Mechanisms for microbubble transfer in the near-wall region of turbulent boundary layer.

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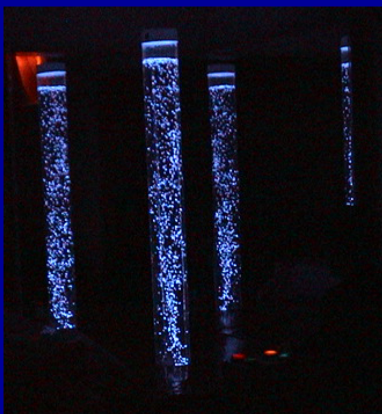
Bubbles in turbulent flows. Applications

Process industry

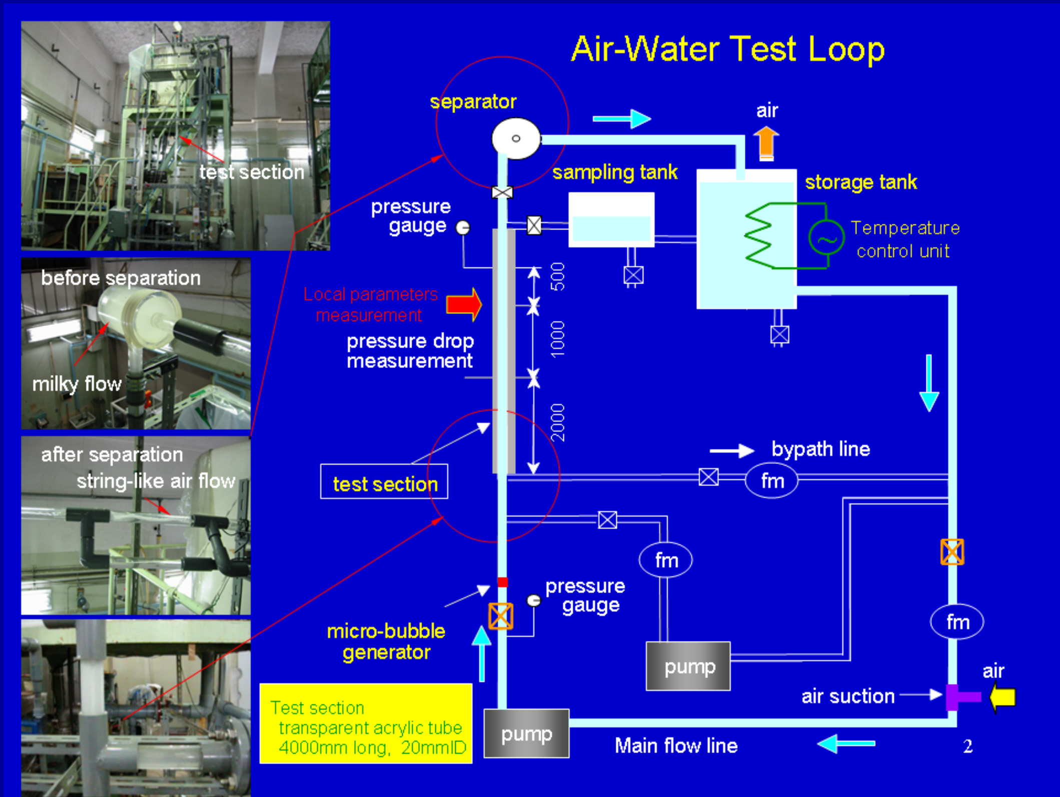
Bubble columns



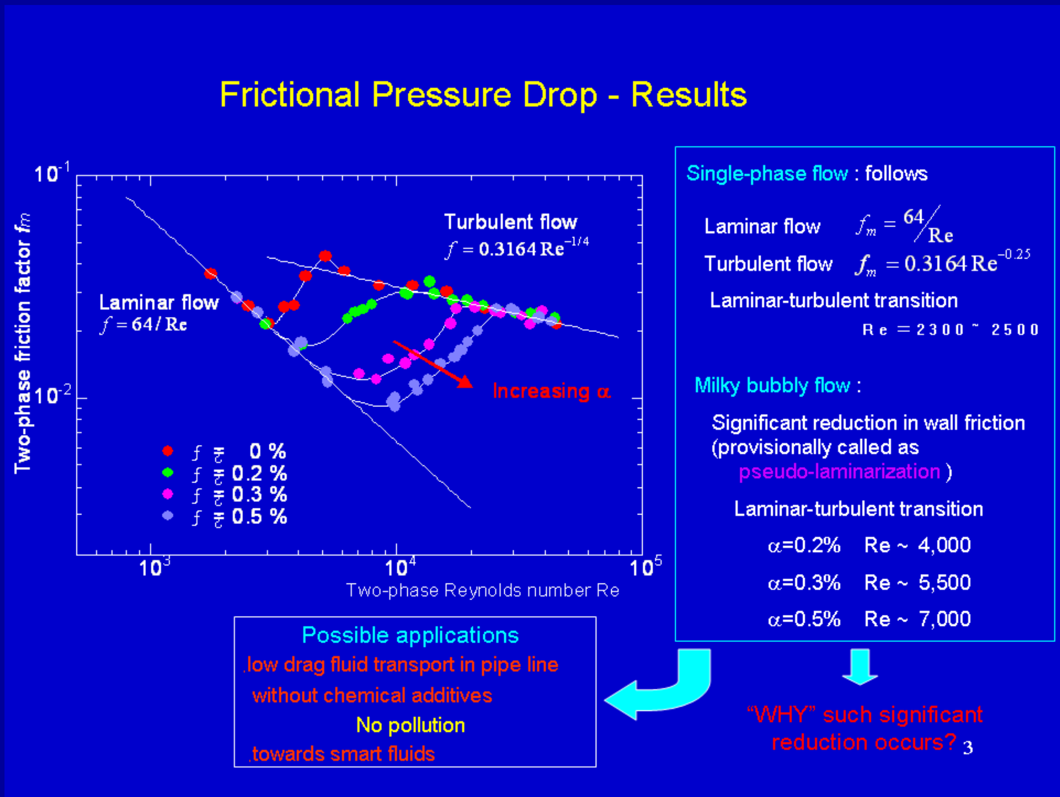
Skin friction reduction

Microbubbles applied to a tanker

Prof. Akimi Serizawa (1)

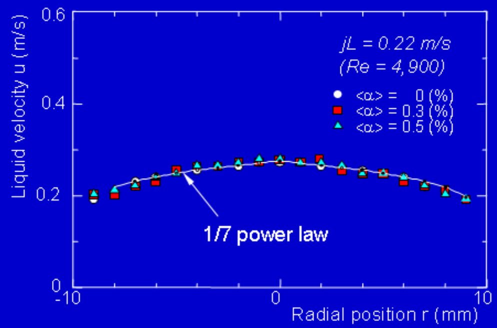


Prof. Akimi Serizawa (2)



Prof. Akimi Serizawa (3)

Liquid Velocity Profiles - Results

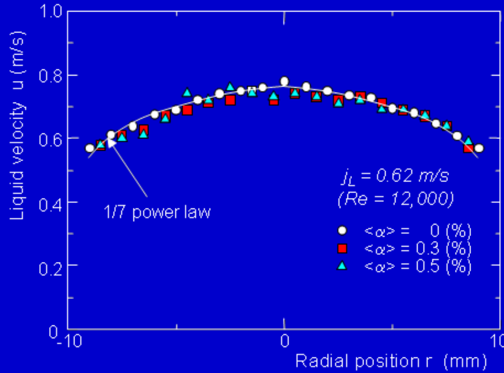


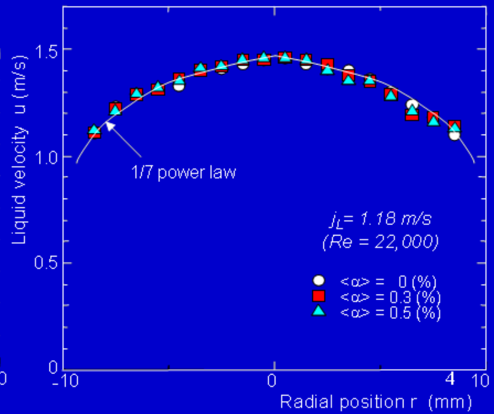
Flow conditions (friction factor)

	Re=4,900	Re=12,000	Re=22,000
α = 0 %	turbulence	turbulence	turbulence
α = 0.3 %	pseudo-laminar	transition	turbulence
α = 0.5 %	pseudo-laminar	transition	turbulence

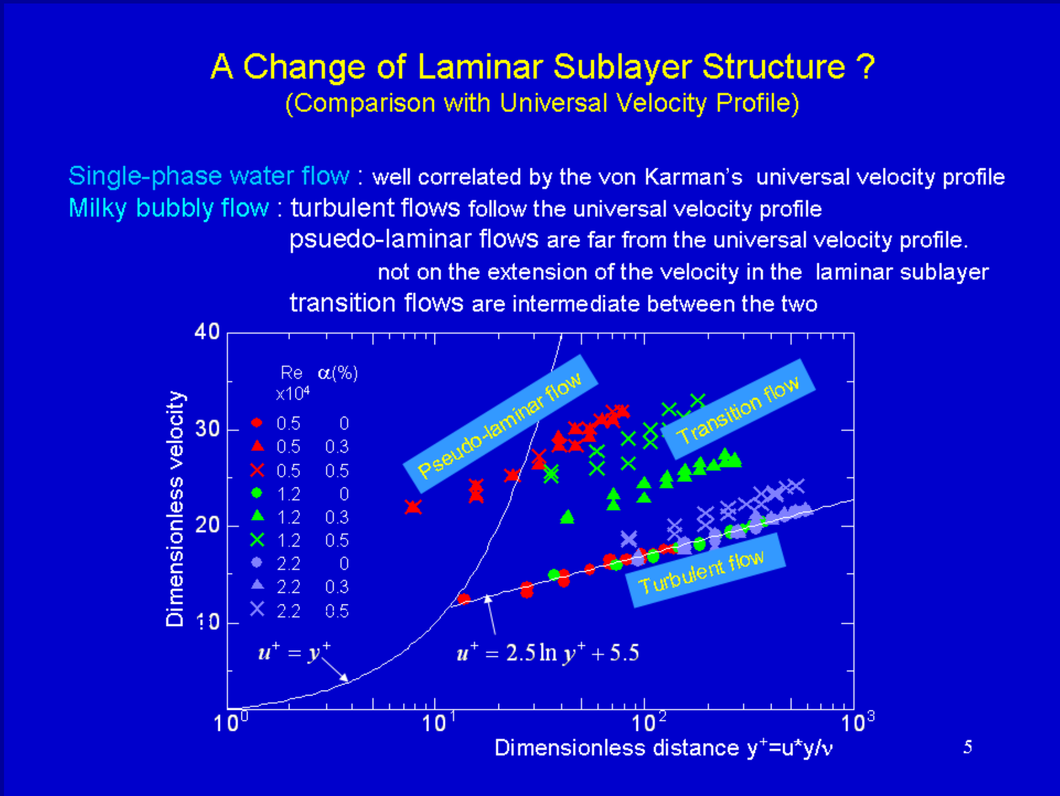
Liquid velocity profile – experimental evidence
turbulence profile at all conditions

Why still pseudo-laminarizaion ?





Prof. Akimi Serizawa (4)



Objects of the talk

1. *Examine macroscopic behavior of bubbles in turbulent boundary layers;*
2. *Review the dynamics of coherent structures in TBL;*
3. *Examine bubble dynamics in connection with turbulence structures;*
4. *Discuss limitations and advantages of current modelling approaches.*

Obs. 1: Bubbles rise in still fluid

Rising velocity determined by equilibrium between drag (Stokes) and gravity:

$$v_s = \frac{d_p^2 g(\rho_f - \rho_b)}{18\mu}$$

Obs. 2: Bubble segregation in vortices

Bubbles rising under gravity

Bubbles segregate in high vorticity, low strain regions

Observation on bubbles

Observation:

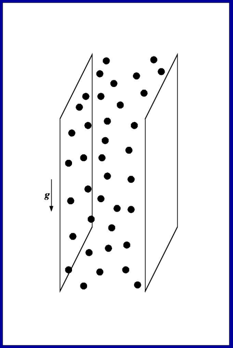
Due to fluid forces → local bubble accumulation in high vorticity, low strain regions (Caporaloni et al., *1975* J. Atmos. Sci., *Reeks, 1983,* J. Aero. Sci., *Wang & Maxey, 1993,* JFM, *...);*

Consequences:

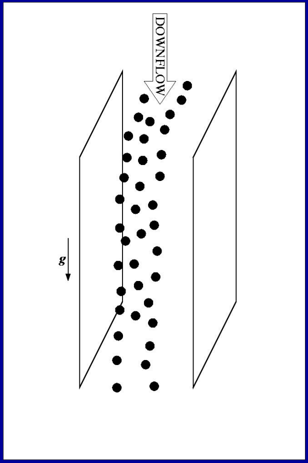
1. *Bubbles do not sample the vortical flow field homogeneously;*
2. *The flow field (statistics) perceived by bubbles may be different from the fluid flow field. Thus, bubble advection is different from fluid.*

Microbubbles in vertical channel flow

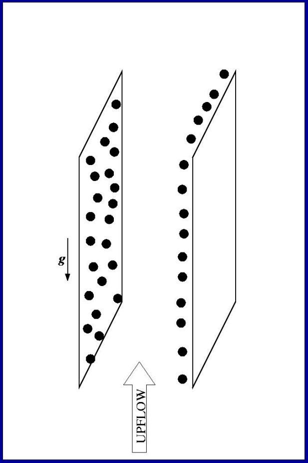
Experiments shows that bubbles with initial uniform distribution in vertical turbulent flows... (Hibiki & al., 2004, Int. J. Heat and Mass Transf.*)*



...move away from the wall (downflow)



...move towards the wall (upflow)



Reasons ?

It is not clear if this phenomenon is "a product of the turbulence gradients, bubble lift forces, weak pressure gradients, bubble sizes, eddy dynamics, or a combination of these factors" *(Felton K., Loth E., 2002,* Int. J. Multiphase Flow*)*

Turbulence is not only Statistics: it is a world of phenomena, much like an eco-system

"Fluid motions in turbulent boundary layers are intermittent and have a strongly organized and coherent nature represented by the large scale motions. These motions, eventhough not exactly repeatable and only quasi-deterministic, control the transport of the dispersed species in such a way that the overall distribution will resemble not at all those given by methods in which these motions are ignored" (thanks to G. Mungal)

F.Hussain, Coherent Structures: Reality or Myth, PoF, *1983*

Revolution one:

Fast Computers

Revolution two:

Concept of Coherent Structure (Brown & Roshko)

Near-wall Turbulent Structures

quasi-streamwise vortices
blue: clockwise
gold: counter-clockwise

wall shear
blue: low-shear
red: high-shear

quasi-streamwise vortices
red: clockwise
pale green: counter-clockwise

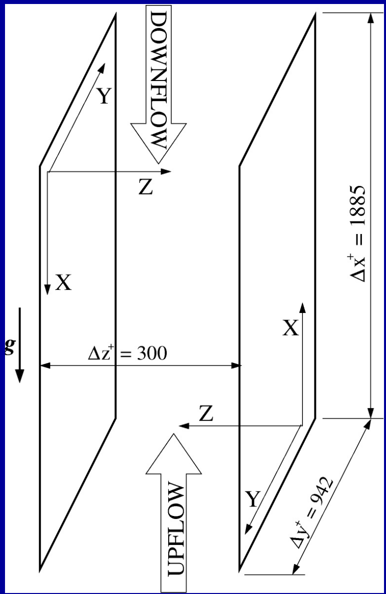
blue: ejections
green sweeps

Simulations data

- *DNS of Turbulent Flow Field*
- *Lagrangian Tracking of Microbubbles*

Hypotheses

spherical bubbles
one-way coupling



Fluid simulation

$Re_\tau = 150$
grid $64 \times 64 \times 65$
$128 \times 128 \times 129$
B.C. x *and* y *dir. : periodic*
B.C. z *dir.: solid wall*

Bubble simulation

10^5 *bubbles*
diameter $220\ \mu m$ $(1.65\ w.u.)$

Configurations of the channel

downflow
upflow

Bubble equation of motion

$$\underbrace{\frac{d\mathbf{v}_p^+}{dt^+}}_{inertia} = \underbrace{\frac{\left(\mathbf{v}^+ - \mathbf{v}_p^+\right)}{\tau_p^+} f\left(Re_p\right)}_{drag} + \underbrace{\left(1 - \frac{1}{\rho_p^+}\right)\mathbf{g}^+}_{grav}$$

Basic equation

($\mathbf{v}_p$ bubble velocity; $\mathbf{v}$ fluid velocity at bubble position)

Steady-state Drag force *(Crowe et al., 1998)*

- *Acts on particle/droplet in a uniform pressure field when there is no acceleration of the relative velocity between the particle and the conveying fluid*

$$F_D = \frac{1}{2}\rho_c C_D A \mid \mathbf{u} - \mathbf{v} \mid (\mathbf{u} - \mathbf{v}) = 3\pi\mu_c D \frac{C_d Re}{24}(\mathbf{u} - \mathbf{v})$$

- *Is different for bubbles or particles due to motion induced inside the bubble*

Bubble equation of motion

$$\underbrace{\frac{d\mathbf{v}_p^+}{dt^+}}_{inertia} = \underbrace{\frac{\left(\mathbf{v}^+ - \mathbf{v}_p^+\right)}{\tau_p^+} f\left(Re_p\right)}_{drag} + \underbrace{\left(1 - \frac{1}{\rho_p^+}\right)\mathbf{g}^+}_{grav}$$

$$+ \underbrace{\frac{1}{\rho_p^+}\frac{D\mathbf{v}^+}{Dt^+}}_{press.grad.}$$

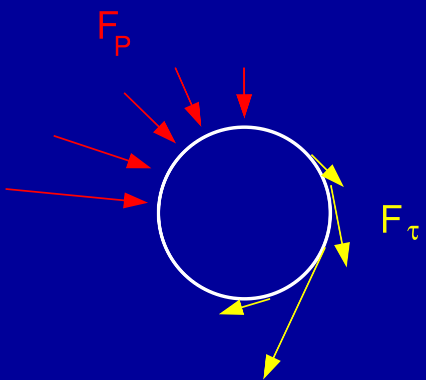
Effect of the non-uniformity of the flow-field around the particle

Pressure gradient and Buoyancy *(Crowe et al., 1998)*

- *Effect of local pressure gradient and shear on bubble surface*

$$F_P + F_\tau = \int_S -p\mathbf{n}dS + \int_S \tau_{ij}\mathbf{n}dS = \int_V -\nabla p + \nabla \cdot \tau dV$$

- *From N-S:*



$$-\nabla p + \nabla \cdot \tau = \rho_c \frac{Du}{Dt} - \rho_c \mathbf{g}$$

$$F_P + F_\tau = V\rho_c \frac{Du}{Dt} - V\rho_c \mathbf{g}$$

Bubble equation of motion

$$\underbrace{\frac{d\mathbf{v}_p^+}{dt^+}}_{inertia} = \underbrace{\frac{\left(\mathbf{v}^+ - \mathbf{v}_p^+\right)}{\tau_p^+} f\left(Re_p\right)}_{drag} + \underbrace{\left(1 - \frac{1}{\rho_p^+}\right)\mathbf{g}^+}_{grav}$$

$$+ \underbrace{\frac{1}{\rho_p^+}\frac{D\mathbf{v}^+}{Dt^+}}_{press.grad.} + \underbrace{\frac{9}{d_p^+ \rho_p^+ \sqrt{\pi}} \int_0^{t^+} \left(\frac{d\mathbf{v}^+}{dt^+} - \frac{d\mathbf{v}_p^+}{dt^+}\right) \frac{d\tau^+}{\left(t^+ - \tau^+\right)^{0.5}}}_{Basset}$$

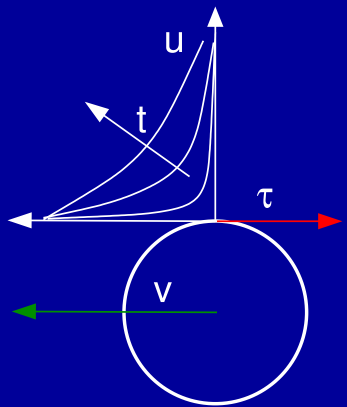
$$+ \underbrace{\frac{1}{2\rho_p^+}\left(\frac{D\mathbf{v}^+}{Dt^+} - \frac{d\mathbf{v}_p^+}{dt^+}\right)}_{added\ mass}$$

Eq. from "Maxey M.R., Riley J.J. (1983), Phys. Fluids **26***(4)"*

Effect of time-variation of the flow-field around the particle

Unsteady forces: Basset force *(Crowe et al., 1998)*

Basset or history force: due to the lagging boundary layer development with changing relative velocity

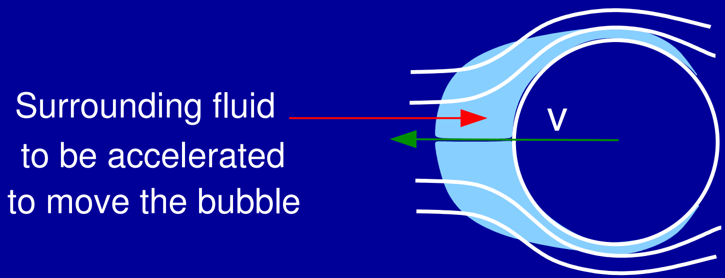


$$F_{Basset} = \frac{3}{2} D^2 \sqrt{\pi \rho_c \mu_c} \int_0^t \frac{\dot{\mathbf{u}} - \dot{\mathbf{v}}}{\sqrt{t - t'}}$$

Unsteady forces: added mass *(Crowe et al., 1998)*

Virtual or apparent mass: Force required to accelerate the surrounding fluid when the particle moves with given relative velocity, U

$$\frac{dKE}{dt} = UF_{vm} = \frac{m_f}{2}\frac{dU}{dt} = \frac{V_d \rho_c}{2}(\dot{\mathbf{u}} - \dot{\mathbf{v}}) = \frac{V_d \rho_c}{2}\left(\frac{D\mathbf{u}}{Dt} - \frac{d\mathbf{v}}{dt}\right)$$



Bubble equation of motion

$$\underbrace{\frac{d\mathbf{v}_p^+}{dt^+}}_{inertia} = \underbrace{\frac{\left(\mathbf{v}^+ - \mathbf{v}_p^+\right)}{\tau_p^+} f\left(Re_p\right)}_{drag} + \underbrace{\left(1 - \frac{1}{\rho_p^+}\right)\mathbf{g}^+}_{grav}$$

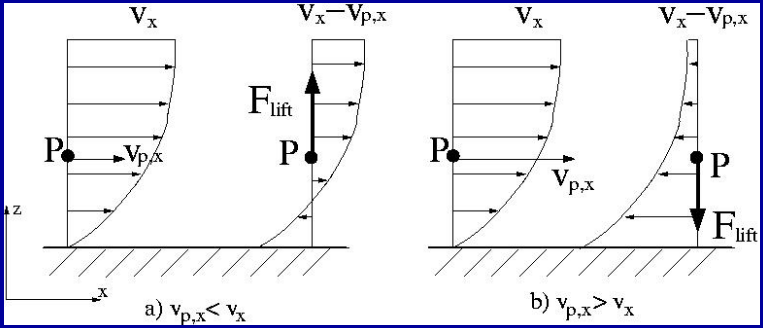
$$+ \underbrace{\frac{1}{\rho_p^+}\frac{D\mathbf{v}^+}{Dt^+}}_{press.grad.} + \underbrace{\frac{9}{d_p^+ \rho_p^+ \sqrt{\pi}} \int_0^{t^+} \left(\frac{d\mathbf{v}^+}{dt^+} - \frac{d\mathbf{v}_p^+}{dt^+}\right) \frac{d\tau^+}{\left(t^+ - \tau^+\right)^{0.5}}}_{Basset}$$

$$+ \underbrace{\frac{1}{2\rho_p^+}\left(\frac{D\mathbf{v}^+}{Dt^+} - \frac{d\mathbf{v}_p^+}{dt^+}\right)}_{added\ mass} + \underbrace{C_L \frac{1}{\rho_p^+}\left(\mathbf{v}^+ - \mathbf{v}_p^+\right) \times \omega^+}_{lift}$$

Effect of the lift

Forces on bubbles - lift

$$f^+_{lift} = C_L \, \frac{1}{\rho^+_p} \left(\mathbf{v}^+ - \mathbf{v}^+_p \right) \times \omega^+$$



(v_p bubble velocity, v fluid velocity at bubble position, ω fluid vorticity at bubble position)

Lift Coefficient (C_L)

$$C_L = \begin{cases} C_{L_{McL}} = \left[5.816\left(\frac{Sr_p}{2\ Re_p}\right)^{0.5} - 0.875\frac{Sr_p}{2}\right]\frac{3}{4\ Sr_p}\frac{J(\epsilon)}{2.255} & Re_p < 1 \\ C_{L_{McL}}\frac{5-Re_p}{4} + C_{L_{KK}}\frac{Re_p-1}{4} & 1 < Re_p < 5 \\ C_{L_{KK}} = \left[K_0\ \left(\frac{Sr_p}{2}\right)^{0.9} + K_1\ \left(\frac{Sr_p}{2}\right)^{1.1}\right]\frac{3}{4\ Sr_p} & Re_p > 5 \end{cases}$$

$C_{L_{McL}}$ *Eq. from "McLaughlin, J. B. (1991),* J. Fluid Mech. **224**"

($Sr_p = |(\mathbf{u}-\mathbf{v}_p)\times\omega|\,d_p/|\mathbf{u}-\mathbf{v}_p|^2$; $\epsilon = (Sr_p/Re_p)^{0.5}$; $J(\epsilon)$ *tabulated in McLaughlin, 1991*)

$C_{L_{KK}}$ *Eq. from "Kurose, R., Komori, S. (1999),* J. Fluid Mech. **384**"

(K_0 *and* K_1 *tabulated as a function of* Re_p *in Kurose, Komori, 1999*)

Bubble equation of motion

$$\underbrace{\frac{d\mathbf{v}_p^+}{dt^+}}_{inertia} = \underbrace{\frac{\left(\mathbf{v}^+ - \mathbf{v}_p^+\right)}{\tau_p^+} f\left(Re_p\right) C_W}_{drag} + \underbrace{\left(1 - \frac{1}{\rho_p^+}\right)\mathbf{g}^+}_{grav}$$

$$+ \underbrace{\frac{1}{\rho_p^+}\frac{D\mathbf{v}^+}{Dt^+}}_{press.grad.} + \underbrace{\frac{9}{d_p^+ \rho_p^+ \sqrt{\pi}} \int_0^{t^+} \left(\frac{d\mathbf{v}^+}{dt^+} - \frac{d\mathbf{v}_p^+}{dt^+}\right) \frac{d\tau^+}{\left(t^+ - \tau^+\right)^{0.5}}}_{Basset}$$

$$+ \underbrace{\frac{1}{2\rho_p^+}\left(\frac{D\mathbf{v}^+}{Dt^+} - \frac{d\mathbf{v}_p^+}{dt^+}\right)}_{added\ \ mass} + \underbrace{C_L \frac{1}{\rho_p^+}\left(\mathbf{v}^+ - \mathbf{v}_p^+\right) \times \omega^+}_{lift}$$

Wall effect on drag

Forces on bubbles - drag (2)

$$\textit{Direction parallel to the wall}$$

$$C_{W_\parallel} = \left\{1 - \frac{9}{16}\left(\frac{d}{2z}\right) + \frac{1}{8}\left(\frac{d}{2z}\right)^3 - \frac{45}{256}\left(\frac{d}{2z}\right)^4 - \frac{1}{16}\left(\frac{d}{2z}\right)^5\right\}^{-1}$$

$$\textit{Direction orthogonal to the wall}$$

$$C_{W_\perp} = \left\{\left[1 - \frac{9}{8}\left(\frac{d}{2z}\right) + \frac{1}{2}\left(\frac{d}{2z}\right)^2\right] \cdot \left[1 - exp\left(-2.686\left(\frac{2z}{d} - 0.999\right)\right)\right]\right\}^{-1}$$

Eq. from "Fukagata, K., Zahrai, S., Bark, F.H., Kondo, S., (1999). Proc. 1st Int. Symp. on Turbulence and Shear Flow Phenomena *(Eds. Banerjee, S. & Eaton, J.K., ISBM 1-56700-135-1)"*

($d/2z$ ratio between bubble radius and distance between wall and bubble center)

Forces on bubbles - movie DWL

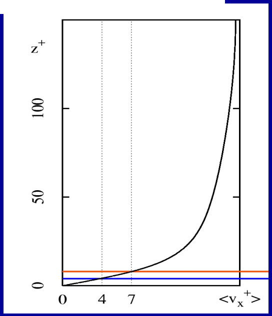
Forces on bubbles - movie UPL

Visualization of bubble behavior

time-range:
$0 < t^+ < 360$

section thickness:
$\Delta x^+ = 100$

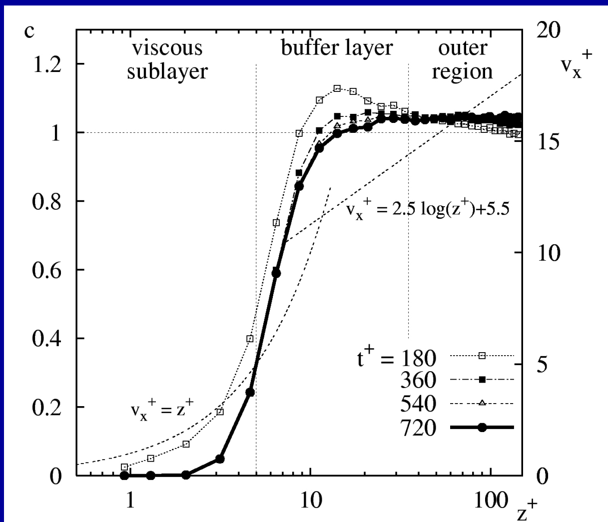
v_x^+ *isolevels:*
blue: $v_x^+ = 4$
orange: $v_x^+ = 7$



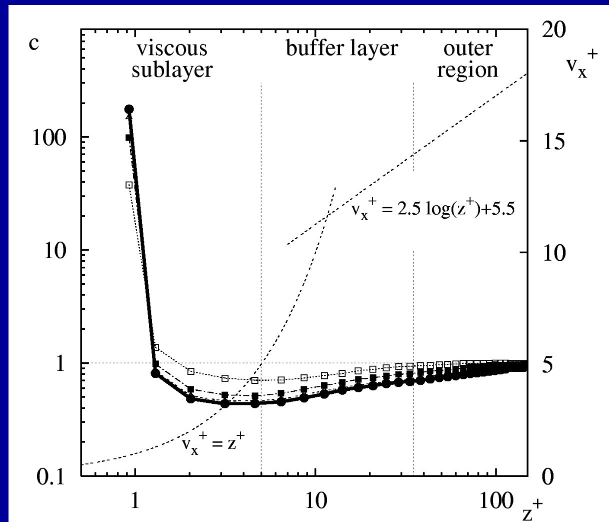
Downflow

Upflow

Concentration profiles

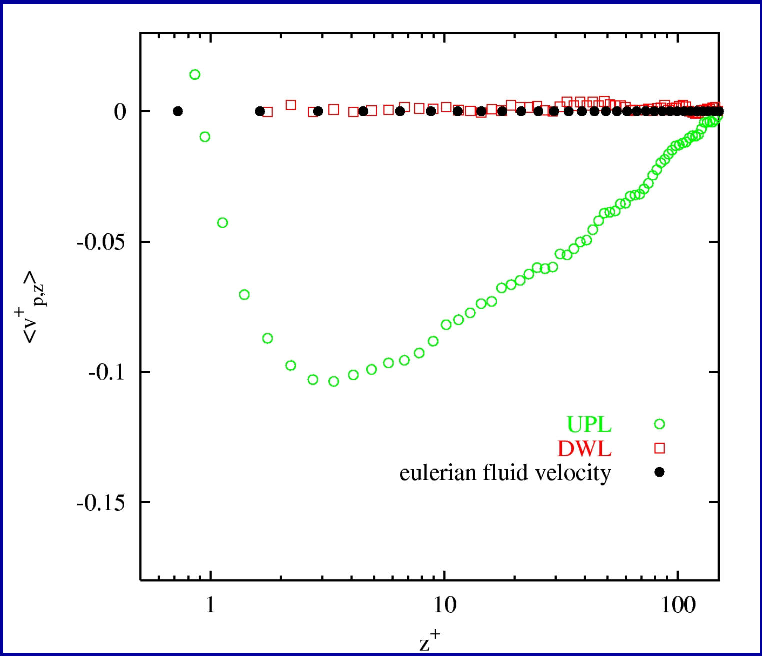


Downflow



Upflow

Bubble Wall-normal Drift Velocity

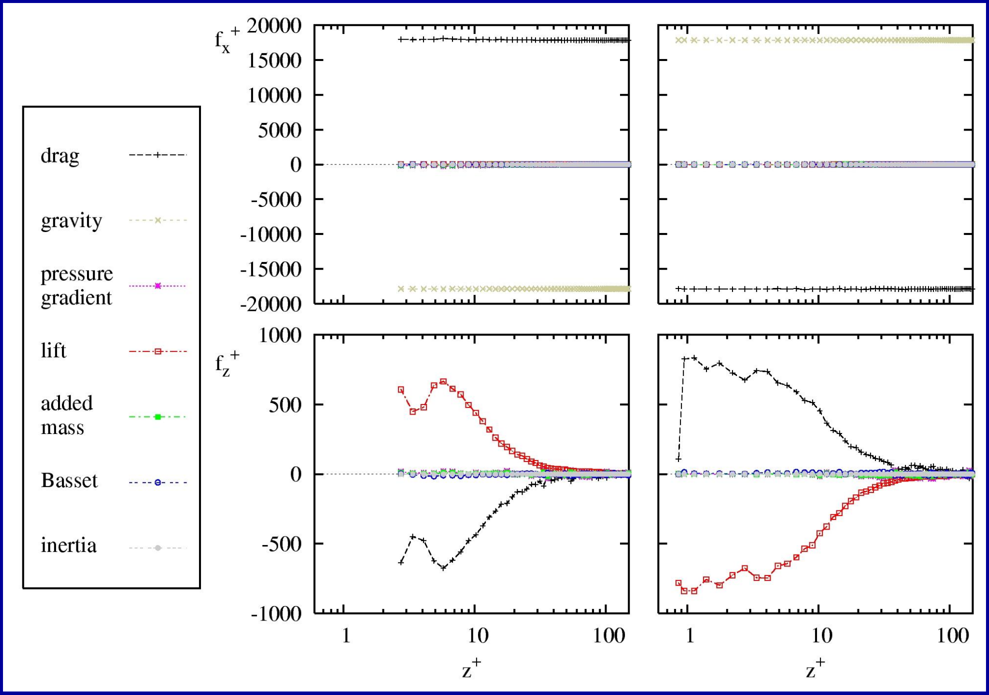


DWL: steady bubble distribution

UPL: bubbles migrate towards the wall

Forces on bubbles

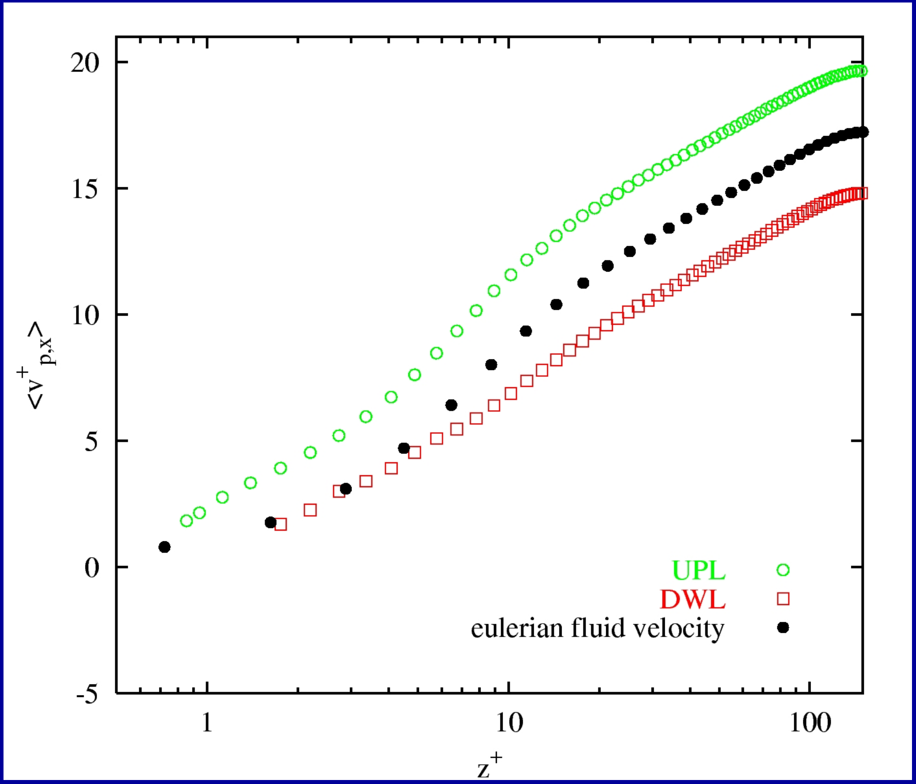
Downflow *Upflow*



Preliminary Conclusions

- *Experimental observations:*
  - *upflow : bubbles migrate towards the wall*
  - *downflow : bubbles migrate away from the wall*
- *Numerical simulations:*
  - *without lift (not shown here): bubbles behave almost like tracers*
  - *with lift : simulate bubble migration towards/away from the wall*
- *Lift force results to be crucial for bubble behavior*

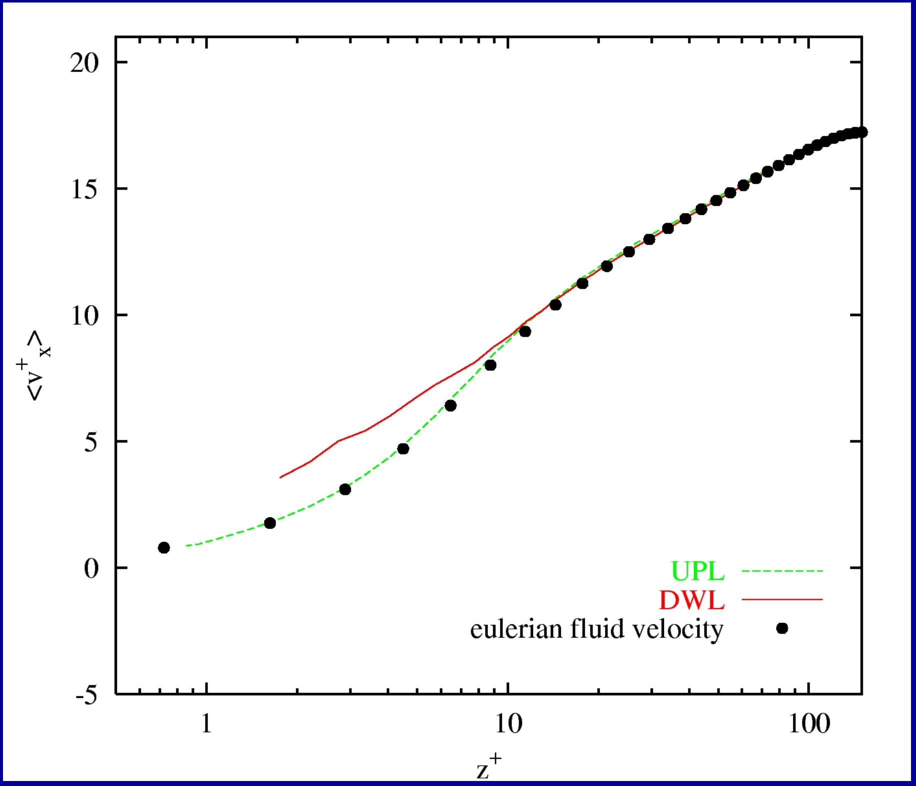
Bubble Streamwise Velocity



DWL: *shift velocity decreases near the wall*

UPL: *constant shift velocity*

Fluid Velocity at Bubble Position



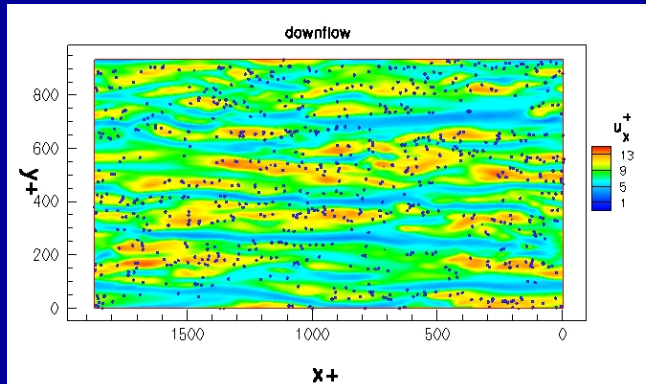
DWL: in the near-wall region, bubbles concentrate preferentially in high-speed regions

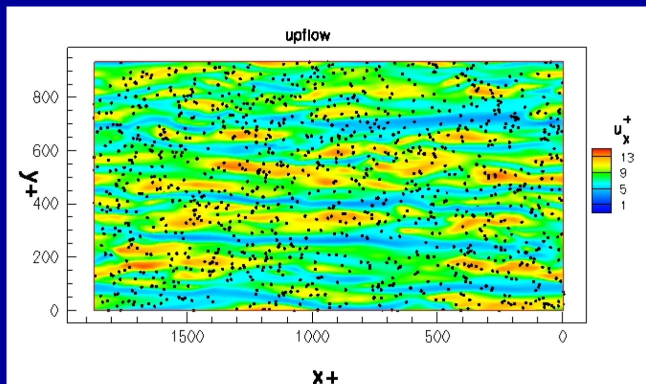
Bubbles in the Near-Wall Region

Downflow

Bubbles distance from the wall: $1 < z^+ < 10$

Isolevels of fluid streamwise velocity: $z^+ = 10$





Upflow

Visualization of bubbles next to the wall

Downflow

zoom of previous movies

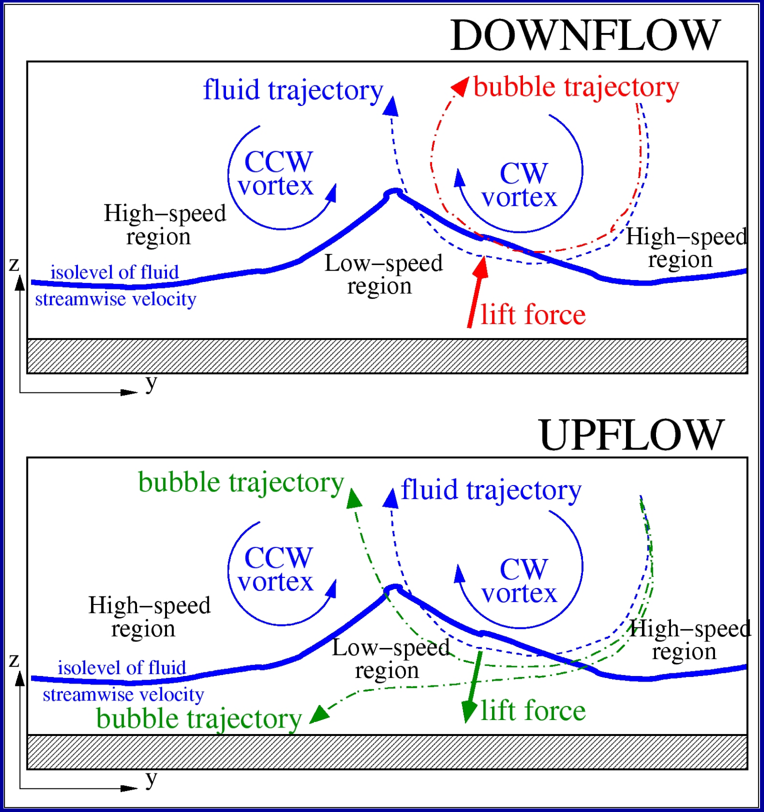
black circles: bubbles trapped at the wall

Upflow

Lift Force Effect - Sketch

DWL: lift force prevents bubbles to reach the low-speed regions

UPL: trajectories of the bubbles (both resuspended or trapped at the wall) cross low-speed regions



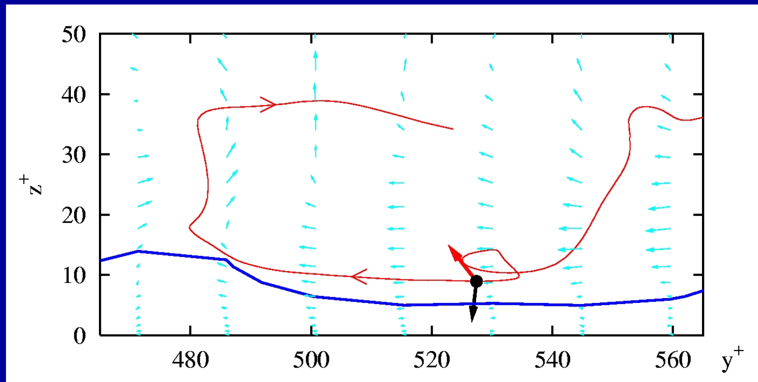
Lift Force Effect - Forces on Bubbles

DOWNFLOW

→: drag force

→: lift force

bubble cannot reach the low-speed region and is resuspended

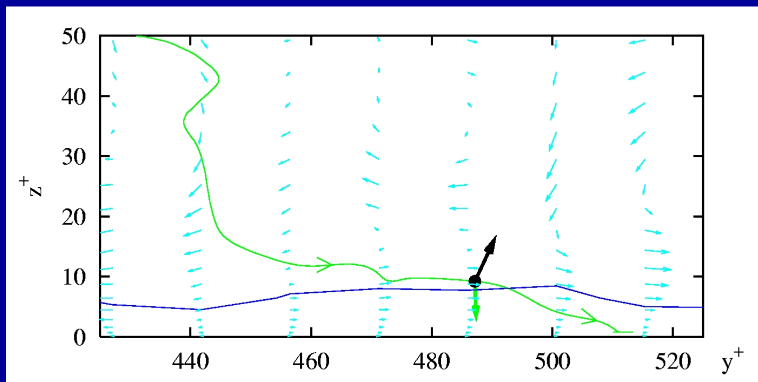


UPFLOW

→: drag force

→: lift force

bubble passes through the low-speed region and reach the wall



Conclusions

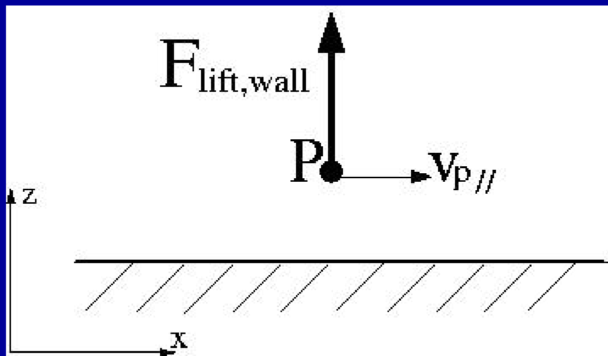
- *In the downflow case, in proximity of the wall, bubbles preferentially concentrate in high-speed regions*
- *Lift is responsible of such preferential concentration*
- *Due to low density ratio, also unsteady forces are important on single-bubbles trajectories*

Future developments (1)

- *In the upflow case, bubble accumulation near to the wall is overestimated by our simulations with respect to experimental data*
- *Importance of the lift force* $\longrightarrow$ *importance of the force model*

Future developments (2)

- *Wall correction to Lift Force*



$$F_{lift,wall} \;=\; 0.5\;\pi\;R^2\;\rho_f\;C_{L,wall}\;\left|\mathbf{v}_{p_{//}}\right|^2$$

Eq. from "Takemura, Magnaudet (2003), J. Fluid Mech."

($v_{p_{//}}$ bubble velocity parallel to the wall, R bubble radius, ρ_f fluid density)

Recent works on bubbles

- *Ferrante and Elghobashi, 2004: DNS of bubble drag reduction on horizontal plate*

- *Felton and Loth, 2001,2002: experimental investigation on bubble behavior in the near wall region of a vertical upward turbulent boudary layer*

- *Takemura and Magnaudet, 2003: wall effect on transverse migration of a rising bubble*

- *Tomiyama et al., 2002: influence of bubble dimension on transverse migration*