Droplet coalescence in turbulent channel flows

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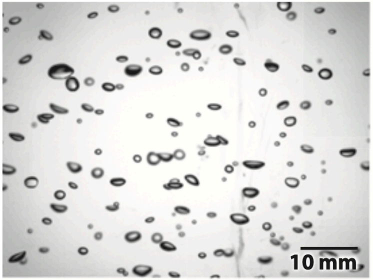
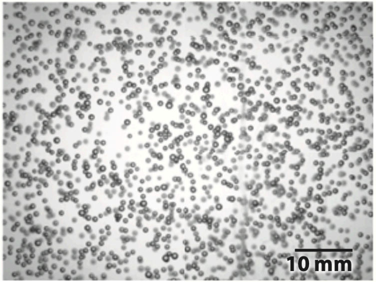
Introduction

"The coalescence of small bubbles hardly occurs in the presence of surfactant"[1].



Bubbles in tap water.



Bubbles in tap water with 2ppm Triton X-100 solution.

[1] Takagi, S. & Matsumoto, Y. 2011. Surfactant Effects on Bubble Motion and Bubbly Flows. *Annual Review of Fluid Mechanics* 43, 615–636

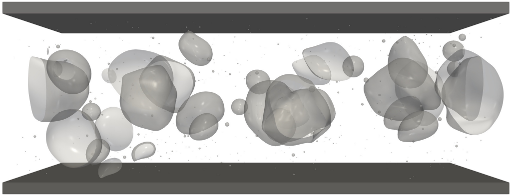
Methods

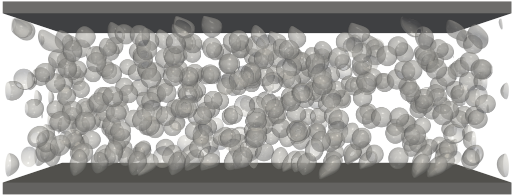
In the **volume of fluid** (VOF) method, an indicator function H is advected with the fluid,[2]

$$\frac{\partial H}{\partial t} + \mathbf{u} \cdot \nabla H = 0.$$

In the **front tracking** (FT) method, the velocity of the interface is a sum over fluid velocities at nearby grid points, [3]

$$\mathbf{u}^{(l)} = \sum_i D(\mathbf{x}_i - \mathbf{x}^{(l)})\mathbf{u}_i.$$





[2] Unverdi, S. O. & Tryggvason, G. 1992. A front-tracking method for viscous, incompressible, multi-fluid flows. *Journal of Computational Physics* 100, 25–37.

[3] S. Ii, K. Sugiyama, S. Takeuchi, S. Takagi, Y. Matsumoto, & F. Xiao, 2012. An interface capturing method with a continuous function: The THINC method with multi-dimensional reconstruction, *Journal of Computational Physics* 231, 2328–2358.

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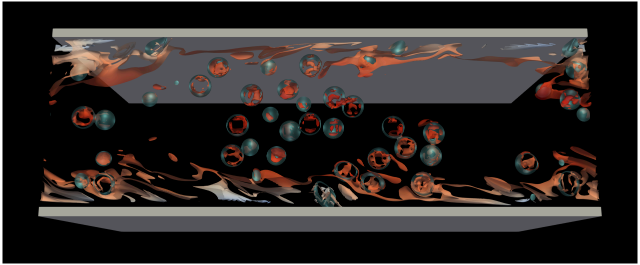
Setup

Pressure driven channel flow.



The single phase flow was at $Re_b \equiv u_b L/\nu = 2834$.
Channel dimensions: $6L \times 2L \times 3L$.
FT: non uniform Grid $566 \times 240 \times 288$ grid.
VOF: uniform $1296 \times 432 \times 648$ grid.

Φ (%)	method	Ca	We	N
0	SP	∞	∞	0
2.5	FT	0.10	18	110
2.5	FT	0.05	9	110
5	FT	0.10	18	220
5	FT	0.05	9	220
10	FT	0.10	18	440
10	FT	0.05	9	440
2.5	VOF	0.10	18	110
2.5	VOF	0.05	9	110
5	VOF	0.10	18	220
5	VOF	0.05	9	220
10	VOF	0.10	18	440
10	VOF	0.05	9	440

$$Ca \equiv \frac{\nu u_\tau}{\sigma}$$

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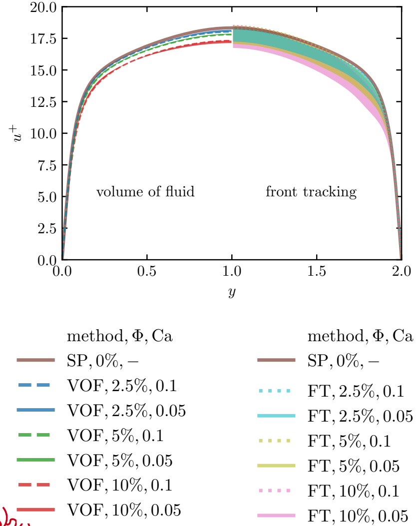
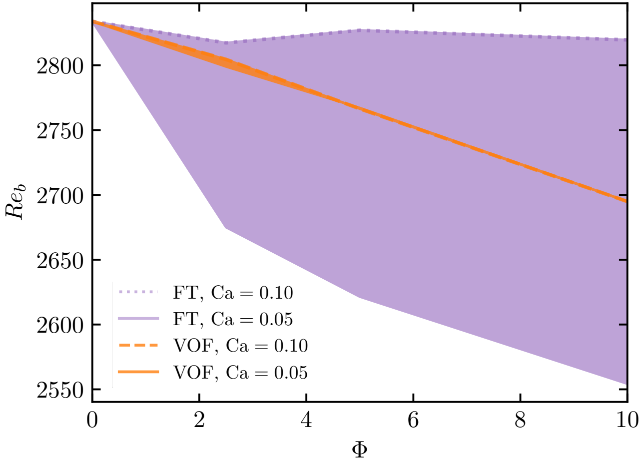
Bulk Reynolds number





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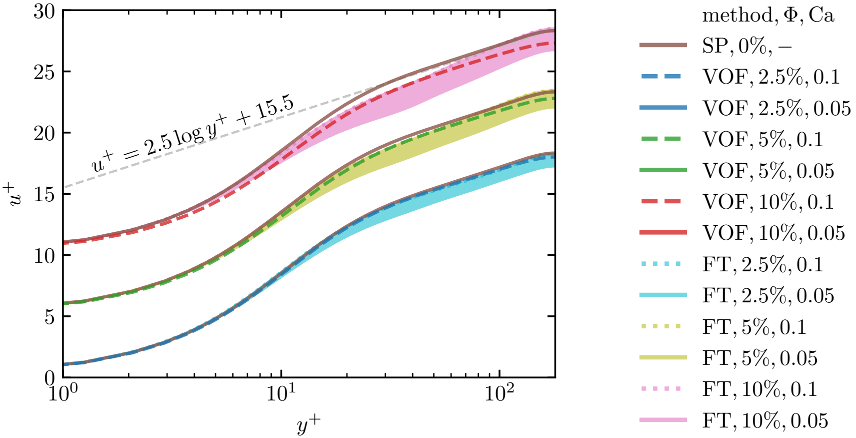
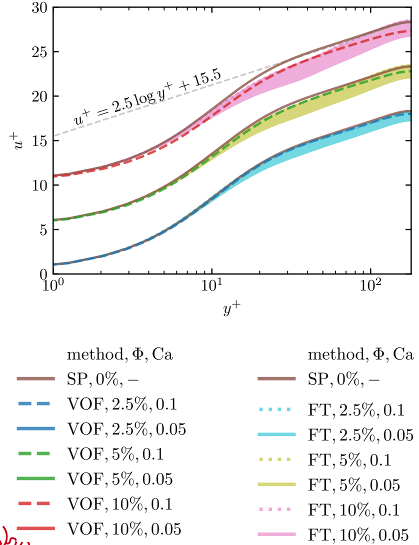
Log-law

The streamwise velocity profiles follow the log-law for a turbulent channel flows, with an additional shift[4] $u^+ = 2.5 \log y^+ + 5.5 + \Delta u^+$.

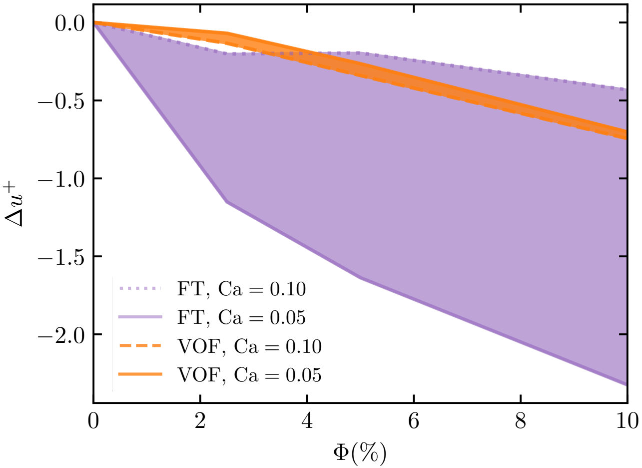


[4] von Kármán, T. 1930. Mechanische Ahnlichkeit und Turbulenz. Math-Phys. Klasse.

Log-law velocity shift



$$u^+ = 2.5 \log y^+ + 5.5 + \Delta u^+$$



$$Ca \equiv \frac{\nu u_\tau}{\sigma}$$

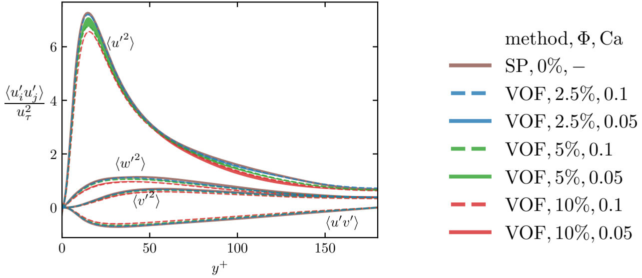
Reynolds stresses

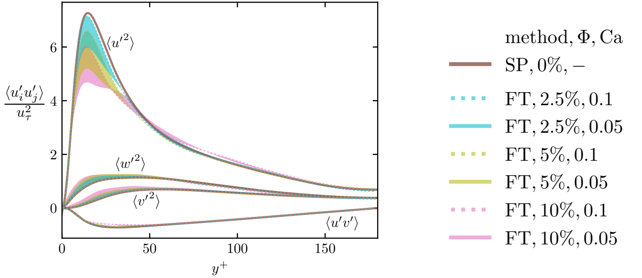
1. Fluctuations are **reduced** in the streamwise direction $\langle u'^2 \rangle$.

   Fluctuations are **increased** in the wall normal $\langle v'^2 \rangle$, and spanwise $\langle w'^2 \rangle$ directions.

2. Isotropy is **increased**[4].

3. Dissipation is **increased**.

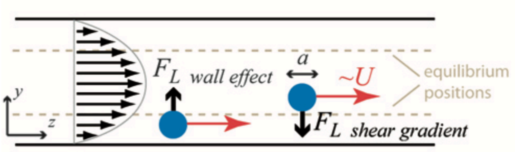


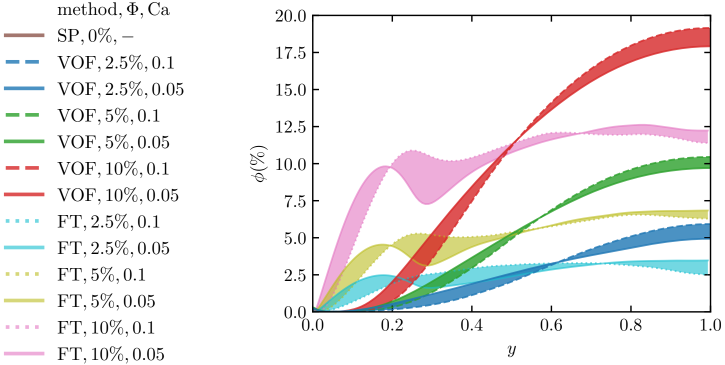


[4] Picano, Breugem, and Brandt. 2015. Turbulent channel flow of dense suspensions of neutrally buoyant spheres. Journal of Fluid Mechanics, 764:463–487

Volume fraction of dispersed phase

Di Carlo, D. 2009. Inertial microfluidics. Lab Chip 9, 3038.





Front tracking droplets experience:

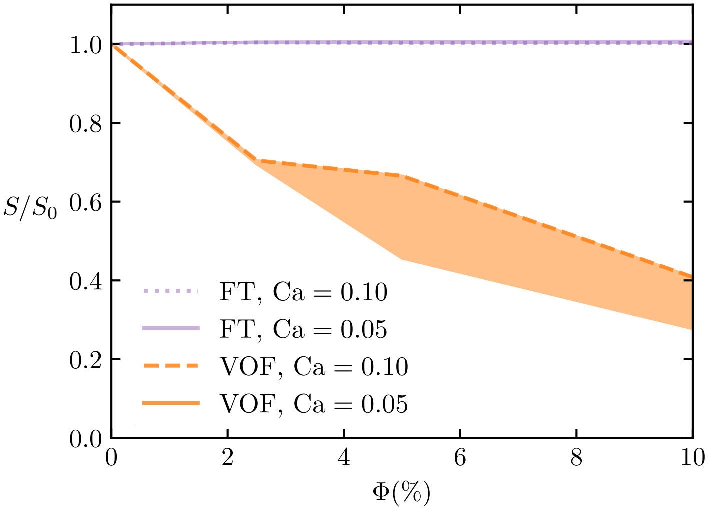
1. A rotation due to the shear, pulling towards the wall.
2. The wall effect, pulling towards the center[4].

Volume of fluid droplets are able to coalesce and move to a region of lower shear[5].

[4] Segré & Silberberg. 1961. Radial Particle Displacements in Poiseuille Flow of Suspensions. Nature 189, 209–210.

[5] Alghalibi, Rosti, and Brandt. 2019. Inertial migration of a deformable particle in pipe flow. Physical Review Fluids, 4(10):104201

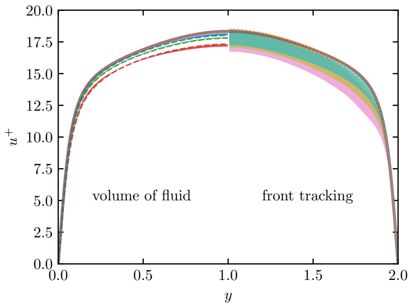
Total area of the droplets



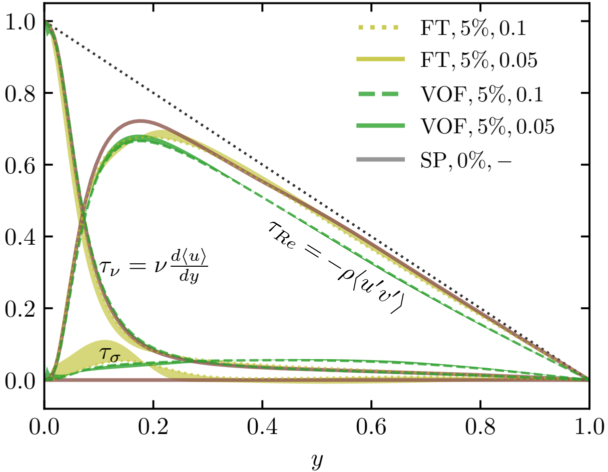
$S/S_0 \approx 1.01$ for the front tracking simulations.

Coalescence leads to a signifincant decrease in surface area in the volume of fluid simulations.

Shear stresses

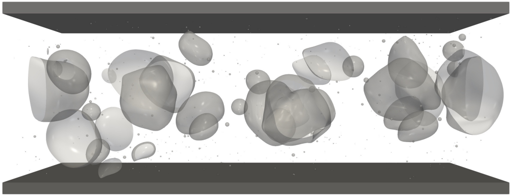


$$\tau = \tau_\nu + \tau_{Re} + \tau_\sigma.$$

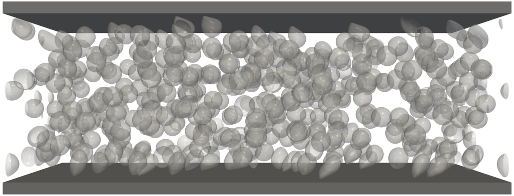


The mean shear stress in the channel is a sum of the viscous, inertial, and surface tension parts. In the front tracking case, we see a large contribution to the shear from the droplets near the wall.

Conclusions



Volume of fluid method.



Front tracking method.

1. The **volume of fluid method** can accurately model droplets which **easily coalesce**.
2. The **front tracking method** can accurately model droplets which **rarely coalesce**.
3. Non-coalescing droplets, such as in surfactant laden fluids, will spread across the channel, forming a **peak in volume fraction** near the channel wall.
4. This leads to large surface tension stresses near the channel wall, reducing the stress budget, and **increasing drag**.

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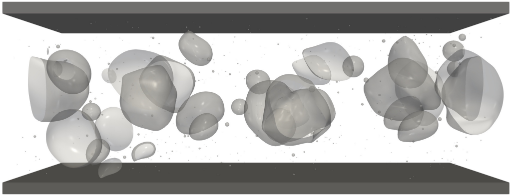
Conclusions



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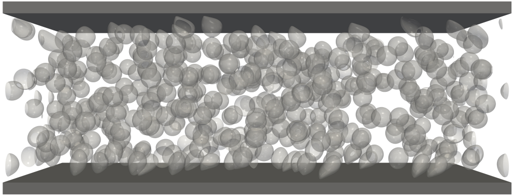

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Thank you! Questions?