Simulation of the Coalescence and Subsequent Mixing of Inkjet Printed Droplets

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Introduction

Coalescence of droplets is a widely investigated phenomenon. However, little is known on the coalescence and internal mixing of droplets smaller than a millimeter, common in e.g. inkjet printing.

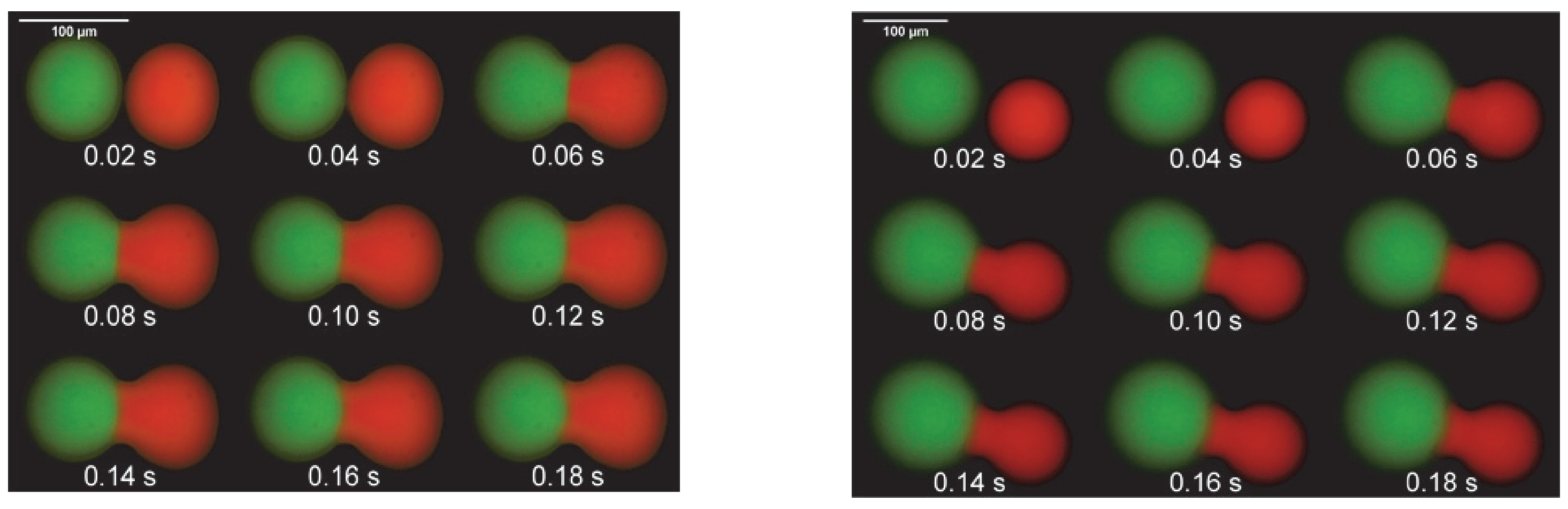

Figure 1. Montage of coalescing inkjet printed droplets containing different fluorescent dyes with volume ratios **(a)**1:1 and **(b)** 4:1.

In this investigation, we study the time evolved coalescence and subsequent mixing of inkjet printed droplets with different volume and composition both experimentally and simulated with Comsol Multiphysics. Special interest is taken in distinguishing the material flow due to the coalescence and diffusion based material flow due to a concentration gradient just after coalescence.

Methods

Experimental methods

Diethyleneglycol-dimethacrylate containing 0.1wt% fluorescent dyt (D_{ab}=2·10-11 m^2/s) is inkjet printed on glass slides in volume ratios 1:1 up to 4:1 (20 pl to 80 pl). Coalescence is initiated by UV-light and tracked in time.

Computational methods

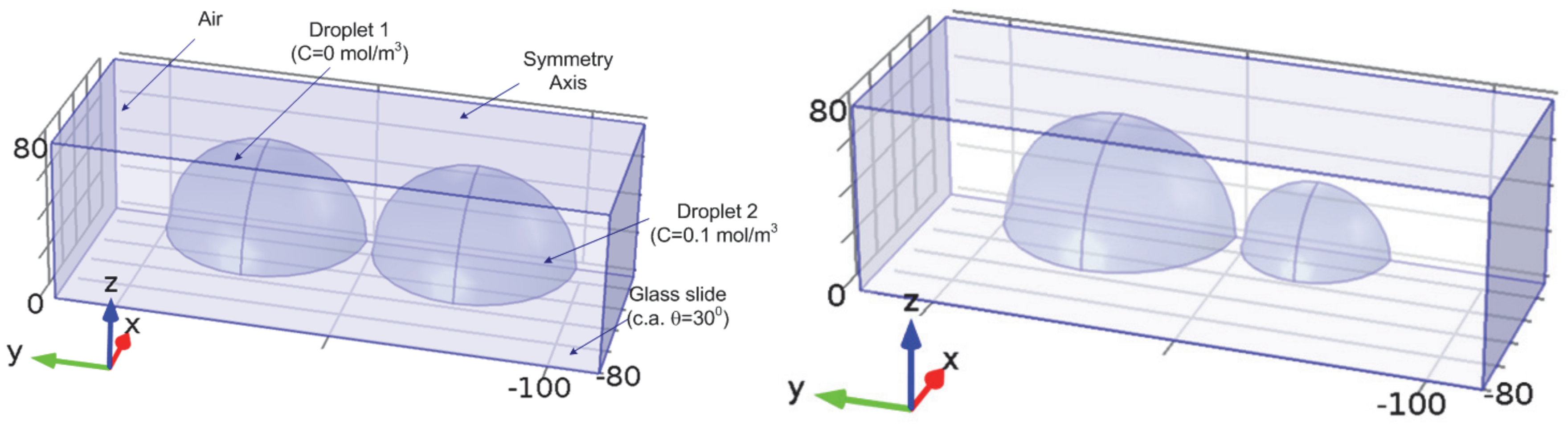

Figure 2. Geometry for droplets with volume ratio 1:1 **(a)** and 4:1**(b)**. Small droplet is filled with 0.1 mol/m^3 dye (distances in µm).

The Laminar Two-Phase Flow (Phase field) is used to track the interface of the two droplets and Transport of Diluted species is used to track the concentration of the dye during coalescence.

Model equations are Navier Stokes (1) for the interface, and Mass Transport balance (2) for the dye transport. For equal sized droplets equation (2) can be simplified to Fick's Law of diffusion (3) in the length of the droplet, describing the concetration ratio as function of time (t) and position (x).

$$\rho\frac{\delta u}{\delta t}+\rho\left(u\cdot\nabla\right)u=-\nabla p+\eta\left(\nabla\cdot u\right)+F_g \qquad (1)$$

$$\frac{\delta C}{\delta t}+\left(u\cdot\nabla C\right)-D_{AB}\nabla^2 C=0 \quad (2) \quad \Rightarrow \text{Volume ratio 1:1} \Rightarrow \frac{C}{C_0}=\frac{x}{2\sqrt{\pi\cdot D_{AB}\cdot t}}\exp\left(\frac{-\left(x\right)^2}{4\cdot D_{AB}\cdot t}\right) \qquad (3)$$

Results

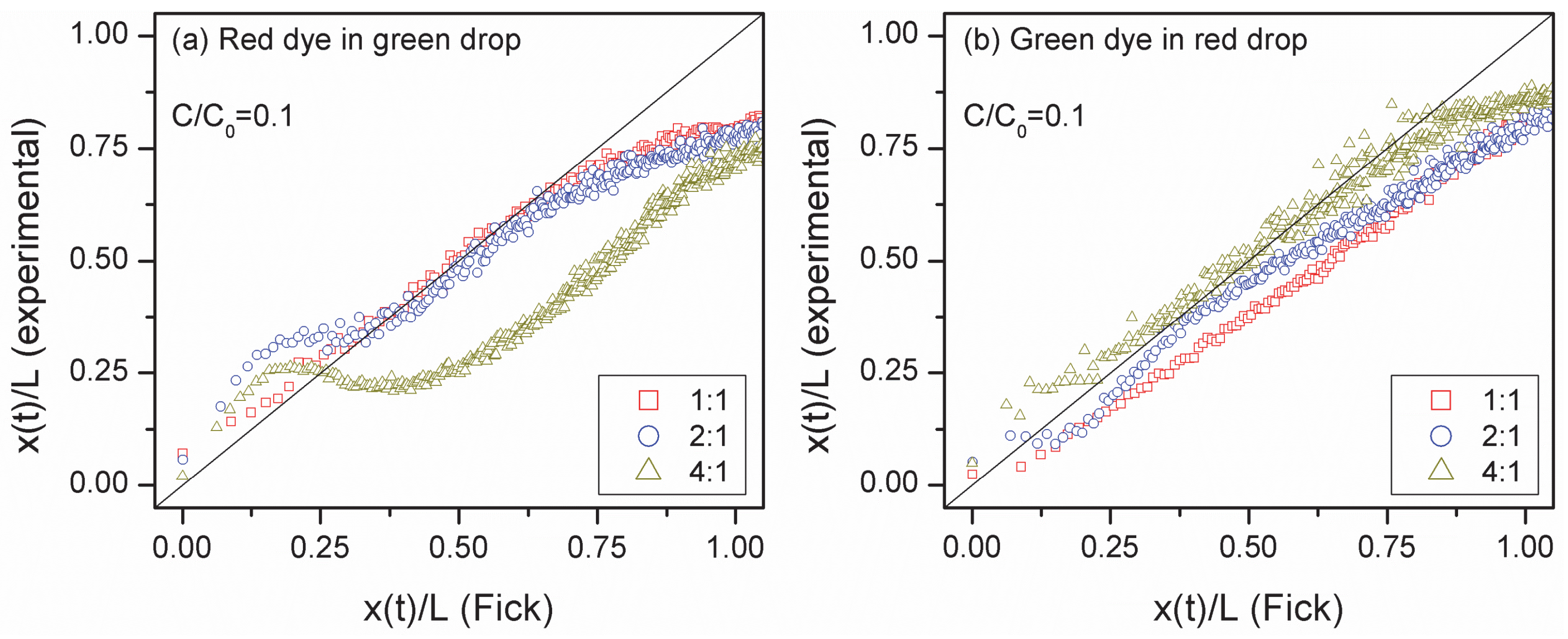

Figure 3. Experimental results of the mixing process, showing the normalized distance x/L(t) for C/C$_0$=0.1 of the dye, compared to expected distance according to Fick's Law of diffusion. (x= position of C/C$_0$ in droplet, L=size of original (red of green) droplet).

Figure 3 shows the experimental results of the dye transport due to convection and diffusion. As expected for volume ratio 1:1, x/L(t) follows Fick's Law. For larger volume ratios, convection plays an important role, especially in t<10 ms (x/L<0.25).

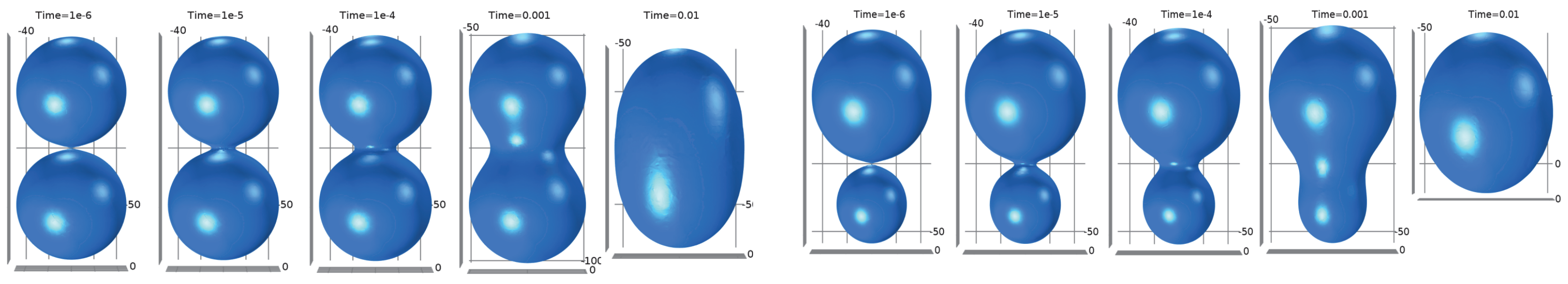

Figure 4. Comsol Multiphysics simulation of the coalescence for volume ratios 1:1 and 4:1

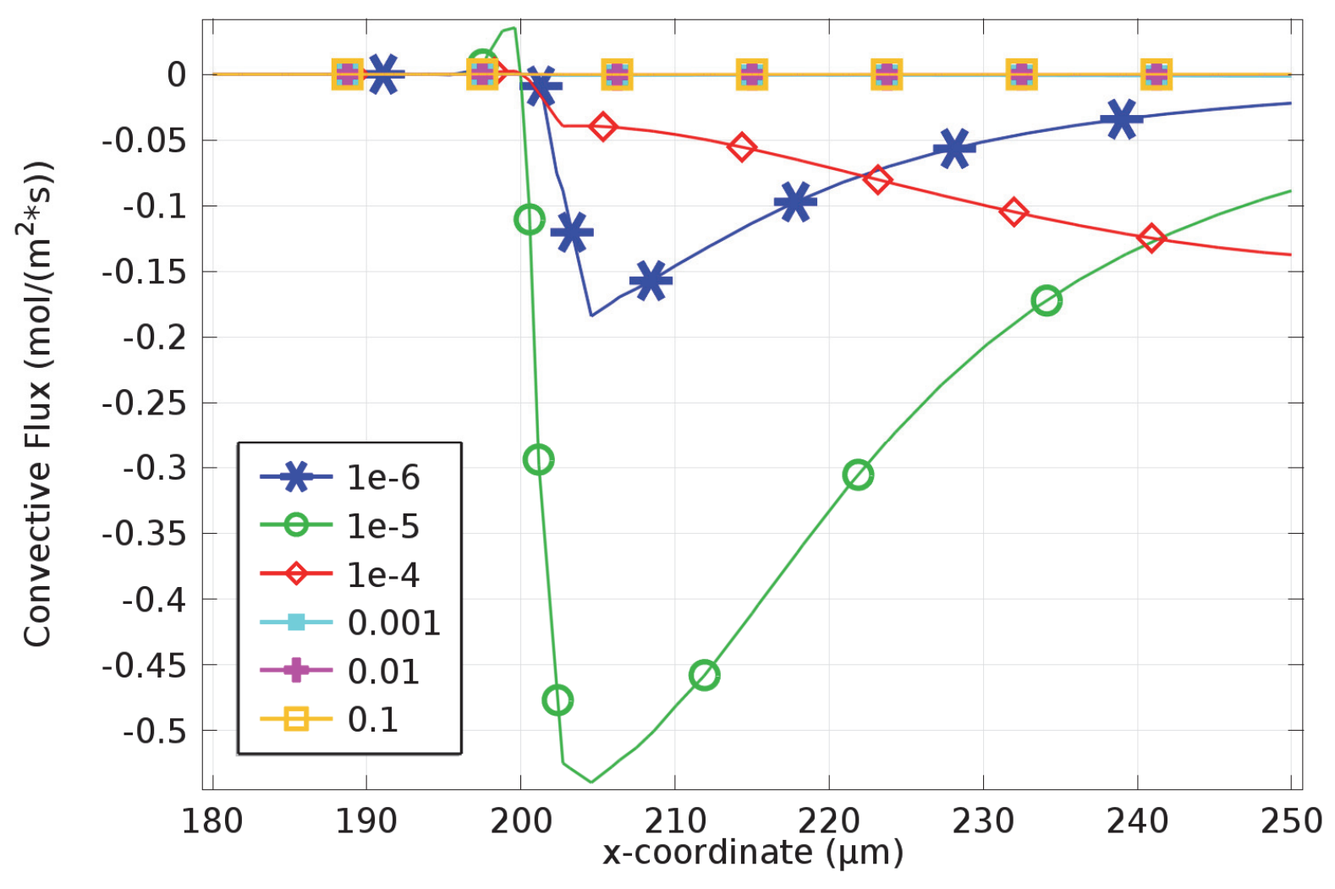

Figure 5. Convective flux (volume ratio 1:1)

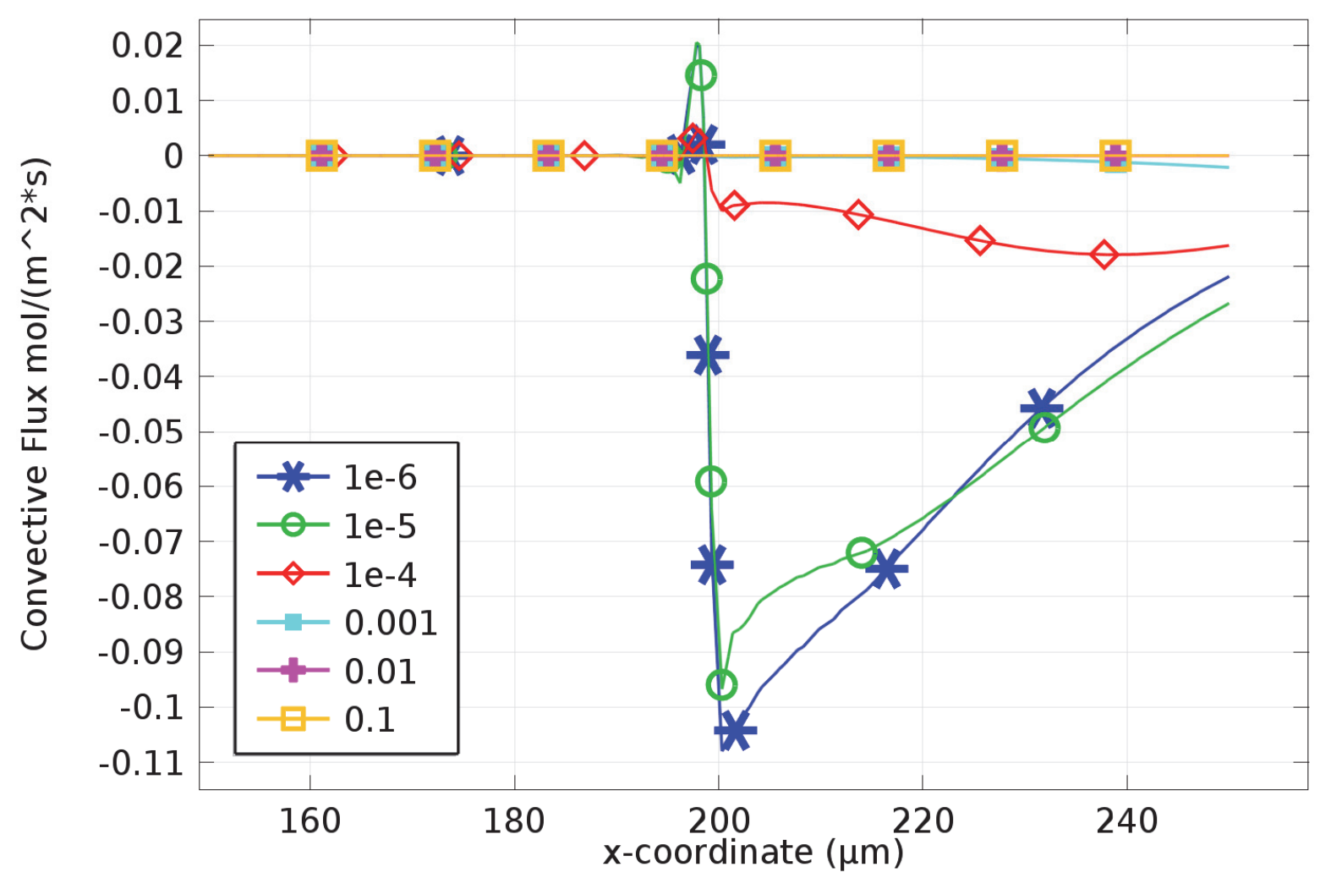

Figure 6. Convective flux (volume ratio 4:1)

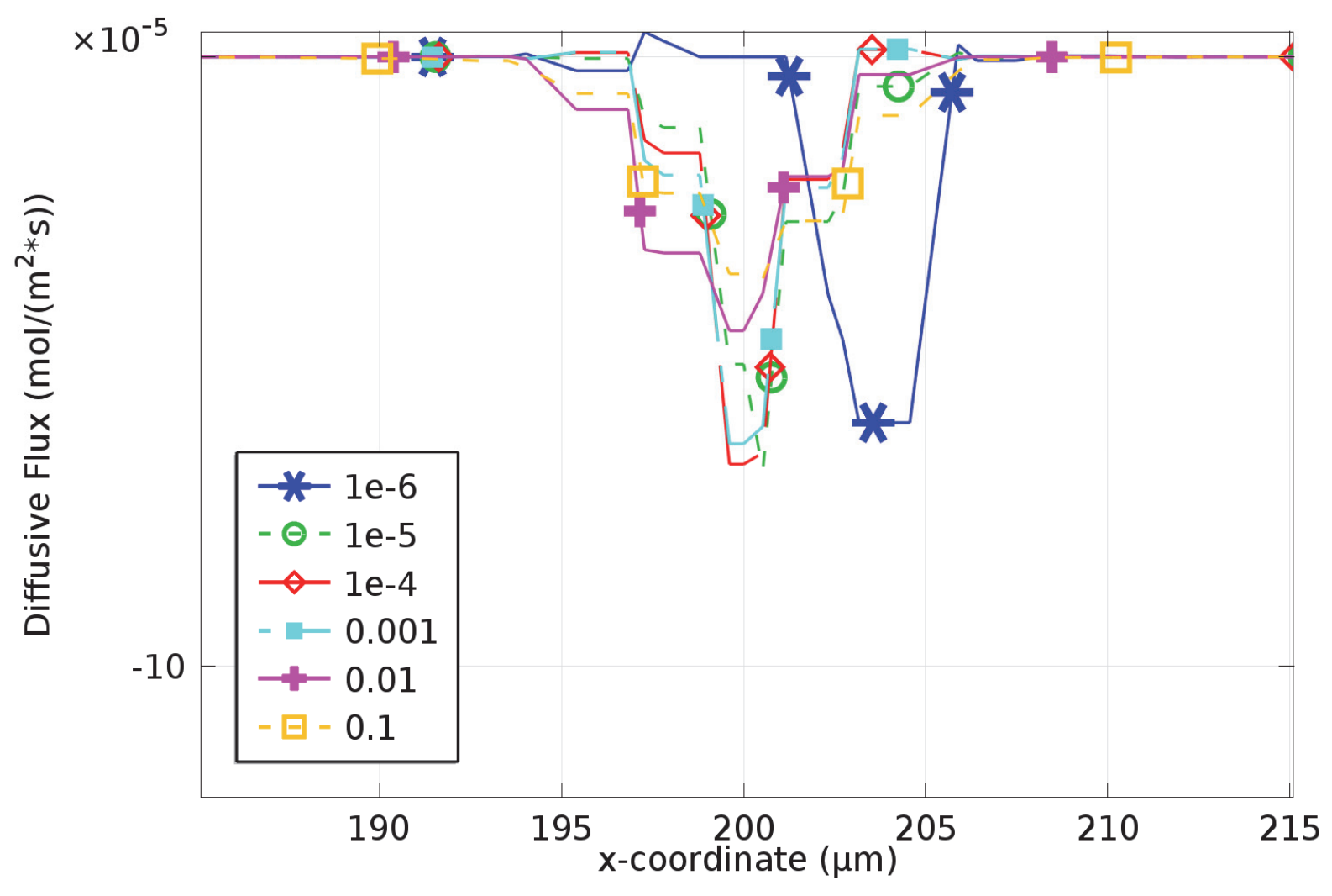

Figure 7. Diffusive flux (volume ratio 1:1)

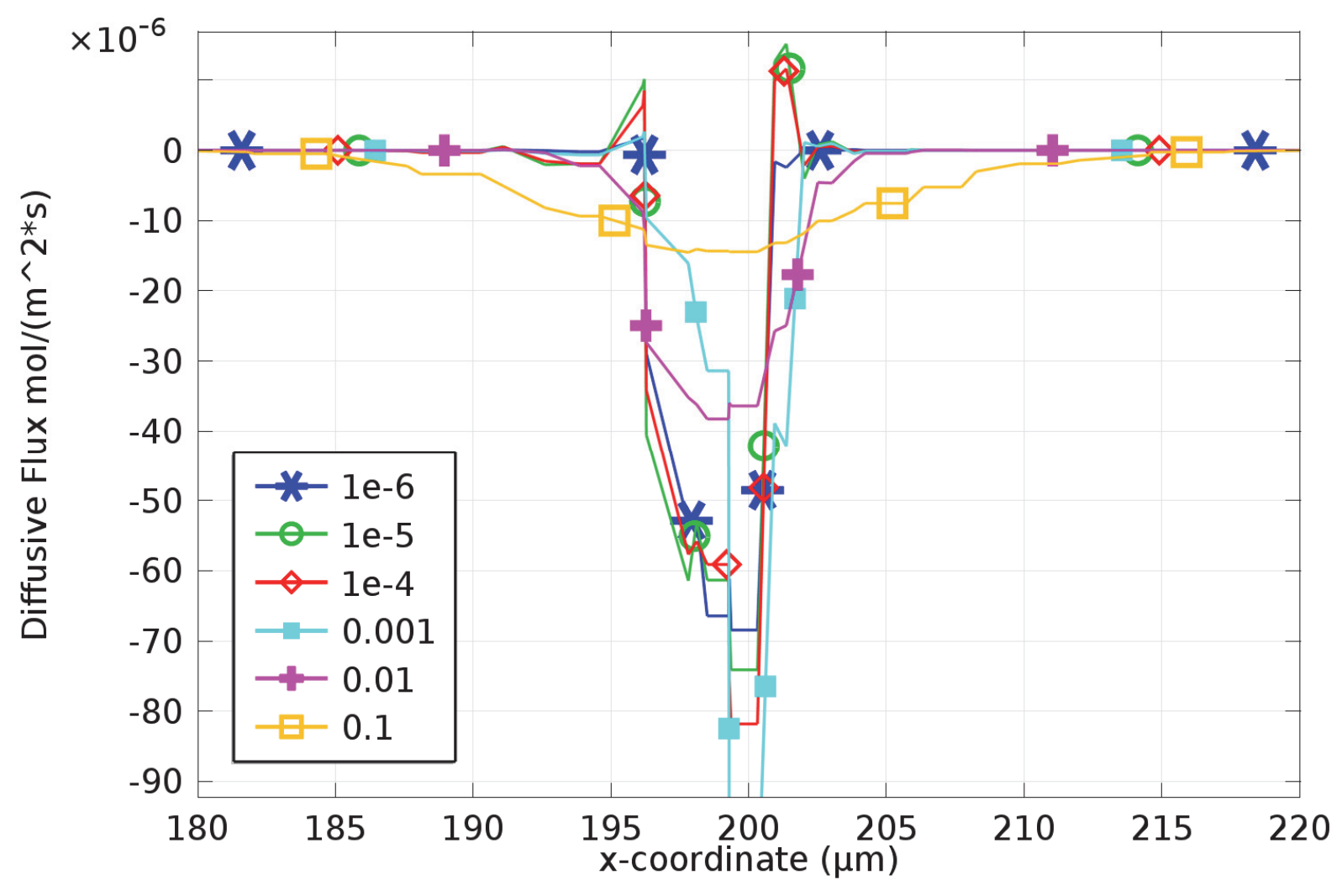

Figure 8. Diffusive flux (volume ratio 4:1)

Figure 4 to 8 show the results for the Comsol simulations. Early stage coalescence is modelled well in Comsol, later stage differs due to pinning of the ink on the substrate. The convective contribution to the mass transport is only present for times<1 ms. No convective flux is present over the bridge (x=200 µm). This is in contrast with the experimental results for volume ratios >1:1. The diffusive flux is as expected still present at later time stages.

Conclusions

The Comsol simulation compares reasonably well with the experimental results. For equal droplets, mass transport is diffusion driven. For unequal droplets, convection due to bridge formation plays an important role in the first millisecond. This is partially confirmed the Comsol simulation

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