

Coalescence reduces drag in turbulent bubbly channel flows

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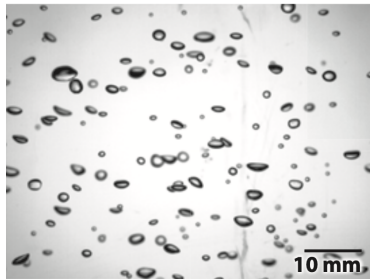


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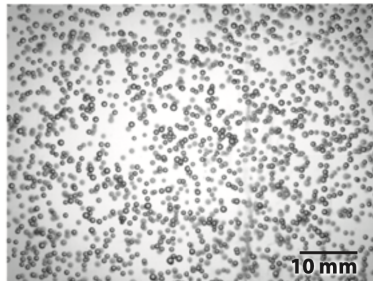
沖縄科学技術大学院大学

Introduction

“The **coalescence** of small bubbles hardly occurs in the presence of surfactant”^[1].



Bubbles in tap water.



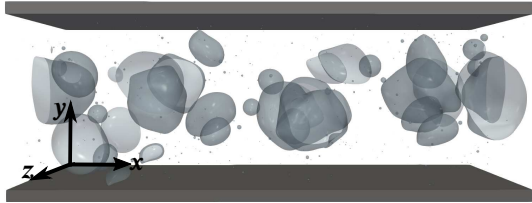
Bubbles in tap water with 2ppm Triton X-100 solution.

[1] Takagi & Matsumoto 2011 *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]

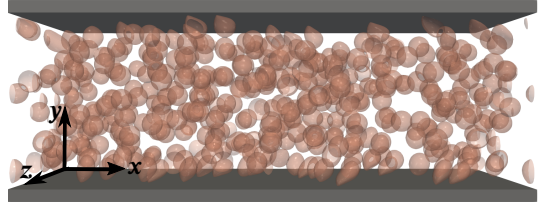
$$\frac{\partial H}{\partial t} + \mathbf{u} \cdot \nabla H = 0. \quad (1)$$



[2] Unverdi & Tryggvason 1992 *Journal of Computational Physics* 100, 25–37.

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

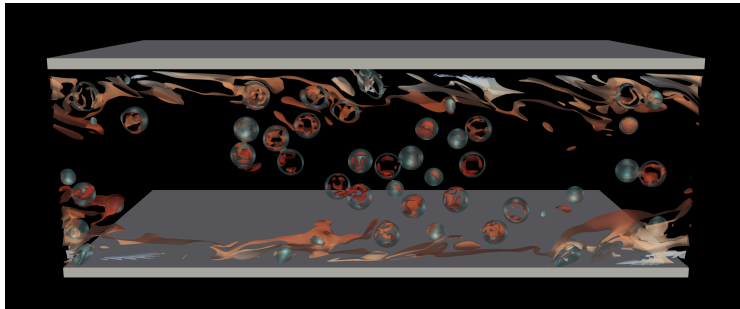
$$\mathbf{u}^{(l)} = \sum_i D(\mathbf{x}_i - \mathbf{x}^{(l)}) \mathbf{u}_i. \quad (2)$$



[3] li, Sugiyama, Takeuchi, Takagi, Matsumoto & Xiao 2012 *Journal of Computational Physics* 231, 2328–2358.

Setup: pressure driven channel flow

Channel dimensions	$6L \times 2L \times 3L$
VOF: uniform grid	$1296 \times 432 \times 648$
FT: non uniform grid	$566 \times 240 \times 288$

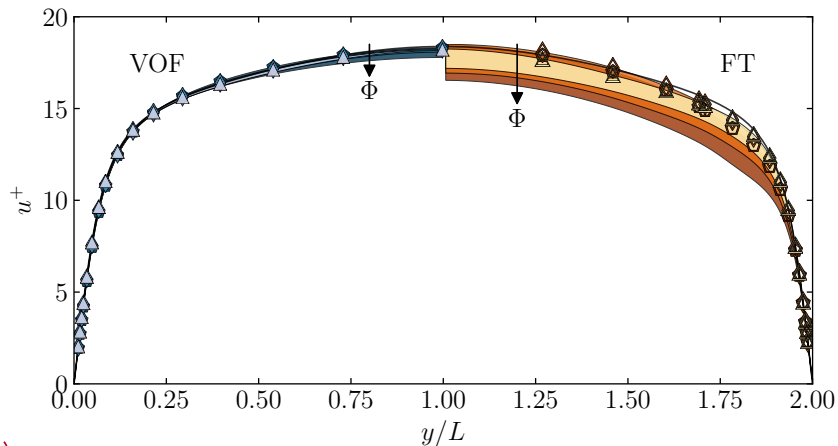


Friction Reynolds number	$Re_\tau \equiv u_\tau L / \nu = 180$
Four volume fractions	$\Phi = 0\%, 2.5\%, 5\%, 10\%$
Two values of surface tension	$We_\tau \equiv \rho_c u_\tau^2 L / \gamma = 0.57, 1.14$

Flow profile

As the volume fraction of droplets increases, the **flow rate is reduced**.

Non-coalescing droplets have a much greater effect.



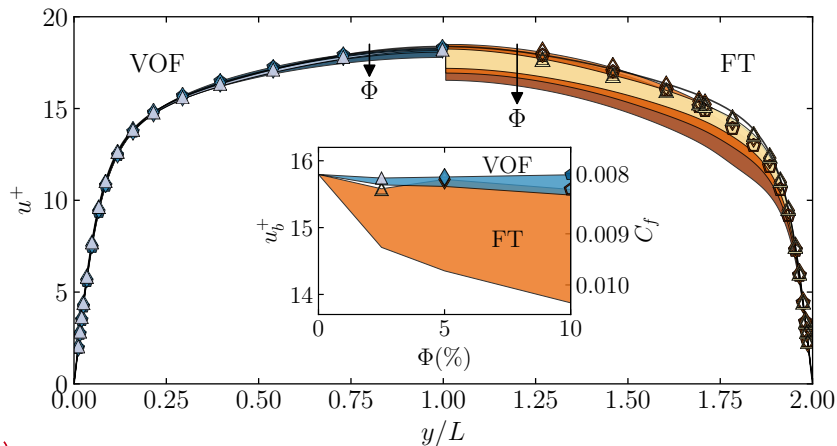
colour	Φ (%)
■ ■	2.5
■ ■	5.0
■ ■	10.0

mark	We_τ
△ ◇ ◻ △ ◇ ◻	1.14
— — — — — —	0.57

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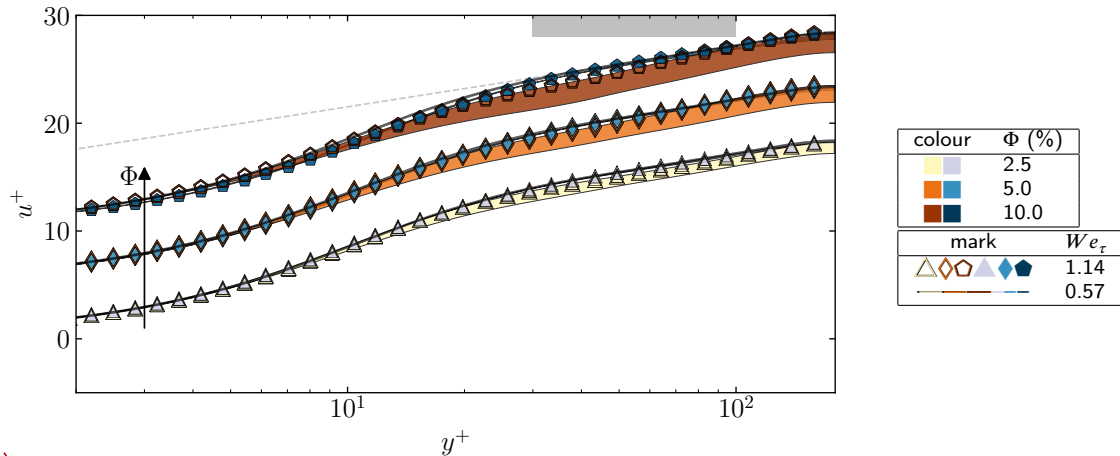


colour	Φ (%)
■ ■	2.5
■ ■	5.0
■ ■	10.0

mark	We_τ
△ ◇ ◻ △ ◇ ◻	1.14
— — — — — —	0.57

Log-law

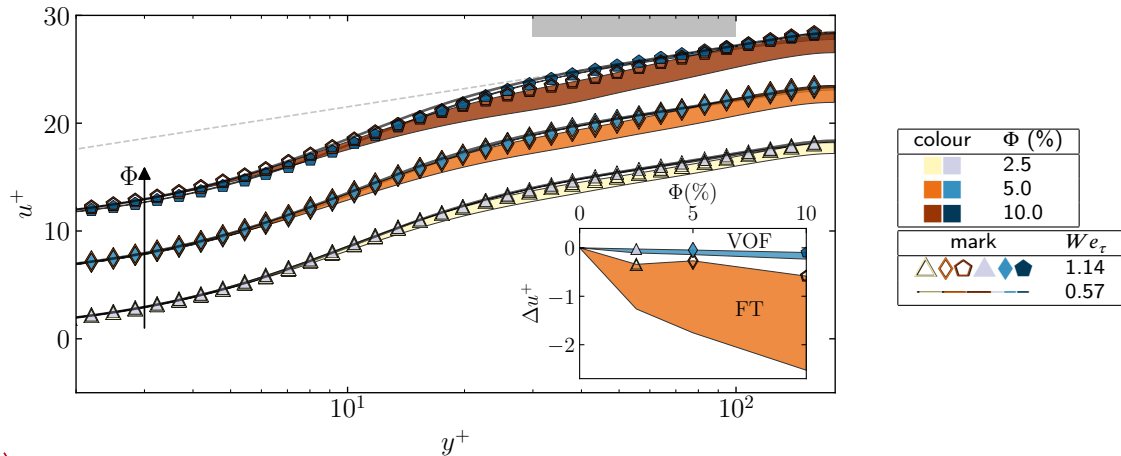
The streamwise velocity profiles follow the log-law for a turbulent channel flows, with a **negative shift**^[4] $u^+ = 2.5 \log y^+ + 5.5 + \Delta u^+$.



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

Log-law

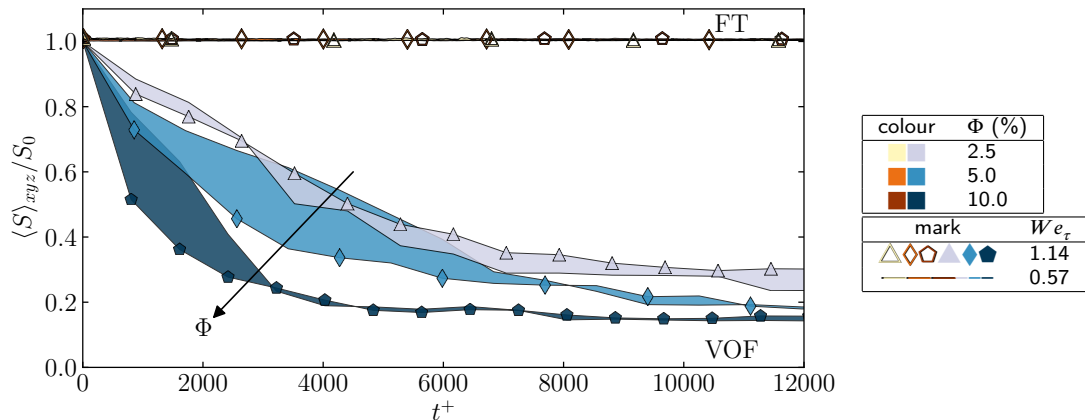
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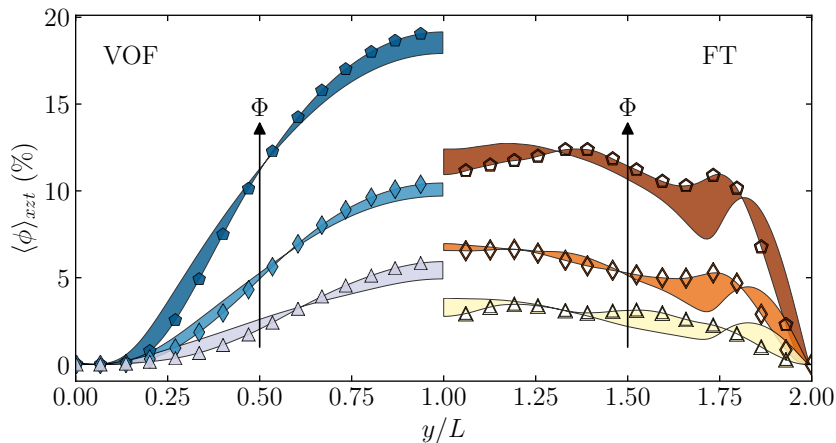
[4] von Kármán, T. 1930. Mechanische Ähnlichkeit und Turbulenz. Math-Phys. Klasse.

Total area of the droplets

Coalescence leads to a significant **decrease in surface area**.

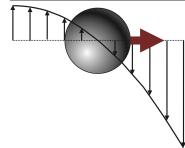


Volume fraction of dispersed phase



colour	Φ (%)
yellow	2.5
orange	5.0
brown	10.0

mark	We_τ
triangle	1.14
diamond	0.57



Martel & Toner 2014 Ann.
Rev. of Bio. Eng. 16,
371–396

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

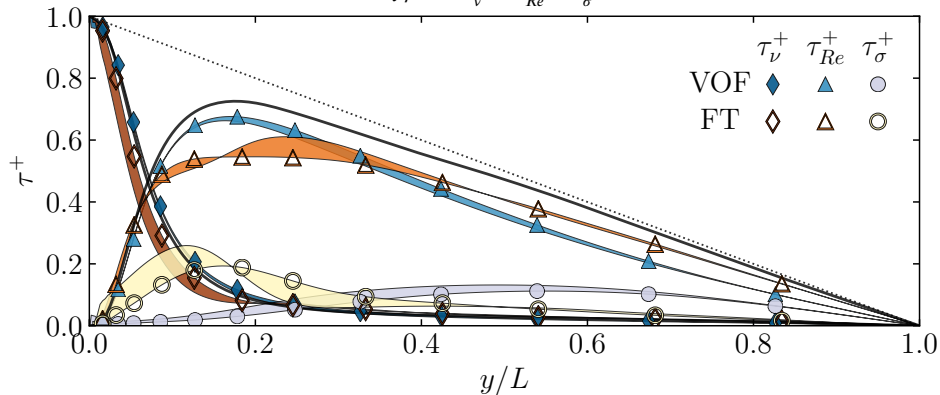
Front tracking droplets experience a **shear-gradient lift force**, pulling them toward the wall.

[5] Alghalibi, Rosti & Brandt 2019 Phy. Rev. Fluids, 4(10):104201

Shear stresses

The shear stress is a sum of the viscous, inertial, and surface tension parts,

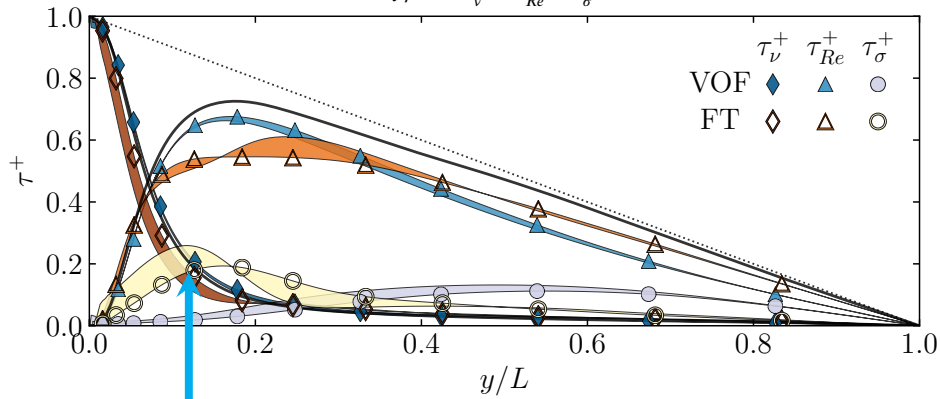
$$1 - y/L = \tau_\nu^+ + \tau_{Re}^+ + \tau_\sigma^+ \quad (3)$$



Shear stresses

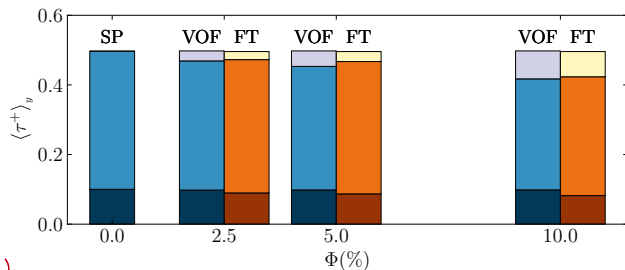
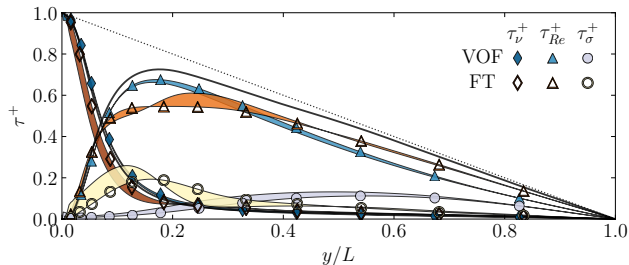
The shear stress is a sum of the viscous, inertial, and surface tension parts,

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The front tracking **surface tension stress** has a peak near the wall.

Shear stresses

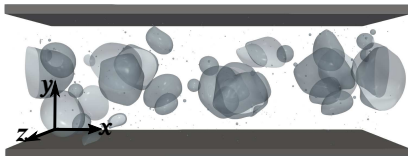


The mean viscous shear stress is reduced in the front tracking simulations. This stress is proportional to the centreline velocity,

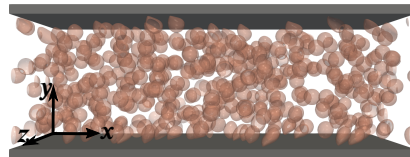
$$\langle \tau_\nu^+ \rangle_y = \frac{1}{L} \int_0^L \frac{du^+}{dy^+} dy = \frac{\delta_\nu}{L} u_{cen}^+. \quad (4)$$

Hence the flow velocity is reduced in the front tracking simulations.

Conclusions



Volume of fluid method.

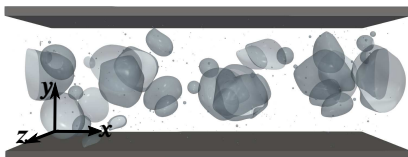


Front tracking method.

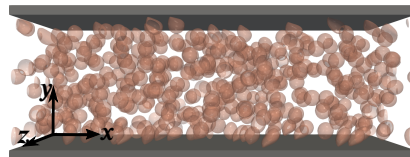
1. Non-coalescing droplets produce a significant **drag increase** compared to coalescing droplets.
2. The non-coalescing droplets experience a **shear-gradient lift force**, which attracts them to the viscous sublayer in the channel.
3. This leads to large surface tension stresses near the channel wall, **reducing the budget for viscous stress**, and increasing drag.

Cannon, I., Izbassarov, D., Tammisola, O., Brandt, L. & Rosti, M. E. 2021 *The effect of droplet coalescence on drag in turbulent channel flows*. *Physics of Fluids*

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Front tracking method.

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Thank you!

Questions?

Cannon, I., Izbassarov, D., Tammisola, O., Brandt, L. & Rosti, M. E. 2021 *The effect of droplet coalescence on drag in turbulent channel flows*. Physics of Fluids