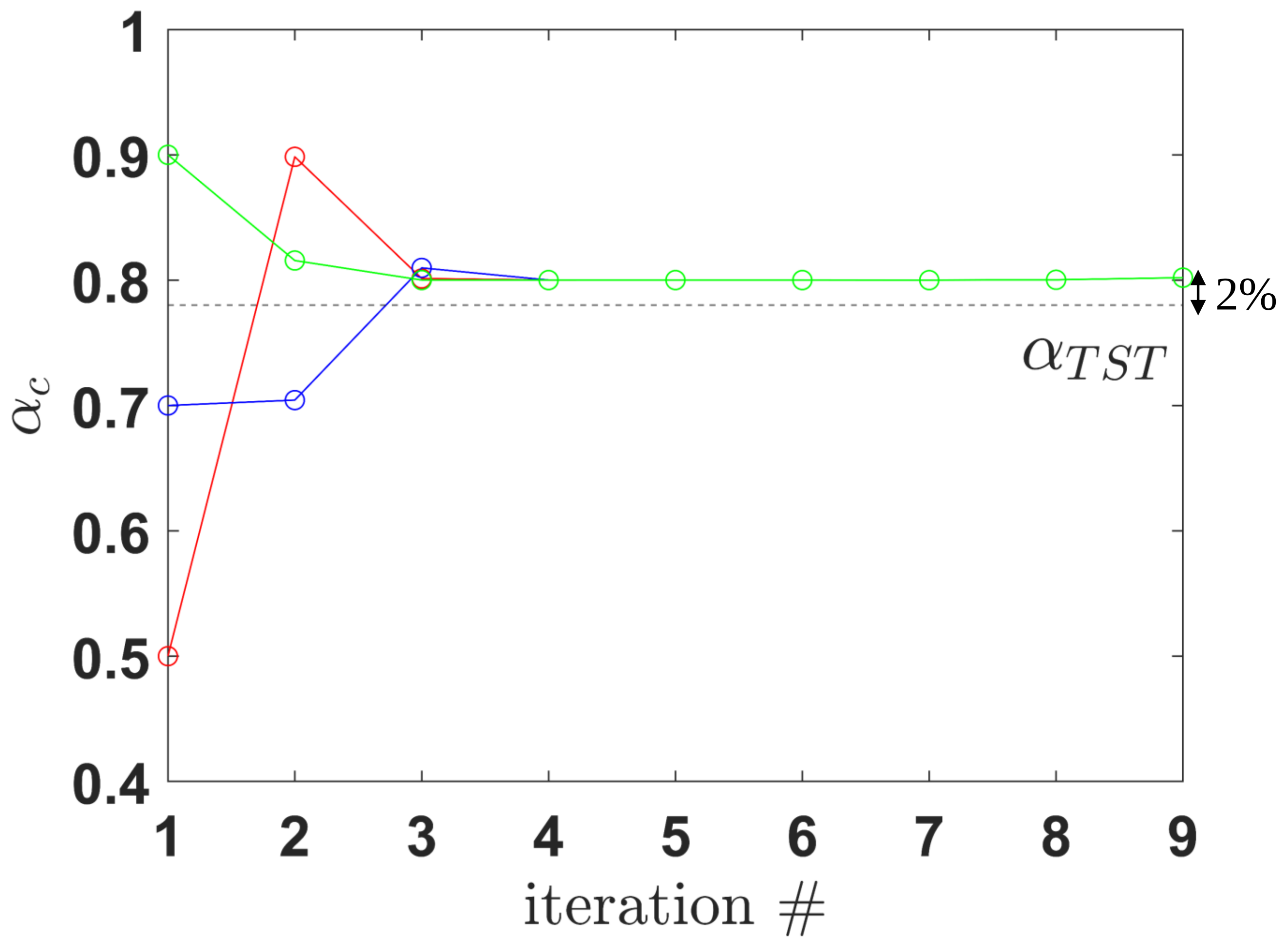
$$\beta = \frac{\alpha_e}{\alpha_c}$$

$$Q_{in}^{net} = hfg \int_{evap} \dot{m}''.dA$$

$$\int \dot{m}''.dA = 0$$



Results for α_c and β



$\alpha_c = 0.8003$, $\beta=0.9967$,
$\alpha_e = \beta\alpha_c = 0.797$

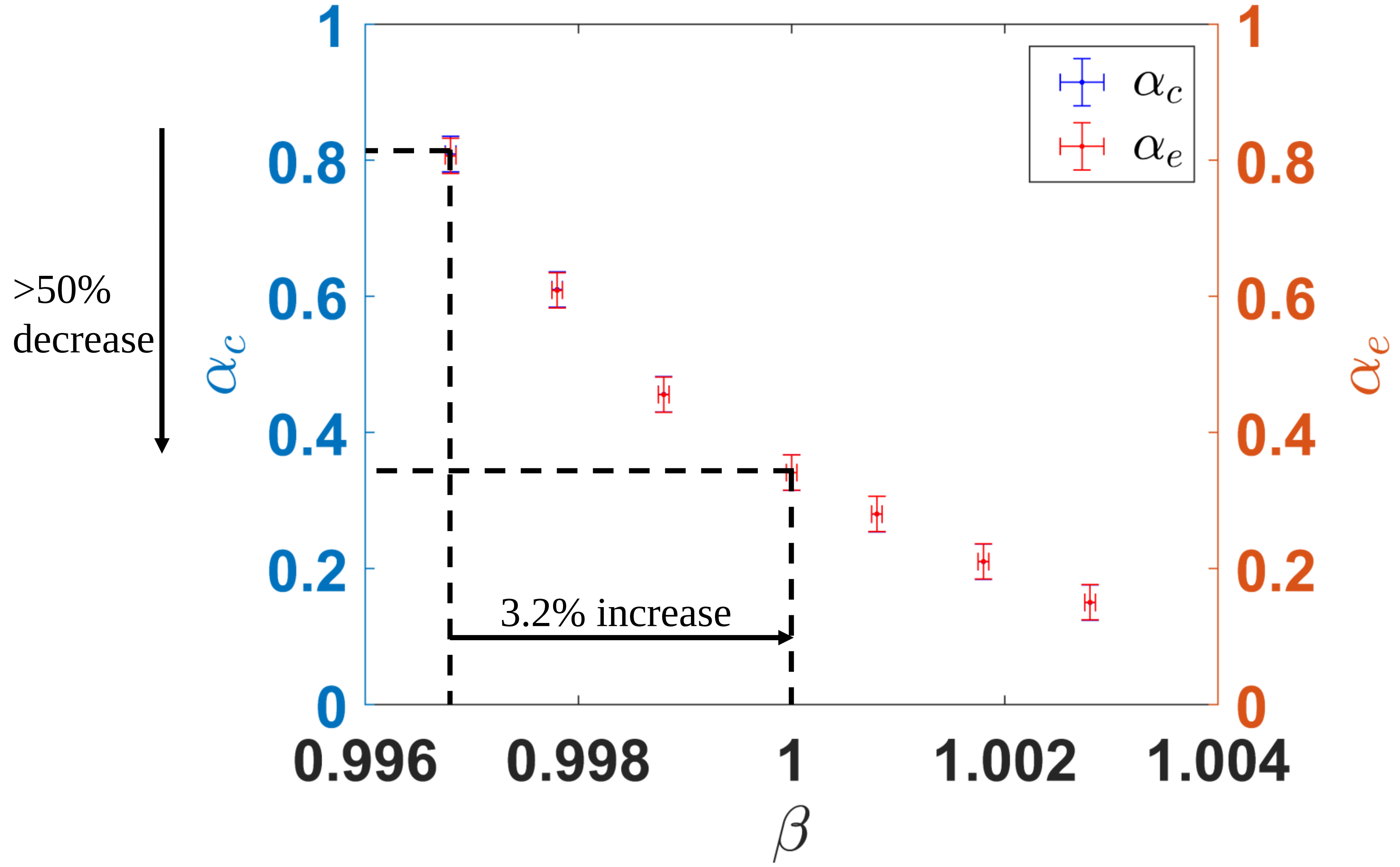
Average condensation coefficient from Transition State Theory [4]:

$$\alpha_{TST} = \left(1 - \sqrt[3]{l}\right) exp\left(-\frac{1}{2}\frac{1}{\sqrt[3]{l} - 1}\right)$$

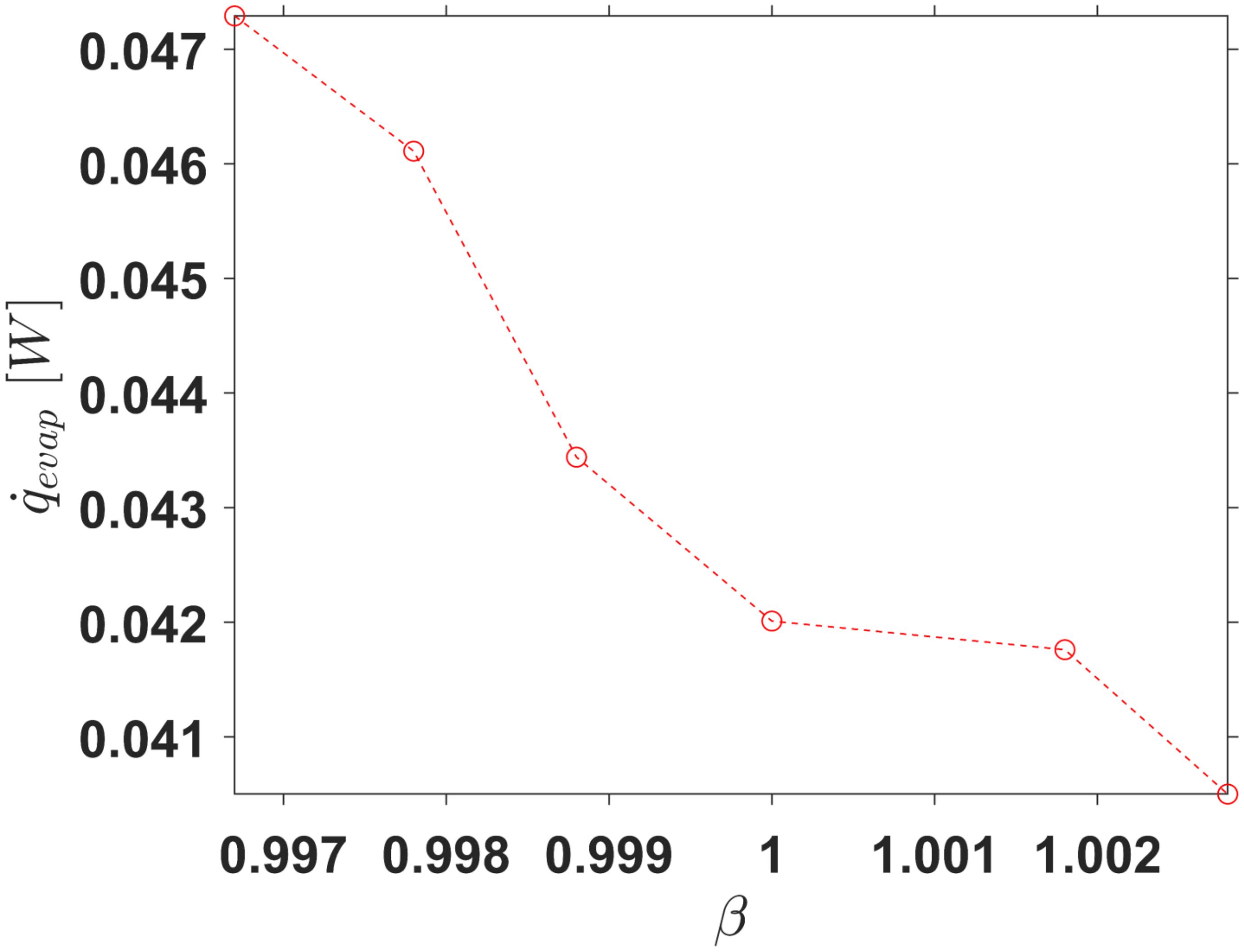
$$l = \frac{p_{sat}^{v}}{p_{sat}^{l}}$$

[7] G. Nagayama et al. Energy. 2005

Results with fixing β

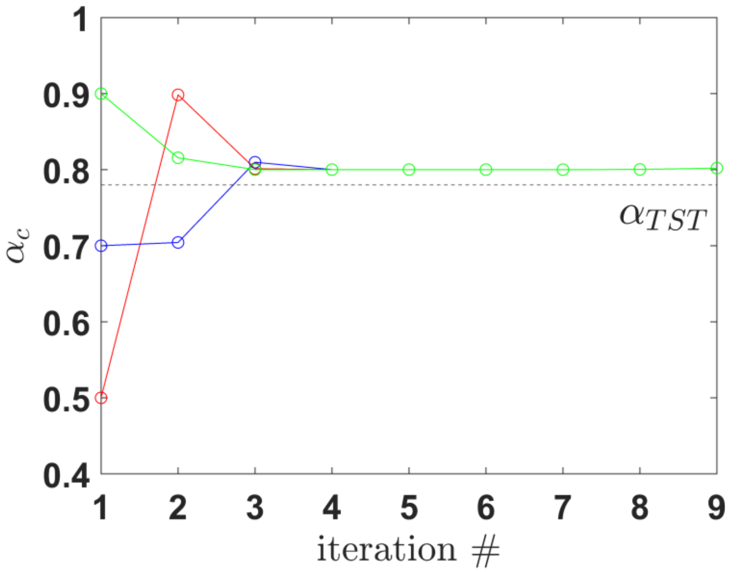


Results with fixing β

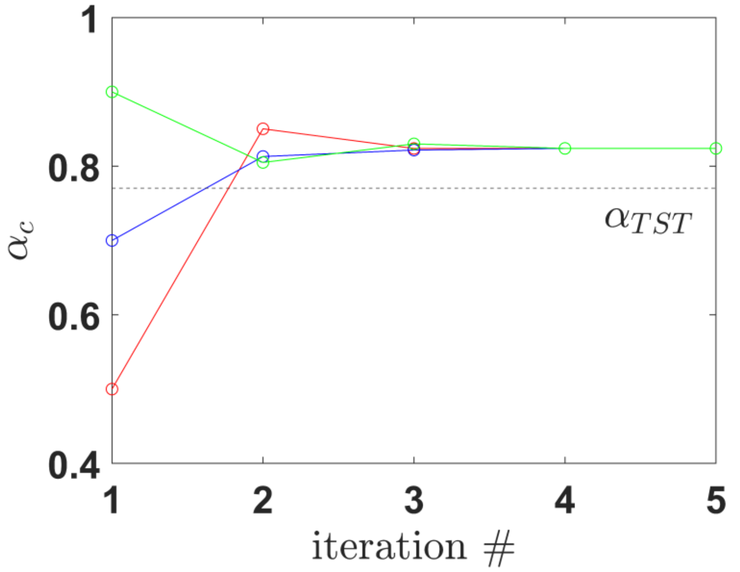


Varying heater settings

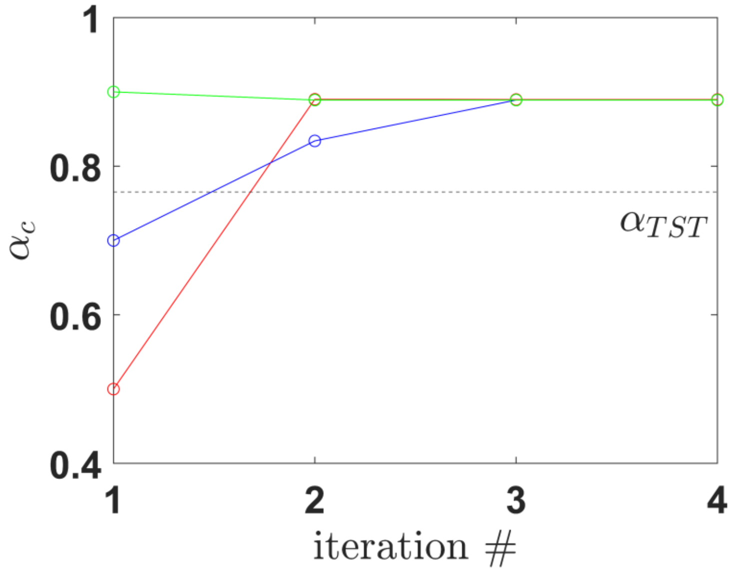
0.2 W setting



0.4 W setting



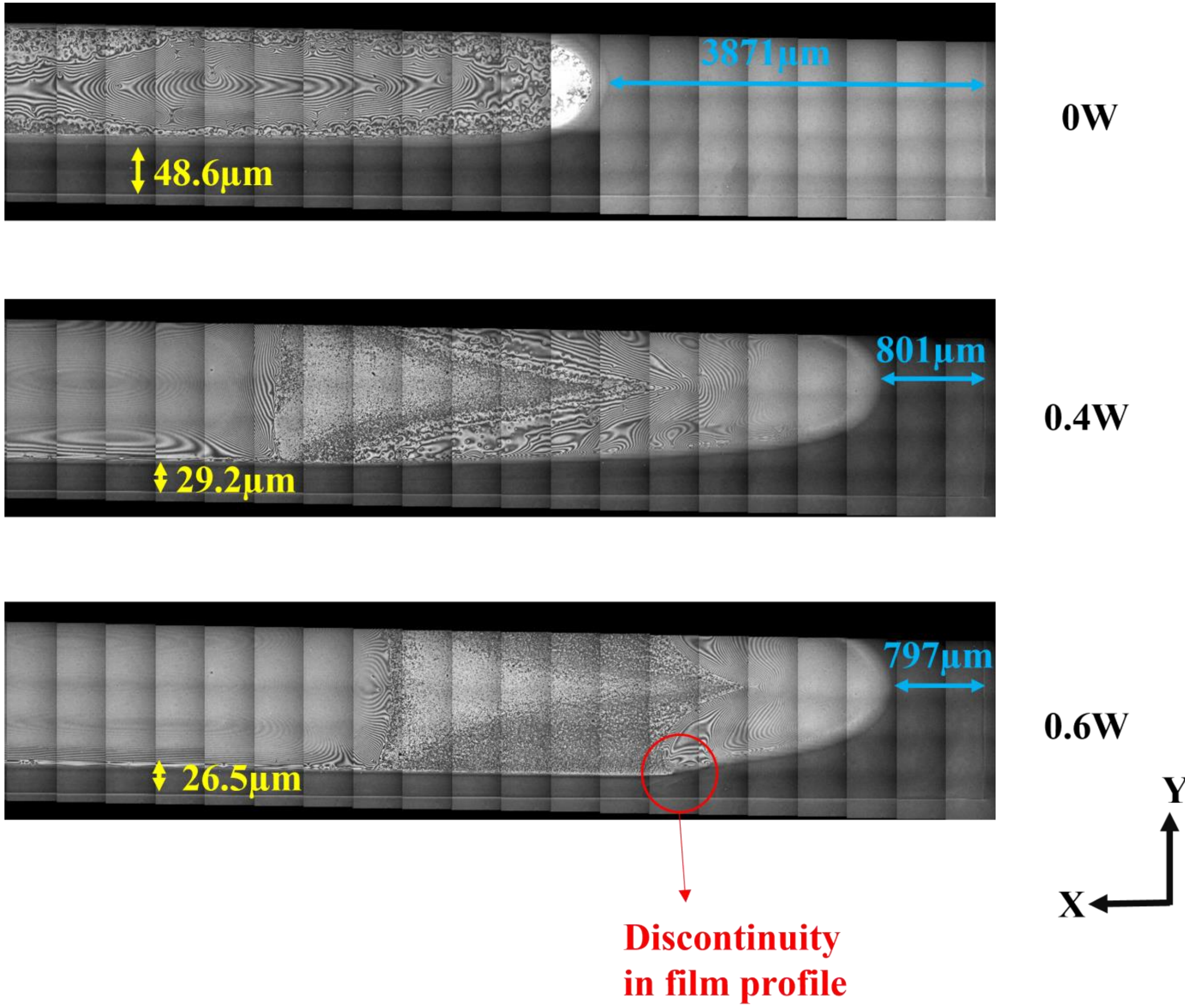
0.6 W setting



Correlation with experiments

Heater (W)	α_c	α_{TST}	%area increase	α_c^{new}
0.4	0.824	0.770	6.8	0.812
0.6	0.888	0.765	17.1	0.722

Underestimation of interfacial area → Overestimation of α_c



Summary/Conclusions

- A multiscale model for phase change during the CVB experiments shows non-uniform interfacial evaporation/condensation.
- This leads to flow recirculations as a result of Marangoni forces.
- These flow recirculations are correlated with heater-side flooding observed at higher heater settings.
- A 3.2% change in β can lead to errors >50% for the calculation of the evaporation and condensation coefficients.

Acknowledgements

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