Computational modelling of droplet evaporation with an improved Coupled Level Set and Volume of Fluid (i-CLSVoF) framework

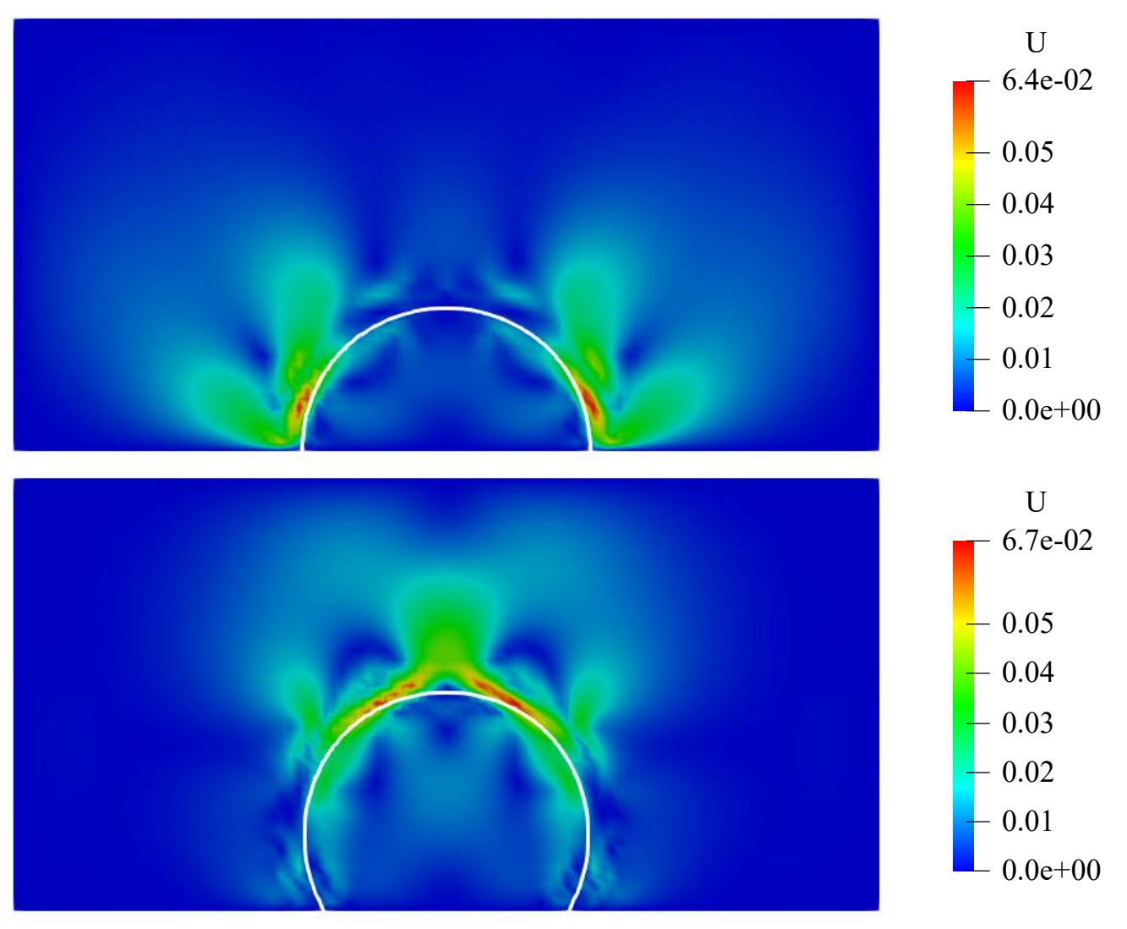
Huihuang Xia*, Marc Kamlah

Introduction

- Surface-tension-dominant droplet evaporation is ubiquitous and of importance to many applications [1].
- Un-physical spurious velocities destabilize the numerical simulations and affect the internal flow [2].

Motivation

- Capturing sharp interface and suppressing the un-physical velocities.
- Computational modelling of droplet evaporation subjected to three different evaporation models [3].



Governing equations

$$\nabla \cdot \mathbf{U} = \dot{m}\left(\frac{1}{\rho_g} - \frac{1}{\rho_l}\right)$$

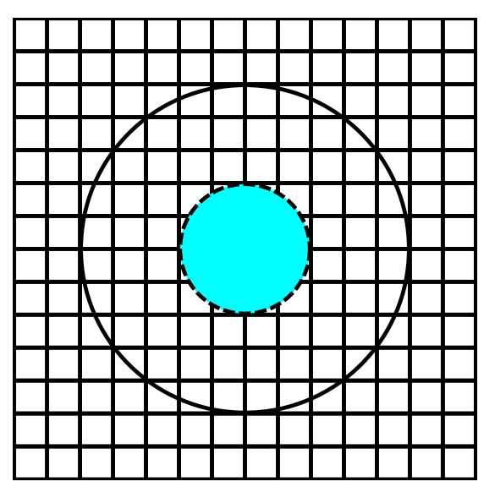
$$\frac{\partial(\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathbf{U}) = -\nabla p + \nabla \cdot [\mu(\nabla \mathbf{U} + (\nabla \mathbf{U})^T)] + \rho \boldsymbol{g} + \mathbf{F}_{st}$$

$$\frac{\partial \alpha_l}{\partial t} + \nabla \cdot (\alpha_l \mathbf{U}_\Gamma) = \alpha_l \nabla \cdot \mathbf{U}_\Gamma$$

$$\frac{\partial(\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p \mathbf{U} T) = \nabla \cdot (k \nabla T) - \dot{m} h_{ev} + \left[\frac{\partial(\rho c_p)}{\partial t} + \nabla \cdot (\rho c_p \mathbf{U})\right] T$$

$$\frac{\partial Y}{\partial t} + \nabla \cdot (Y \mathbf{U}) = D_v \nabla^2 Y$$

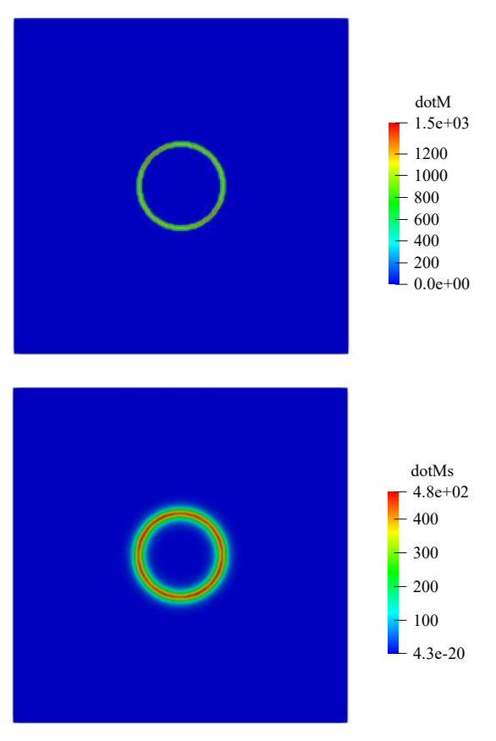
model	I	II	III
J	const.	$\frac{T-T_{sat}}{R_{int} h_{ev}}$	$\frac{\rho_g D_v \nabla^\Gamma Y \mathbf{n}^\Gamma}{1-Y^\Gamma}$



$$\begin{cases} a\phi + \nabla^2 \phi = \dot{m}\left(\frac{1}{\rho_g} - \frac{1}{\rho_l}\right) \\ \mathbf{U}_s = \nabla \phi \end{cases}$$

$$\mathbf{U}_e = \mathbf{U} - \mathbf{U}_s$$

$$\mathbf{U}_\Gamma = \mathbf{U}_e - \frac{J}{\rho_l}\mathbf{n}$$

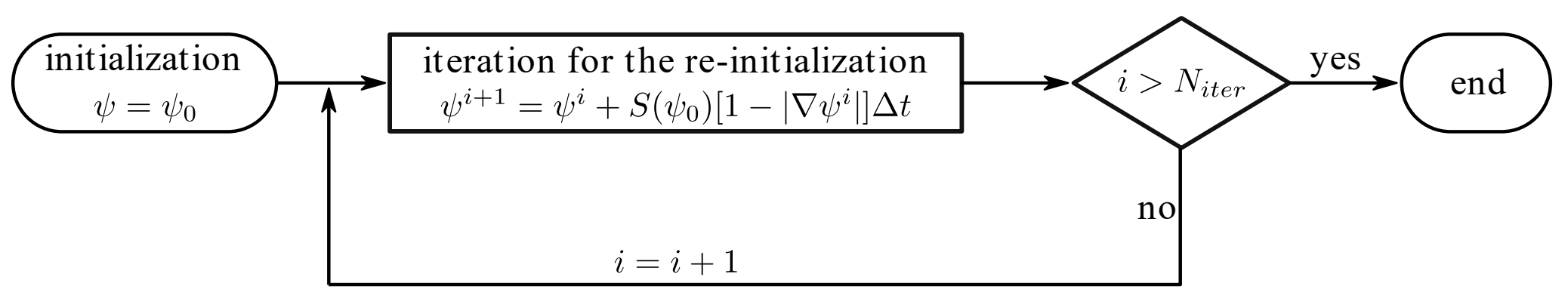


$$\dot{m} = J|\nabla \alpha_l|$$

$$\dot{m}_s = \dot{m} + (\Delta x N)^2 \Delta \dot{m}_s$$

Numerical method

- Coupling LS to VoF



- The improved surface-tension model with filtering steps [2,4]

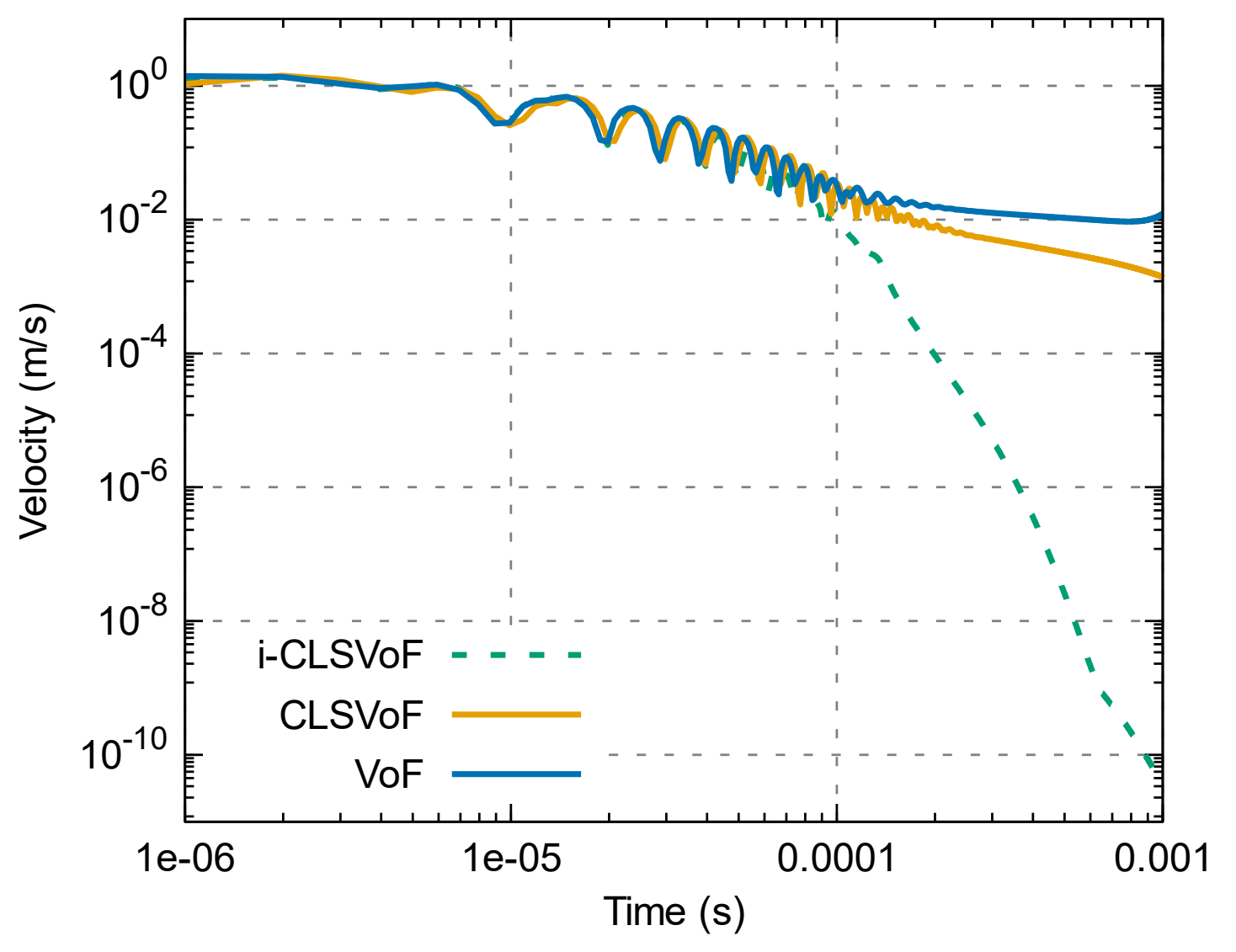
$$\mathbf{F}_{st} = \sigma K(\psi) \nabla H_\psi$$

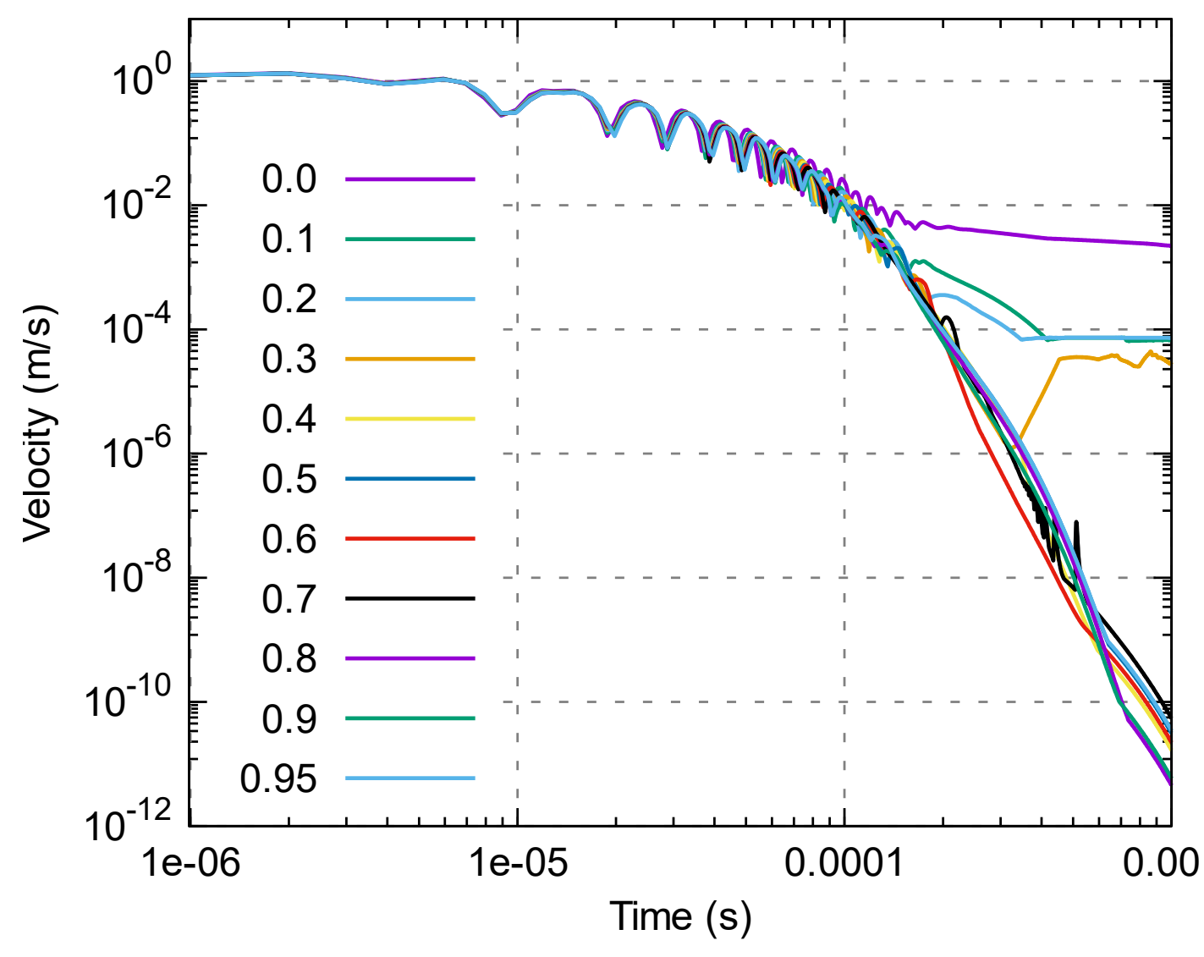
OpenFOAM®

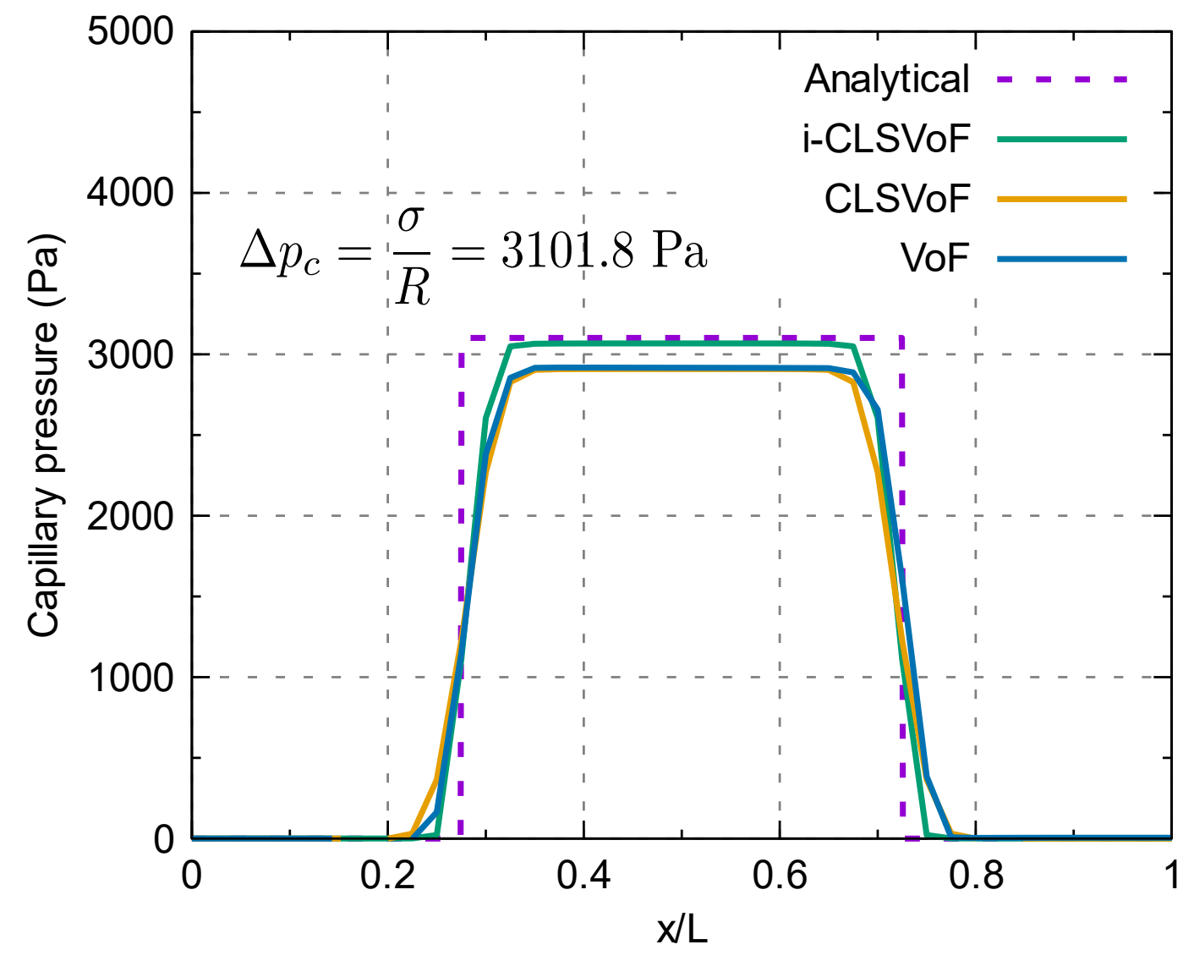
$$F^f_{st,f} = F_{st,f} - \frac{\delta_{st}}{|\delta_{st}| + \delta_n}\left(R_f(F^{filt}_{st,f})_{i-1} + C_{fc}\left\langle \nabla p_{st} - (\nabla p_{st} \cdot \mathbf{n}_s)\mathbf{n}_s \right\rangle_f \cdot \mathbf{n}_f\right)$$

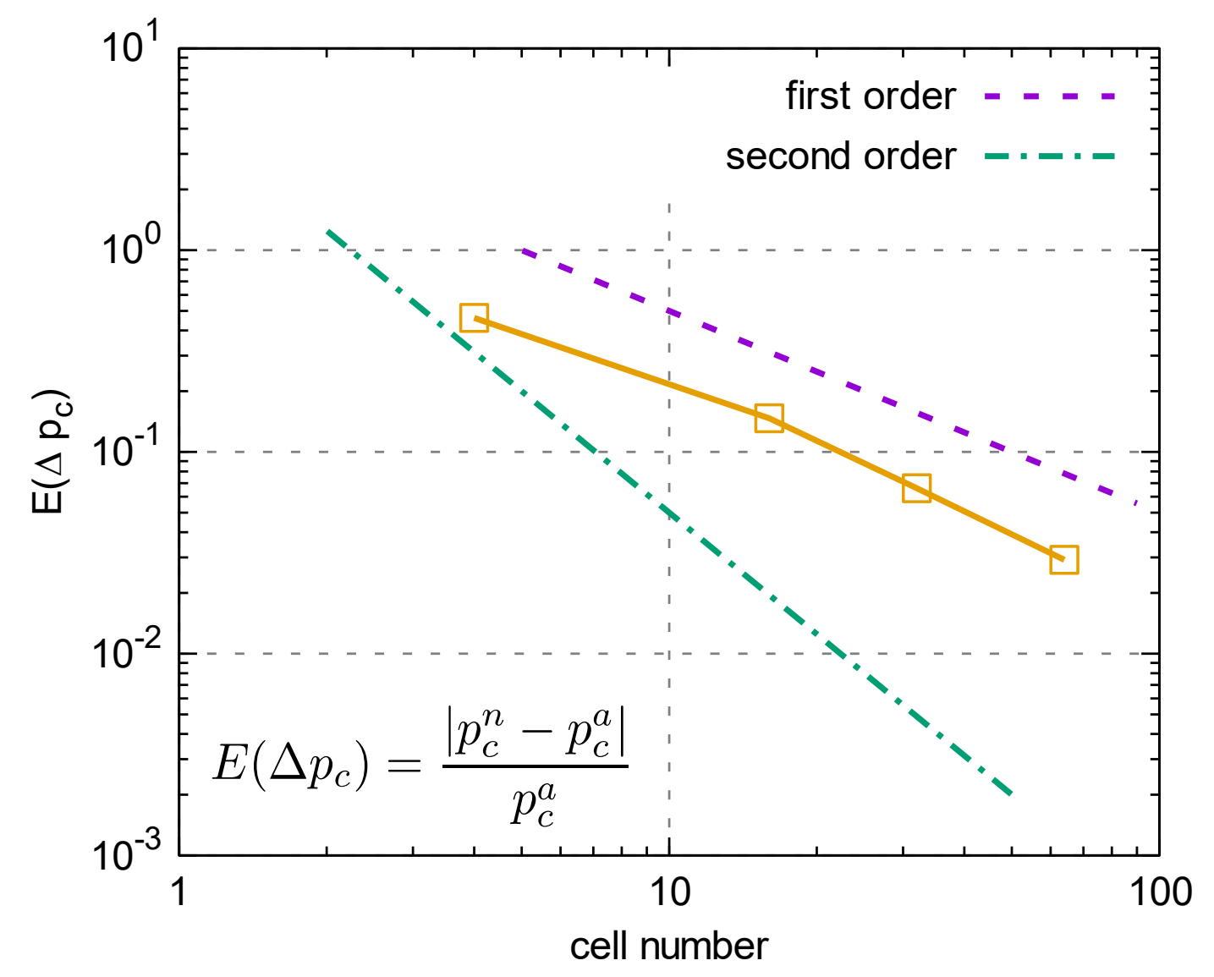
Results

- Suppression of the un-physical spurious velocities with the i-CLSVoF framework [5]



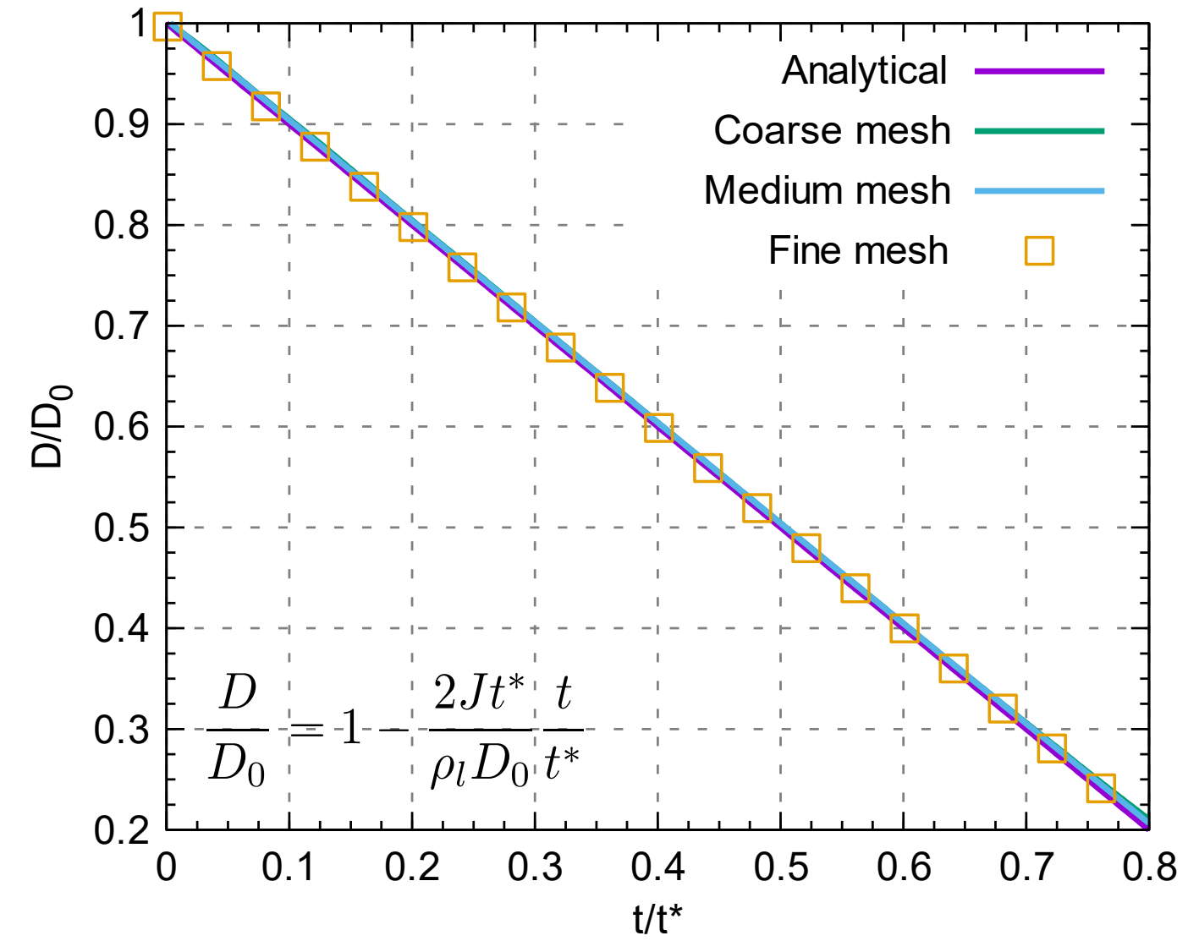


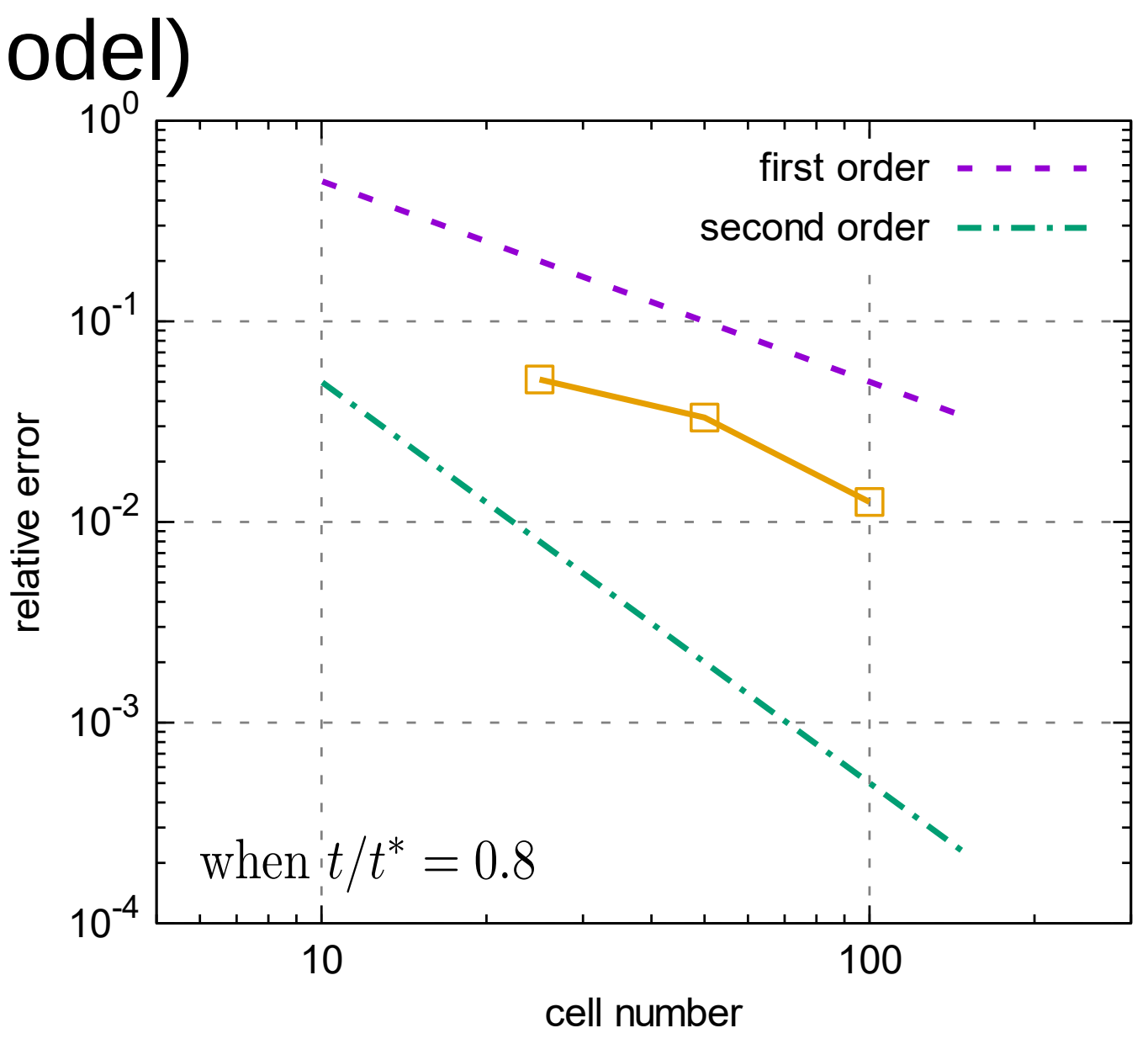


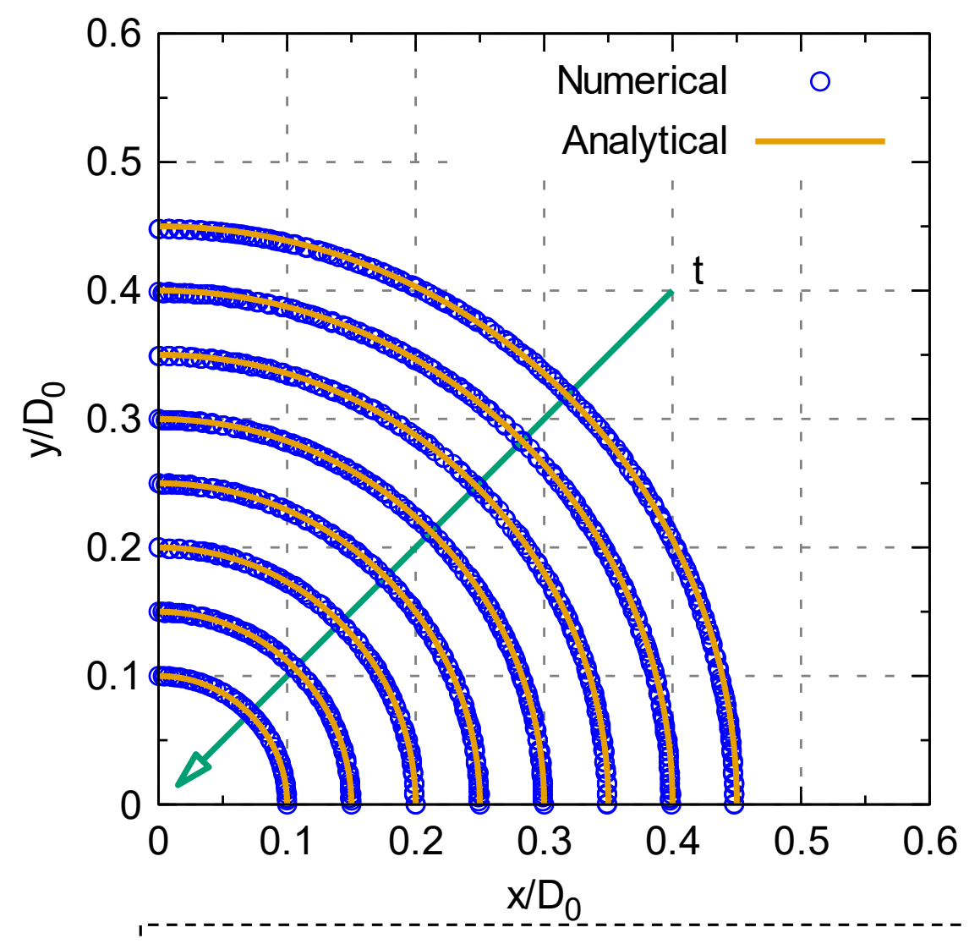


- Validation of the evaporation models [5]

❑ Model I (the constant mass flux model)







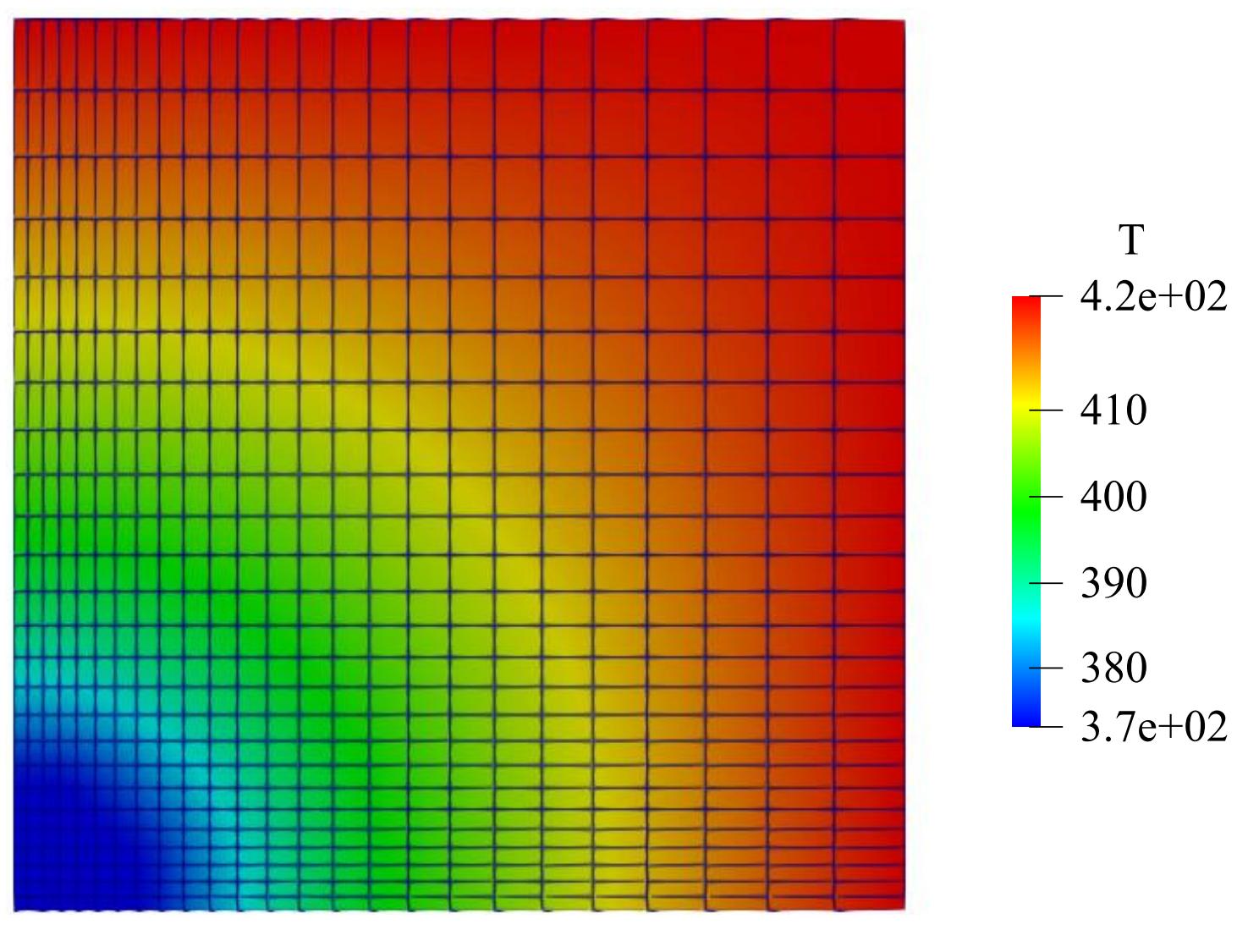
Summary

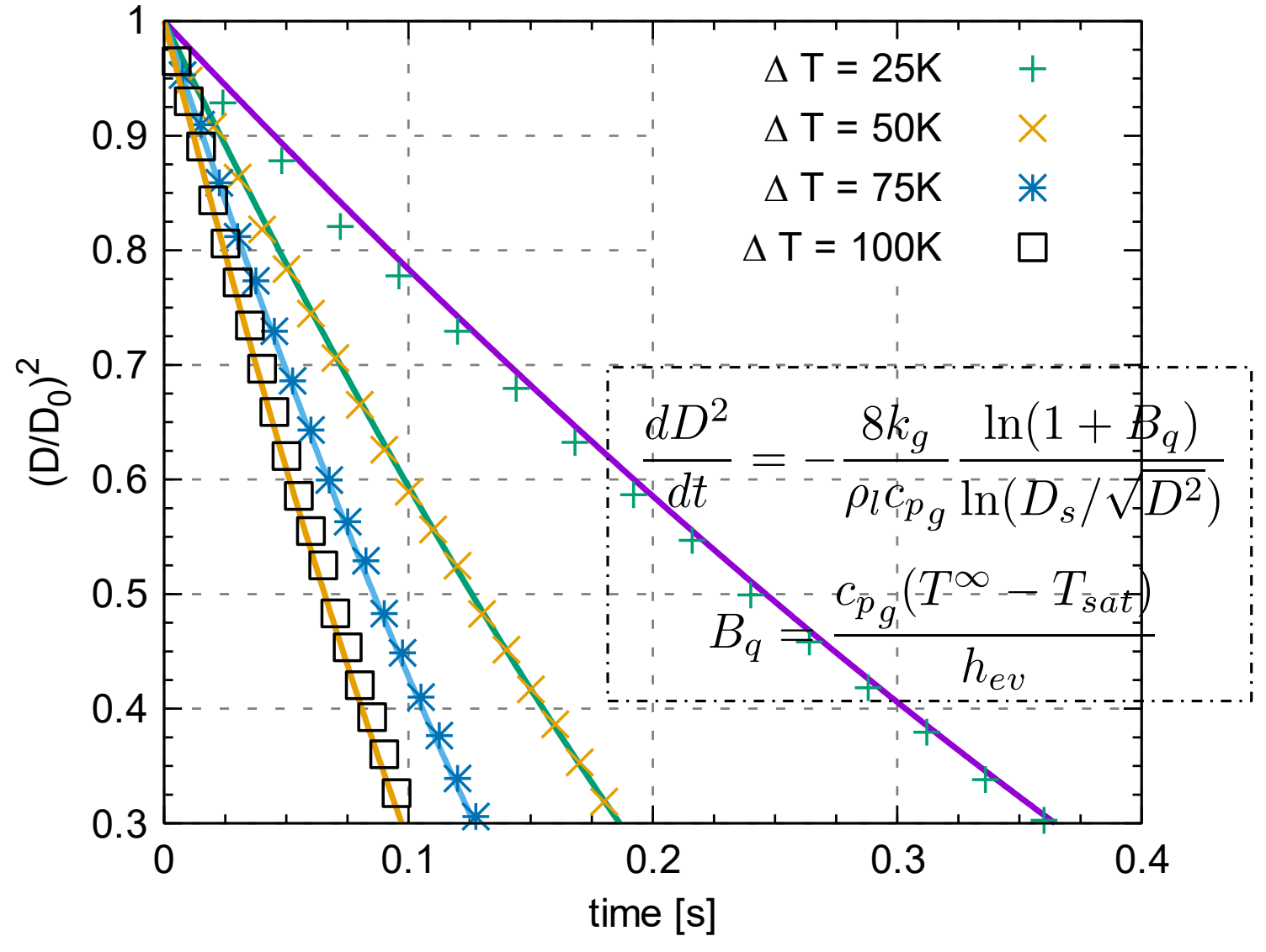
- ❑ Development and implementation of the i-CLSVoF framework in OpenFOAM.
- ❑ Droplet evaporation is accurately predicted for up to 80% of the total evaporation time.
- ❑ Validations of three different evaporation models.

Outlook

- ❑ Evaporation with contact line pinning.
- ❑ Coupling to Discrete Element Method (DEM).

❑ Model II (the thermally driven evaporation model)

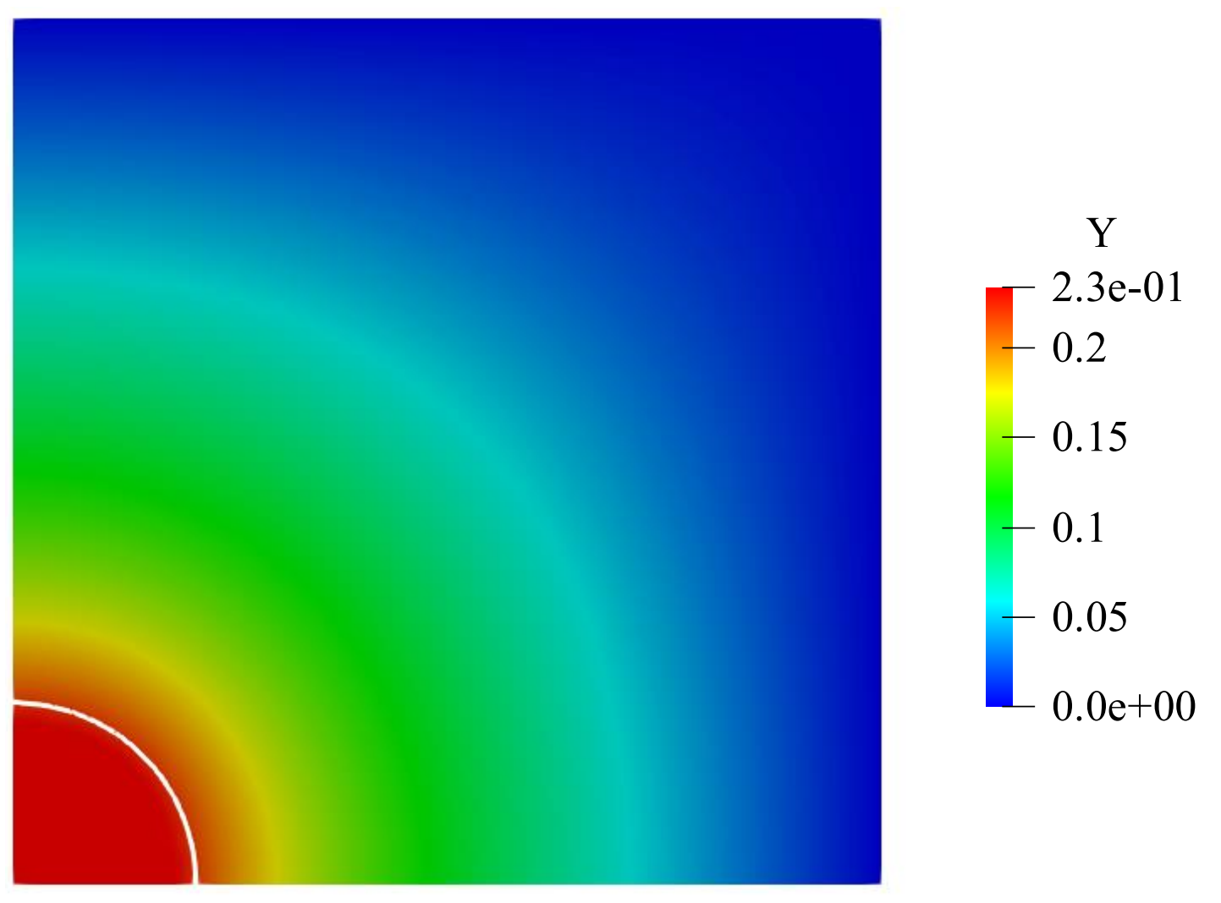


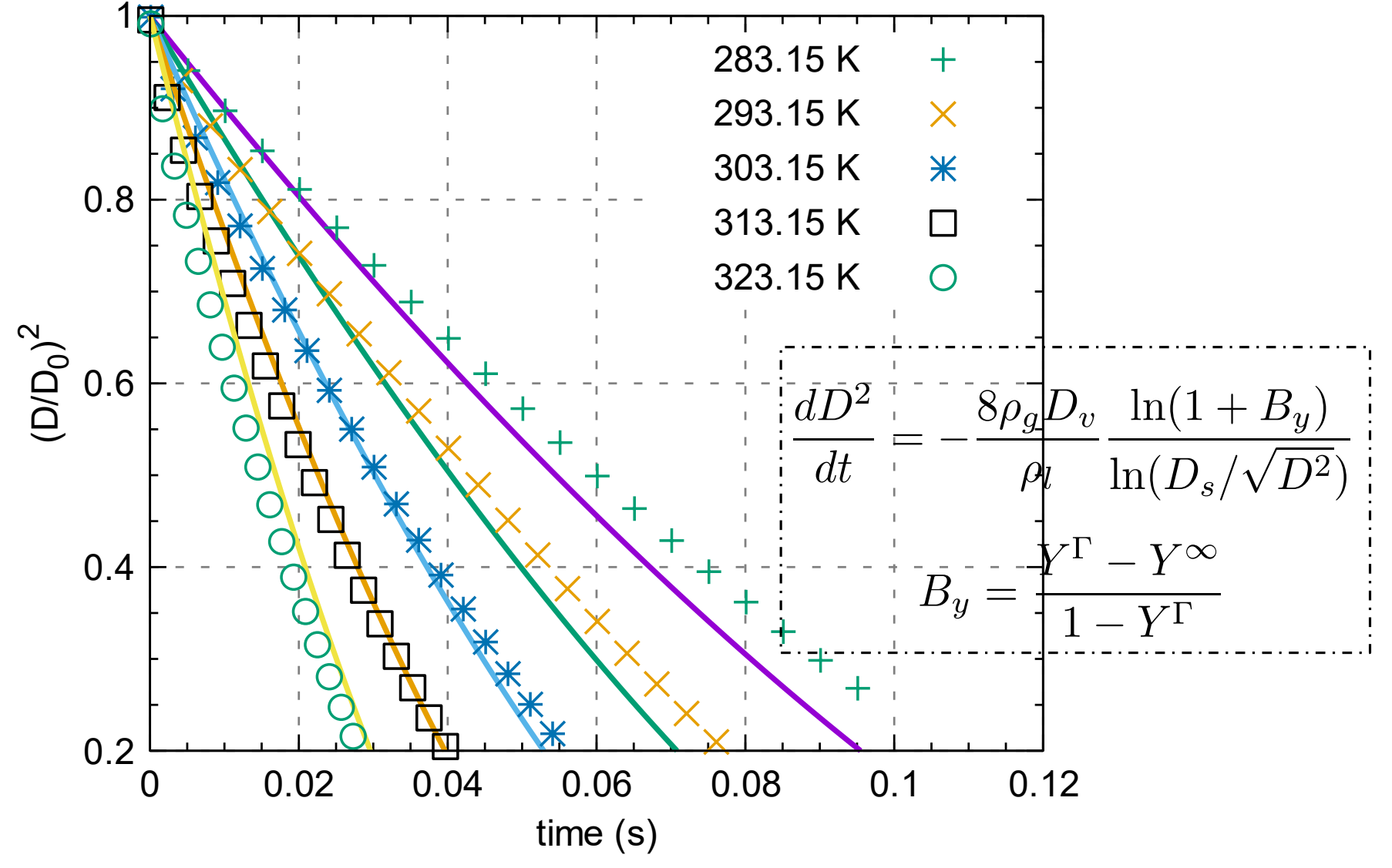


$$\frac{dD^2}{dt} = -\frac{8k_g}{\rho_l c_{p_g}} \frac{\ln(1 + B_q)}{\ln(D_s/\sqrt{D^2})}$$

$$B_q = \frac{c_{p_g}(T^\infty - T_{sat})}{h_{ev}}$$

❑ Model III (droplet evaporation at room temperature)





$$\frac{dD^2}{dt} = -\frac{8\rho_g D_v}{\rho_l} \frac{\ln(1 + B_y)}{\ln(D_s/\sqrt{D^2})}$$

$$B_y = \frac{Y^\Gamma - Y^\infty}{1 - Y^\Gamma}$$

References

[1] Zang, D., et al. (2019). Phys Rep 804: 1-56.
[2] Raeini, A. Q., et al. (2012). J Comput Phys 231(17): 5653-5668.
[3] Irfan, M., et al. (2017). J Comput Phys 337: 132-153.
[4] Yokoi, K. (2014). J Comput Phys 278: 221-228.
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Corresponding author

- ❑ Huihuang Xia
- ❑ huihuang.xia@kit.edu

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