Turbulent bubbly flow in tube under gravity and microgravity conditions

Catherine Colin, Jean Fabre, Arjan Kamp

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Study supported by the French and European Space Agencies (CNES and ESA)

Motivations:

➔simple goemetry addressing the main issues on bubble dynamics in turbulent flow

➔several pratical applications in thermal, nuclear, chemical industries

Some previous experimental studies

In vertical upward flow

Numerous studies in pipes of 30mm to 60mm diameter tubes

Serizawa et al. (1975, 1992), Herringe & Davis, (1976); Van der Welle, (1985); Liu & Bankoff, (1993); Liu, (1998); Wang et al., (1987); Zun et al. (1991); Grossetête, (1995), Hosokawa et al. (2006)

- Strong evolution of the void fraction along the pipe, effect of bubble coalescence
- Different shapes for the void fraction profiles (wall-peaking or void coring) depending on the inlet conditions (flow rates, bubble size) and pipe geometry
- Difficult to compare the experiments

In downward flow

- Some studies in 57mm and 38mm diameter tubes

Wang (1985); Nakoryakov et al. (1994) ; Hibiki et al. (2004)

- Void coring observed in general
- Weak effect of coalescence

Neutrally buoyant particles or bubble flow in microgravity condition

Lahey & Bonetto (1994) - Kamp (1996); Takamasa et al. (2003), Hazaku et al. (2012)

- Rather flat profile of void fraction profiles
- No strong modification of the liquid flow by comparison to single-phase flow

Objectives

Our objective is:

- to highlight the role of the gravity (slip velocity) upon the bubble radial distribution in a tube, the mean liquid velocity and turbulence

- through experiments on bubbly flows with the same experimental facility in constrated gravity conditions:
  - in vertical upward, downward flows in laboratory
  - in microgravity conditions (without bubble slip velocity)

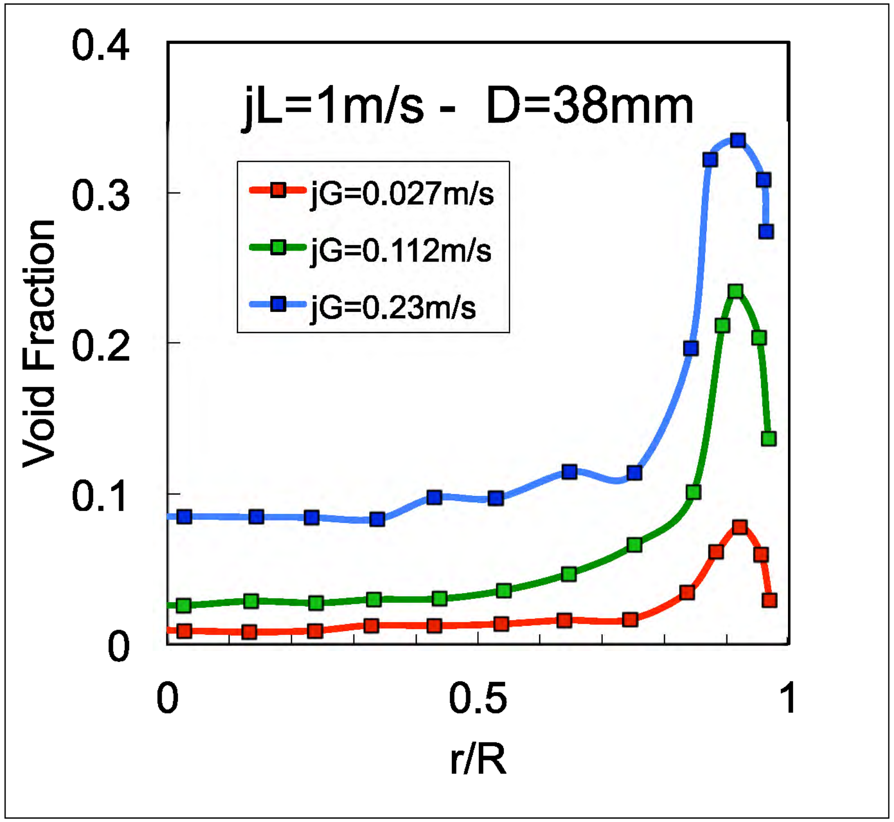
- explain some results through simple analytical models

Present analysis focused on bubbles with size comparable to the turbulent length scales $d_B \sim l_t$ and large range of U_{LG}/u_*

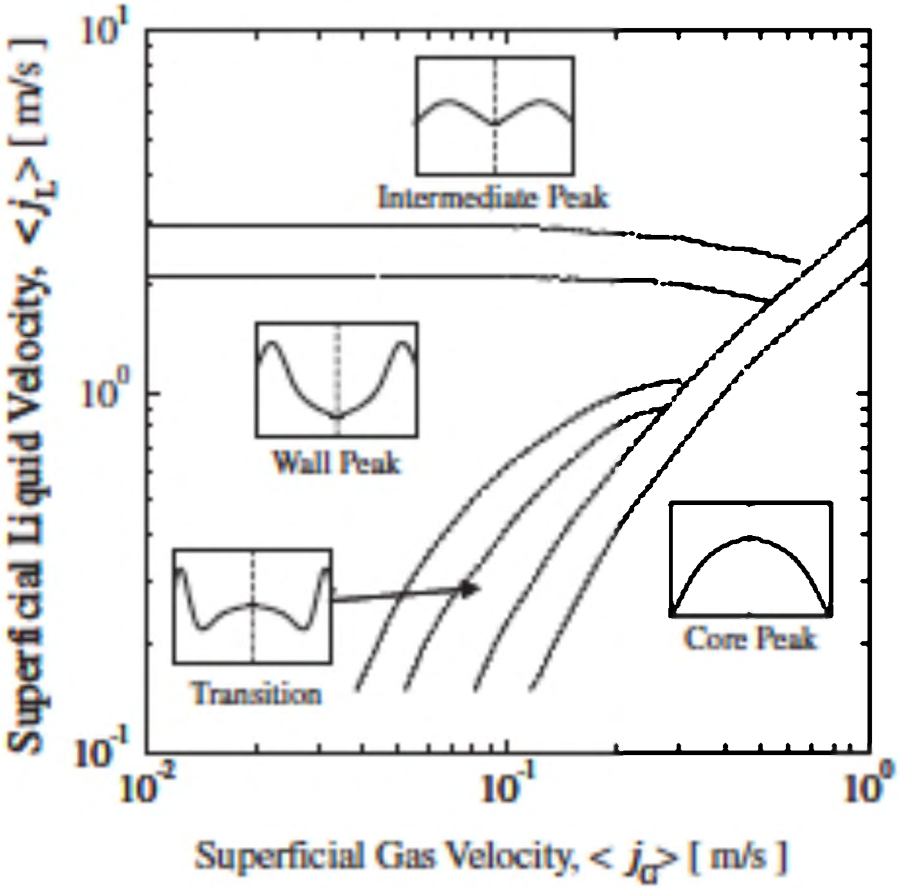
Outline

- Introduction
- Experimental set-up and measurement techniques
- Main results on:
  - vertical upward flow
  - downward flow
  - microgravity flow
- Wall friction and logarithmic law
- Turbulence in bubbly flows
- Void fraction distribution
- Conclusion and perspectives

Vertical upward flow: void fraction distribution



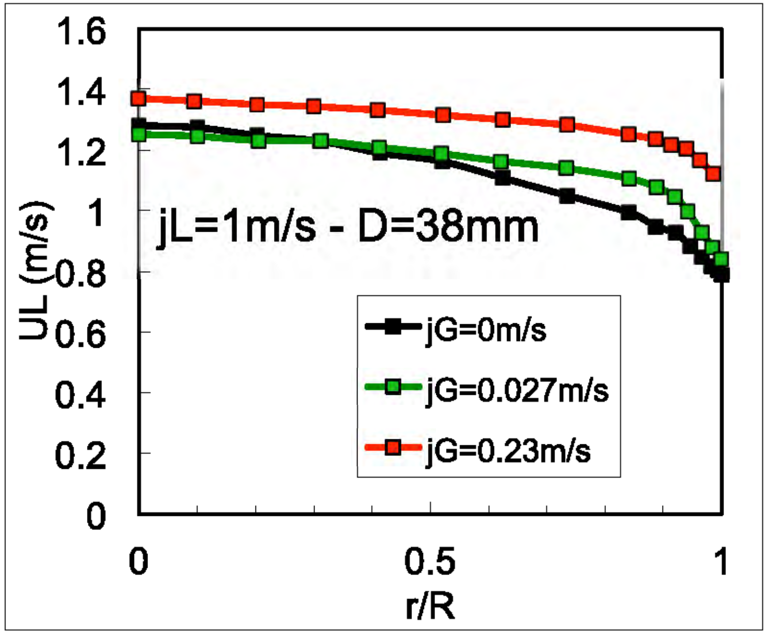
Liu et Bankhoff, IJHMT (1993)



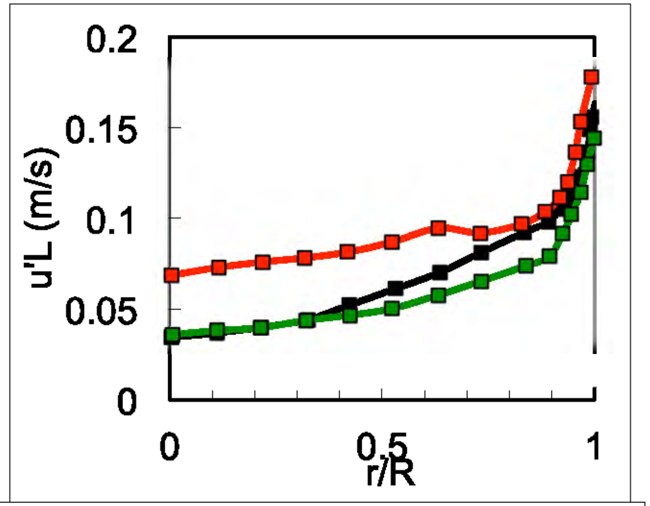
Serizawa & Kataoka, (1988)

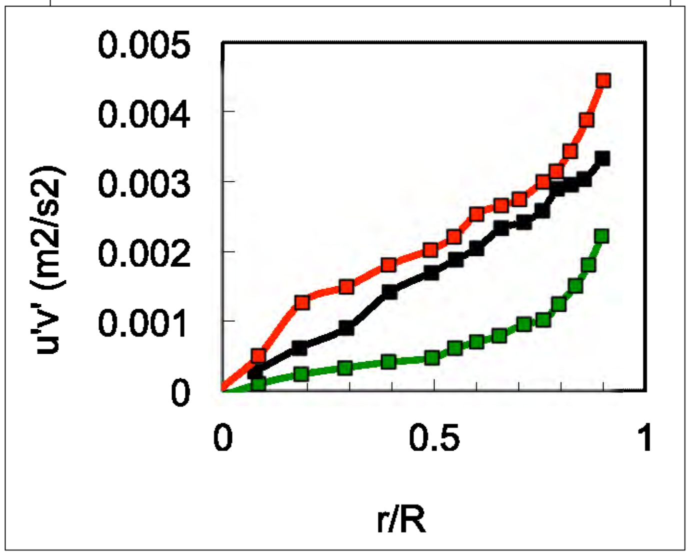
Shape of the void fraction profile depends on the air and liquid flow rates bubble size, pipe size, ratio of the bubble size compared to turbulent length scales

Vertical upward flow: mean velocity and turbulence



Liu et Bankhoff (1993)

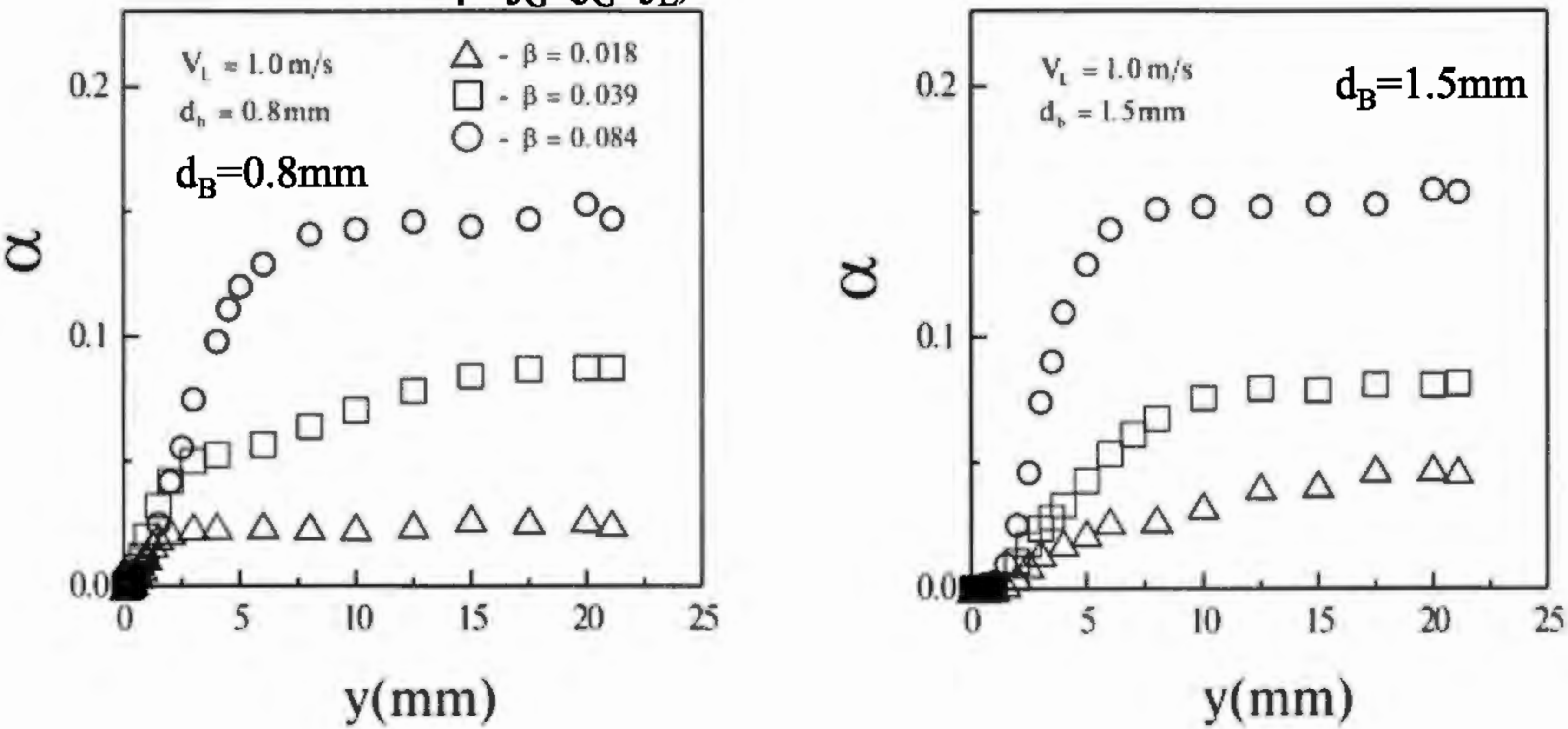




Flattening of the mean velocity profiles, modification of the turbulence level, sometime increased but also decreased (Serizawa et al., 1975)

Vertical downward flow: void fraction profiles

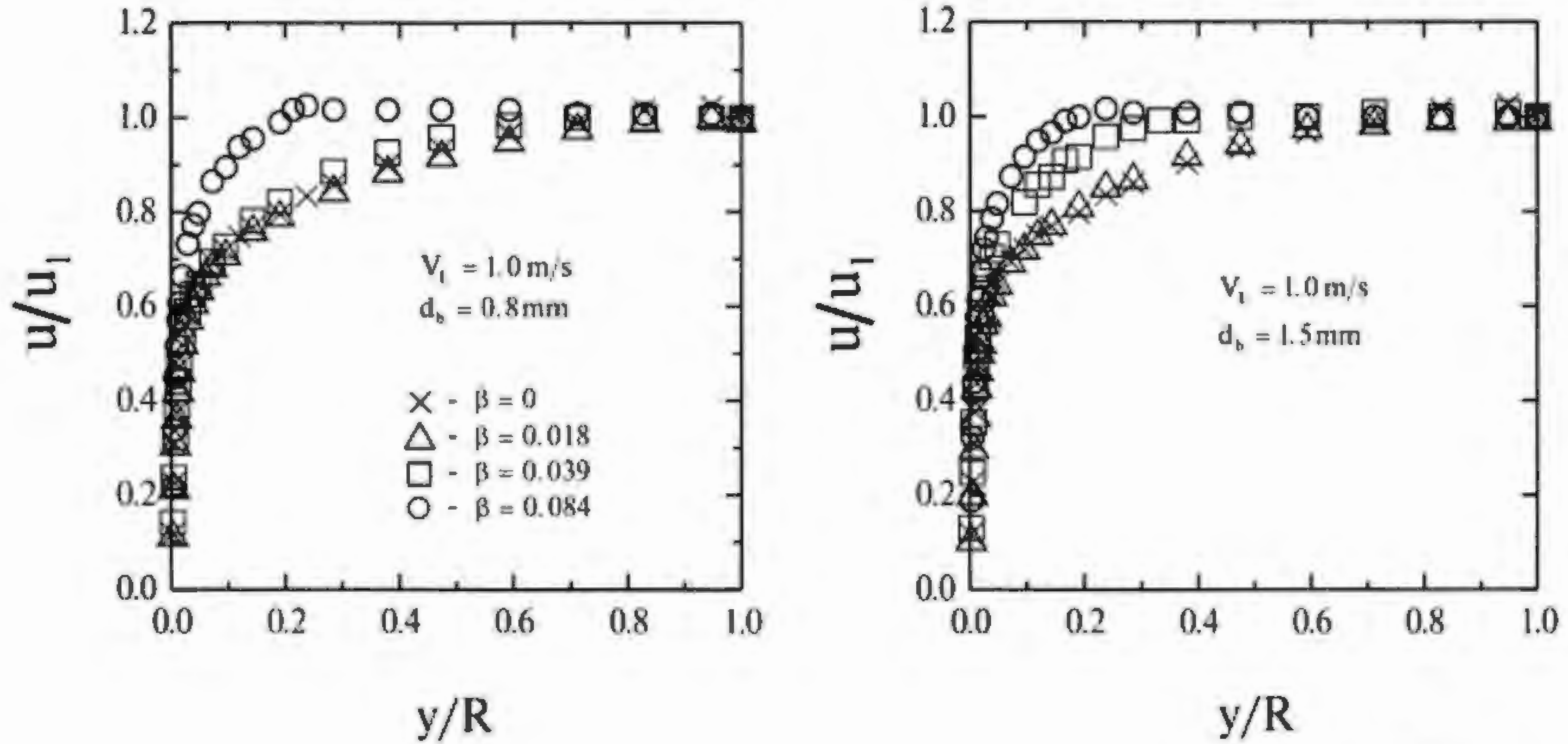
$\beta = j_G/(j_G+j_L)$



j_L=1m/s – D=42mm

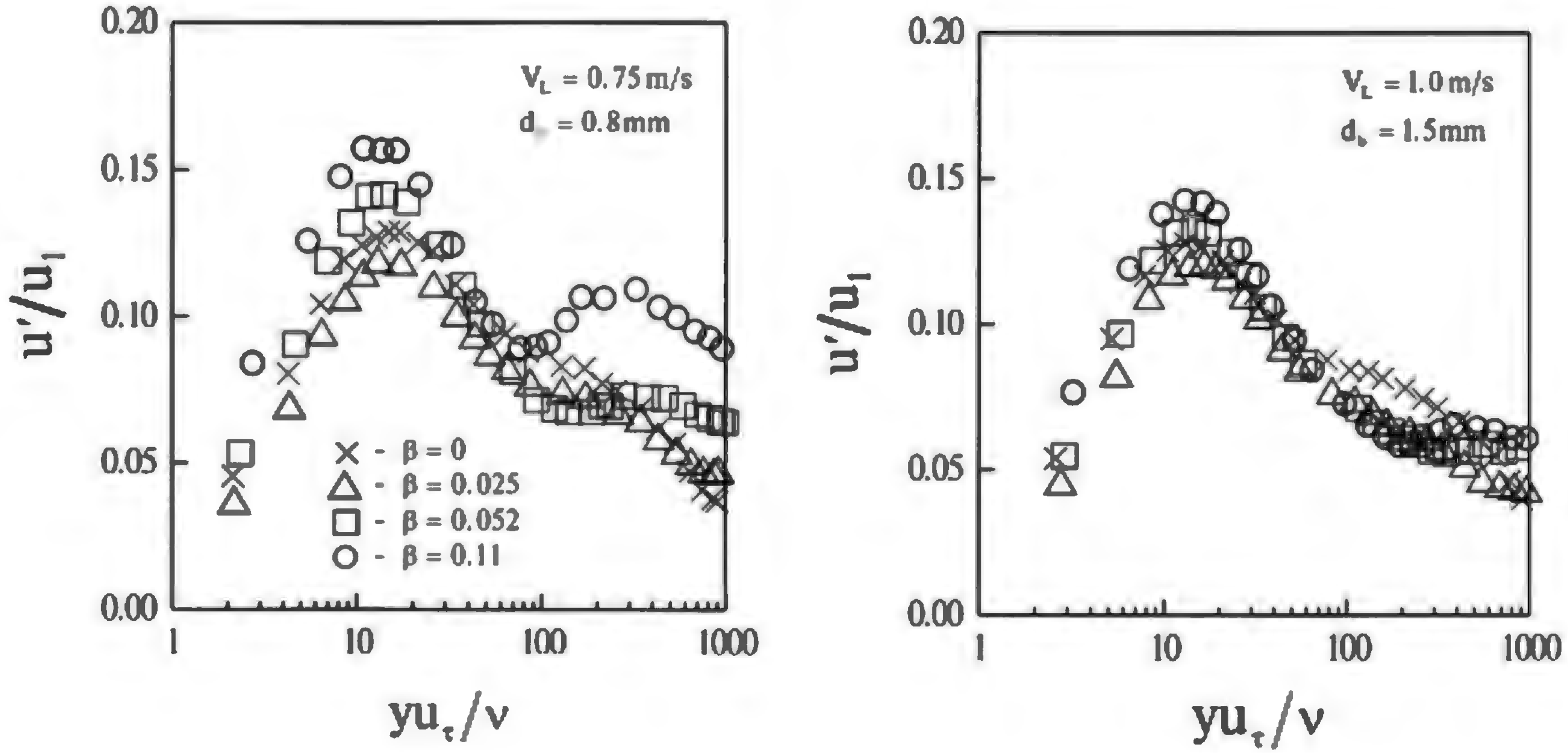
Kashinshy & Randin, IJMF 1999

Vertical downward flow:
Mean velocity profiles



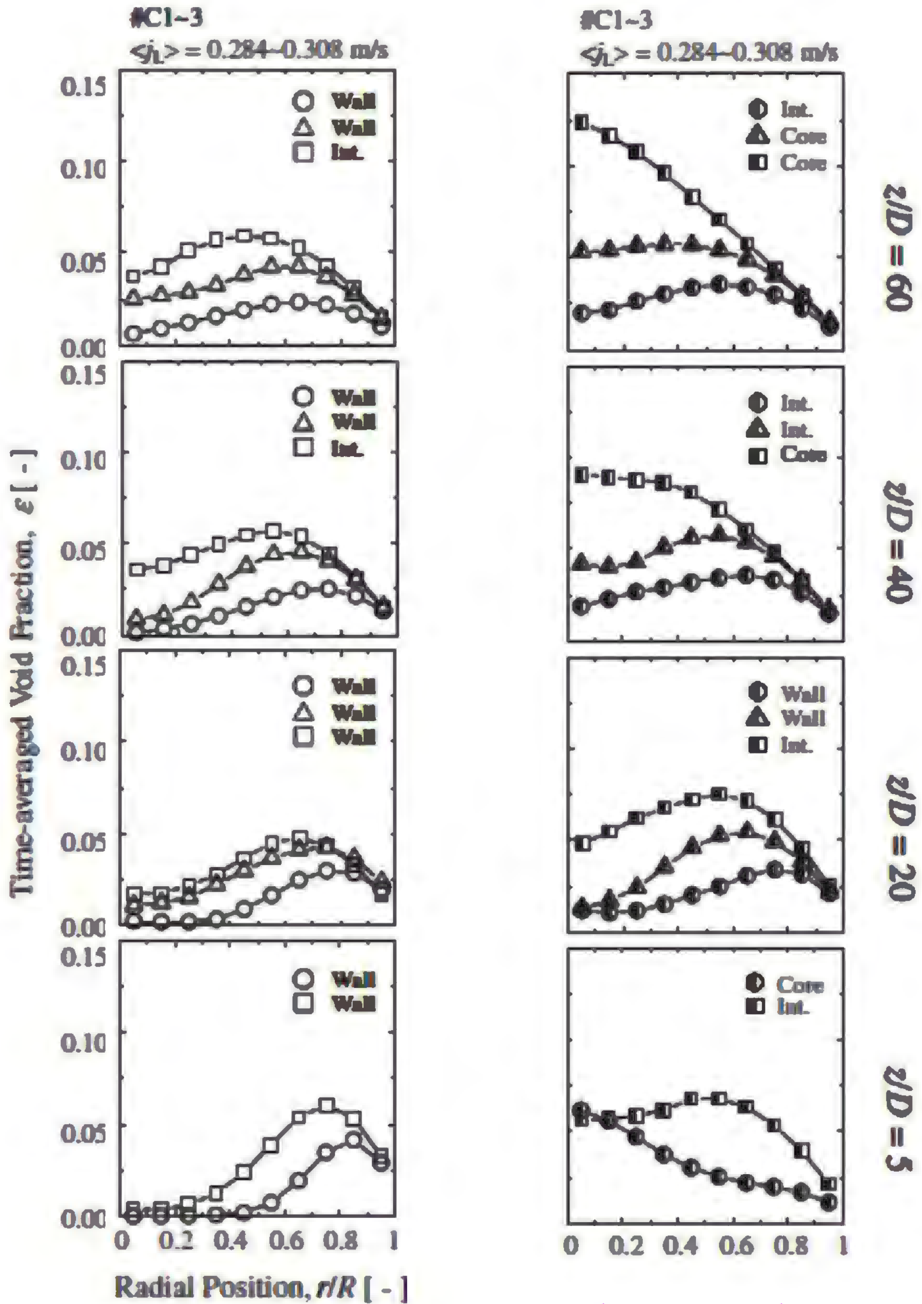
Flattening of the velocity profiles depending on the bubble size

Vertical downward flow:
Streamwise turbulent intensity



Enhancement or reduction of turbulence level compared to single-phase flow, depending on air and water flow rates and bubble size

Microgravity Flows



Upflow

Microgravity

Very few studies

Lahey et Bonetto (1994)

Neutrally buoyant particles

Hazaku, Takamasa, Hibiki, IJMF 2012

Bubbly flow in 1g and 0G- measurements on the gas phase only

Both void peaking and void coring profiles in microgravity in 9mm tube (large bubbles and entrance effect memory)

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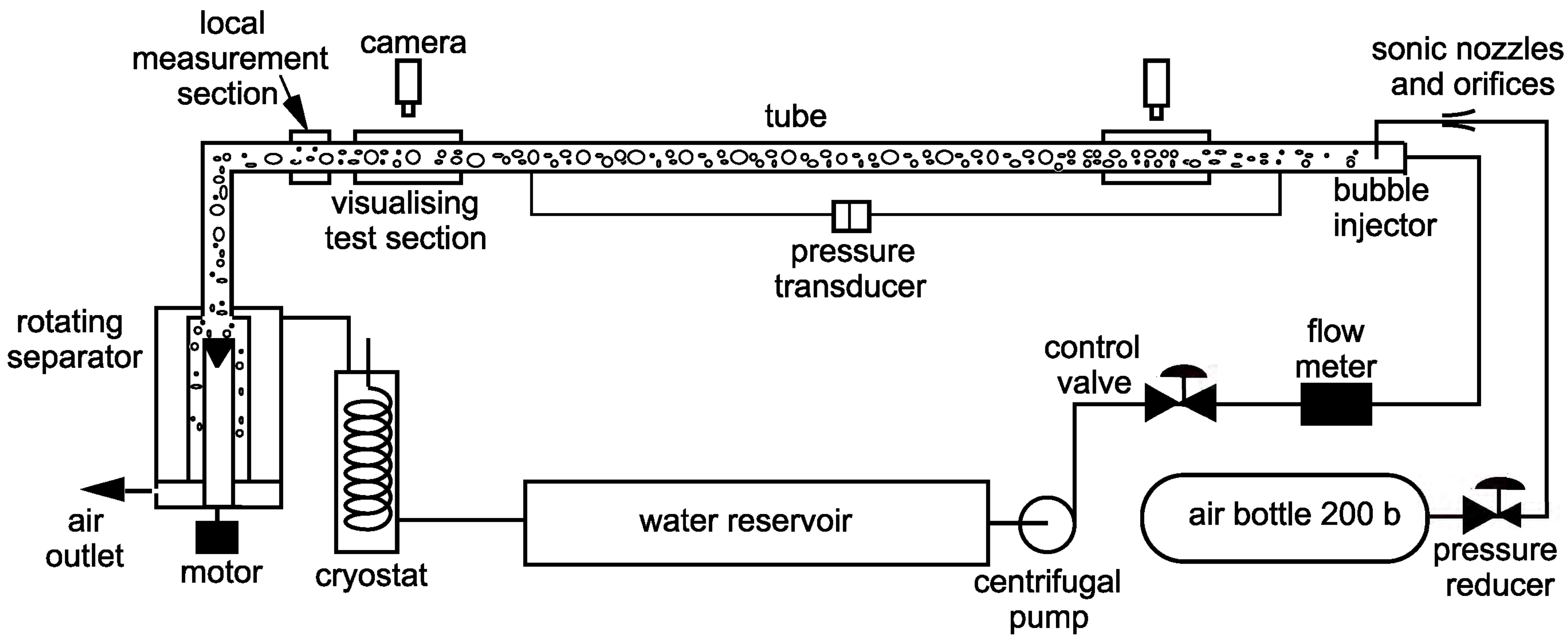
The two-phase flow loop EDIA

Air and water in a tube of 40 mm:



Metrology:

- Pressure transducers Validyne
- Conductive O-ring probes (global void fraction)
- High speed video recording (1000 i/s) and image processing

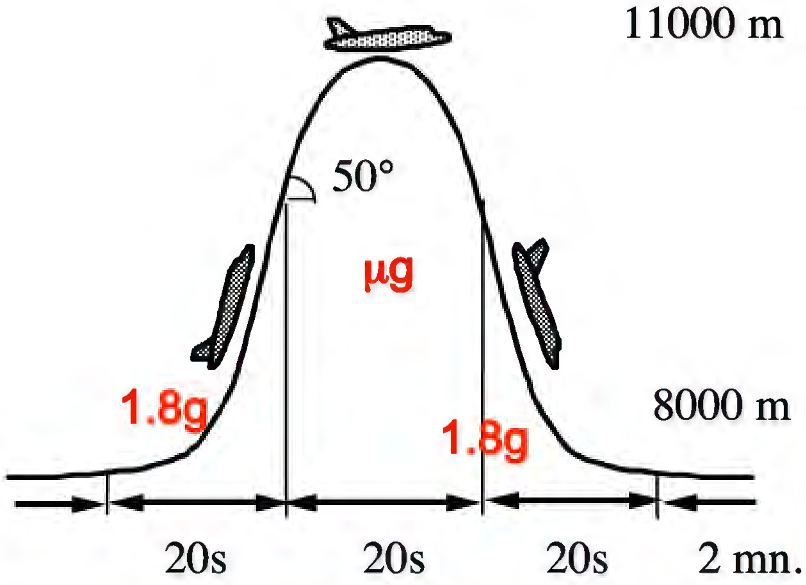
Local measurements in bubbly flows in a 40 mm diameter pipe

Dual optical fibre probe for:
-measurements of local void fraction, bubble velocities
- determination of the bubble diameters distribution using a backward transformation of the measured chord length distributions *(Kamp, 1996)*.

Hot film anemometry for:
-measurement of the axial mean and RMS velocity of the liquid
Specific data processing for phase discrimination

In microgravity conditions several parabolas required for each measurement point (statistical convergence).

Parabolic flights



Caravelle, KC135, Airbus A300 « ZERO G »

1 flight = 30 to 40 parabolas

Micro gravity period T = 20 s with J_z < 0.03 g

Measurement period T - L/U ~ 10 to 15 s

L=pipe length, U flow velocity

Several parabolas required for statistical convergence of local measurements

Flow parameters

U1

upward

Re=10000

Run	g/g_0	j_L (m/s)	j_G (m/s)	$\langle\alpha\rangle_m$	dP/dx (Pa/m)	u_* (m/s)	d mm	Re
S1		0.27	0	0	-29	0.017		10800
S3		0.77	0	0	-160	0.040		30800
S4		1	0	0	-281	0.053		40000
U1	-1	0.27	0.023	0.033	268	0.039	3.3	11720
U3	-1	0.77	0.046	0.038	141	0.053	3.5	32640
U4	-1	1	0.023	0.018	-125	0.056	3.4	40920
D3	1	0.77	0.053	0.095	1148	0.064	4.2	32920
D4	1	1	0.024	0.031	585	0.059	3.1	40960
M1	0	0.27	0.030	0.100	-35	0.019	1.8	12000
M3	0	0.78	0.046	0.054	-222	0.047	2.0	33040
M4	0	1	0.028	0.032	-270	0.052	1.2	41120

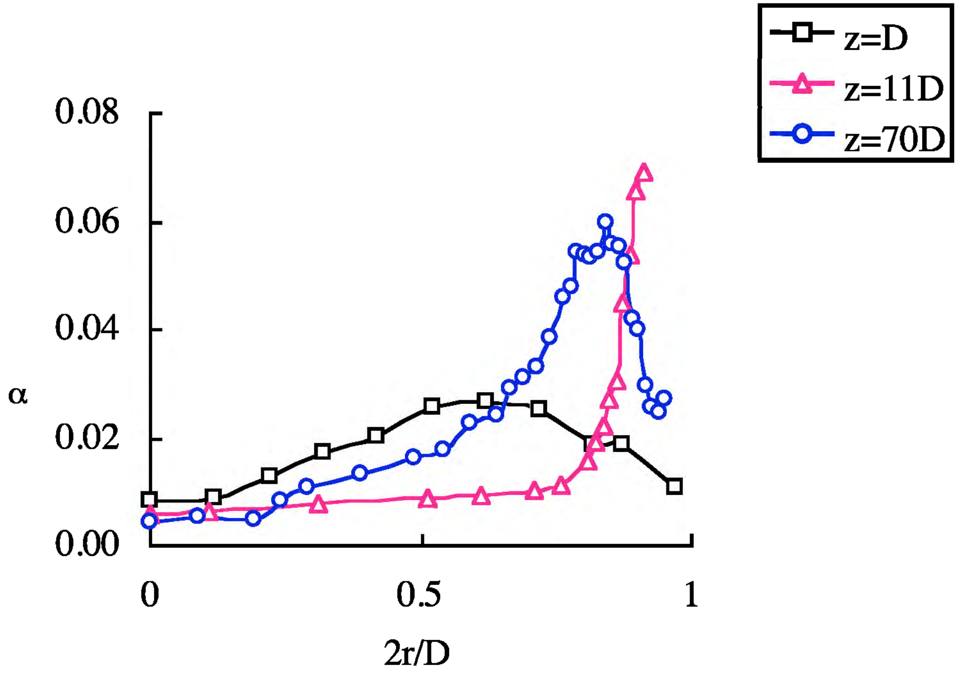
Vertical up-flow: U1, U3, U4

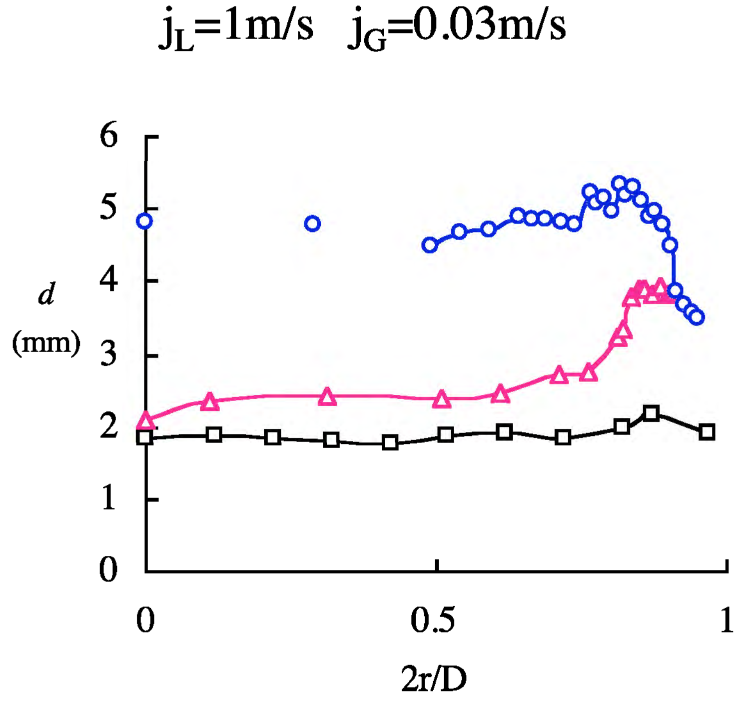
Vertical down-flow: D3, D4

Microgravity flow: M1, M3, M4

In microgravity coalescence inhibited by adding SDS

Vertical upward flow:
Void fraction and bubble size

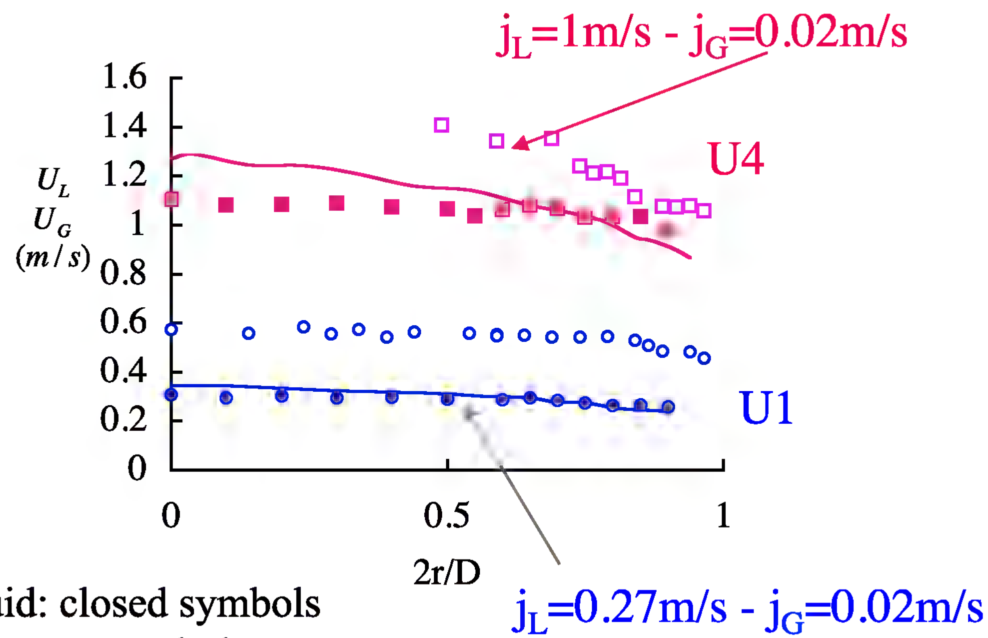




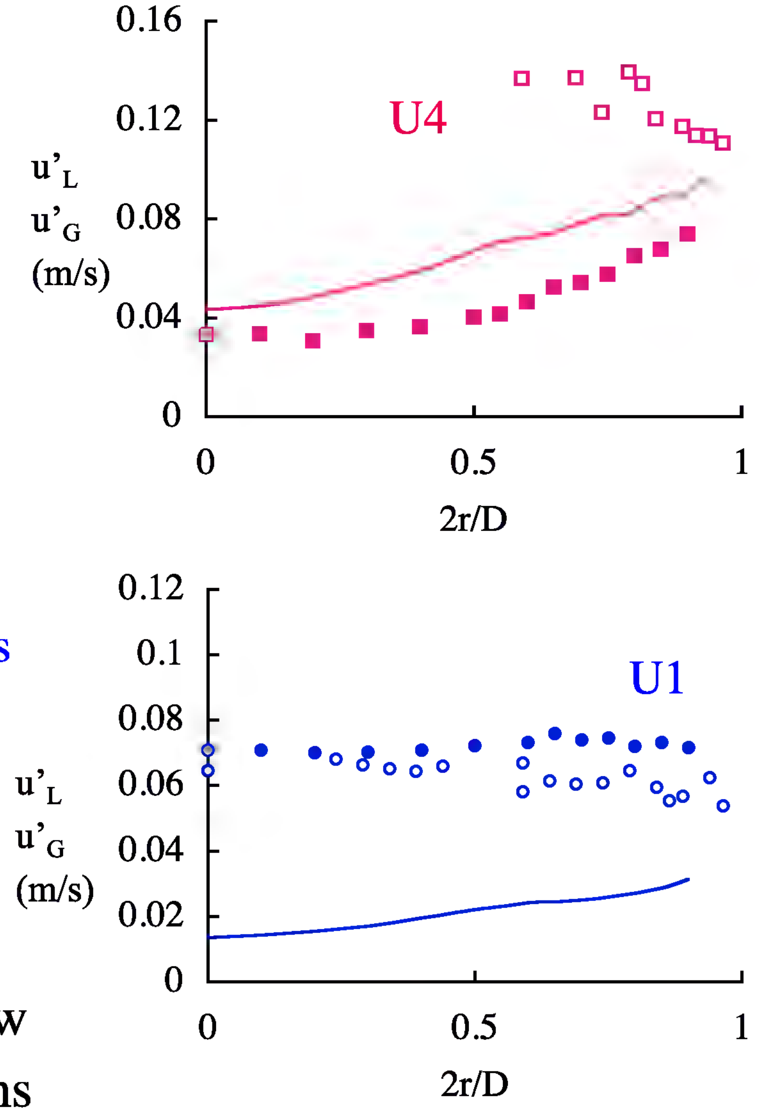
- Bubbles injected through 32 capillary tubes of 0.3mm diameter at z=0
- Maximum of void fraction near the wall
- Axial evolution of the void fraction profiles partly due to bubble coalescence
- Bubble coalescence dominant near the wall (high void fraction and high turbulence)

Vertical upward flow:

mean and RMS velocities of liquid and gas

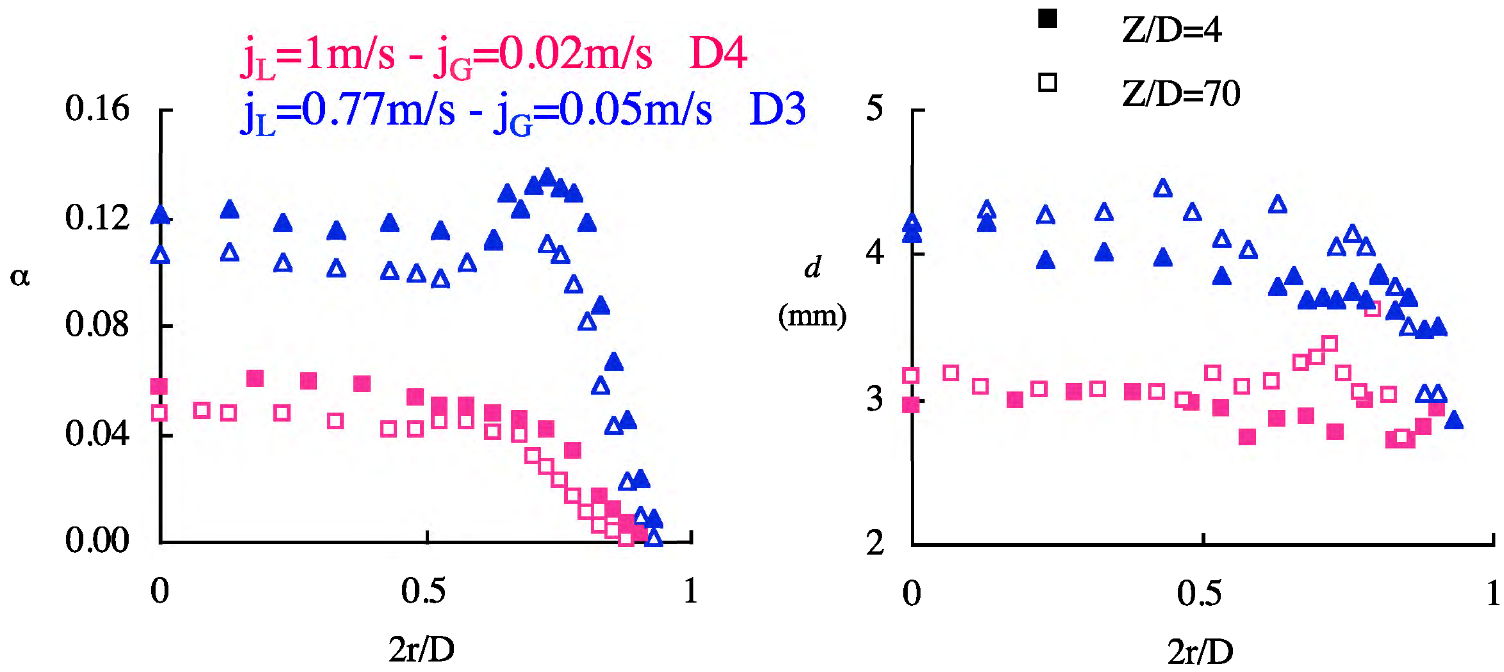


Liquid: closed symbols
Gas: open symbols



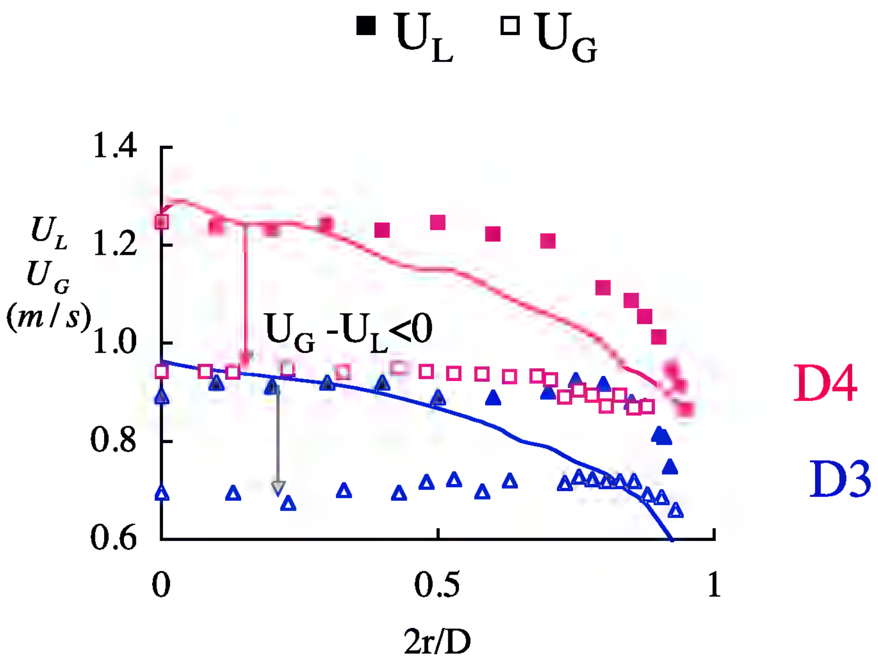
- Flattening of the mean velocity profiles
- Bubble drift velocity 20 to 30 cm/s
- Increase or decrease of turbulence in two-phase flow
- RMS velocities of gas depend on the flow conditions

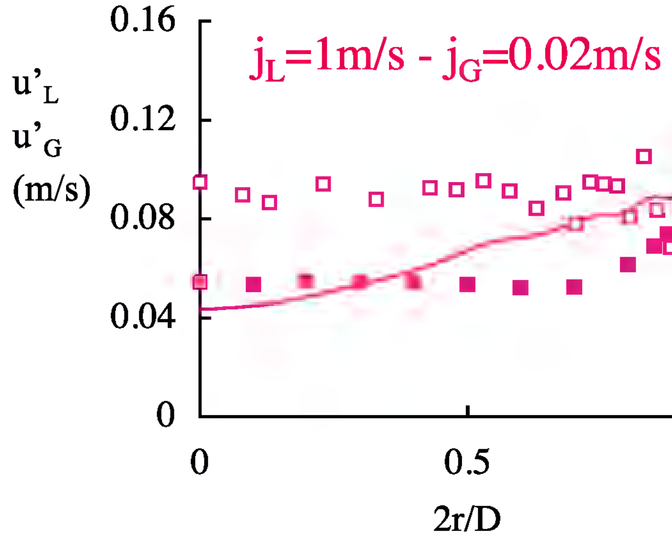
Vertical downward flow:
Void fraction and bubble sizes

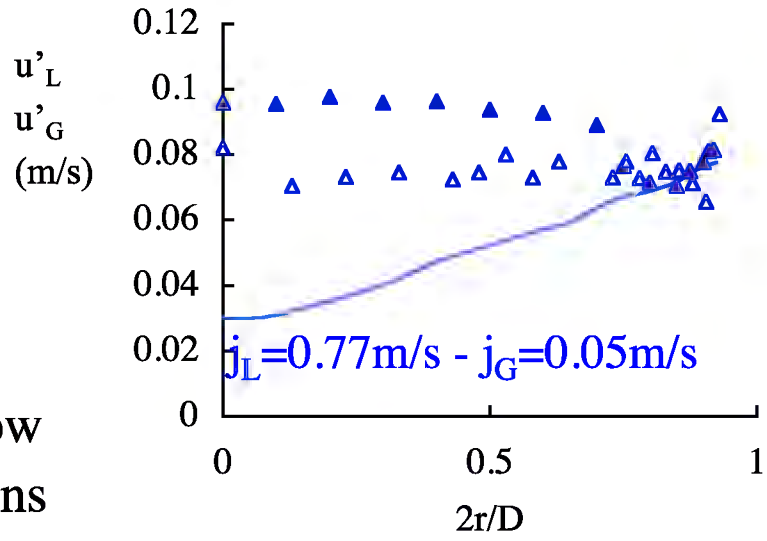


- Void coring effect
- No bubbles in the near wall region
- Weak effect of bubble coalescence
- Slow development of the flow in the axial direction

Vertical downward flow



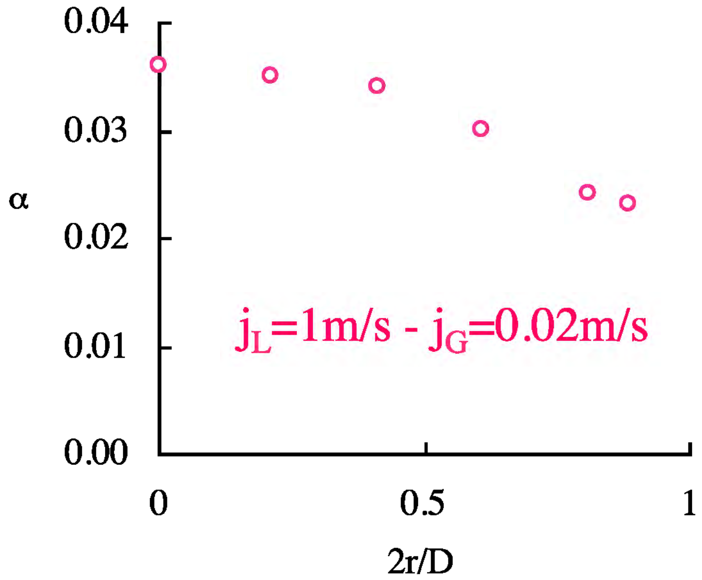


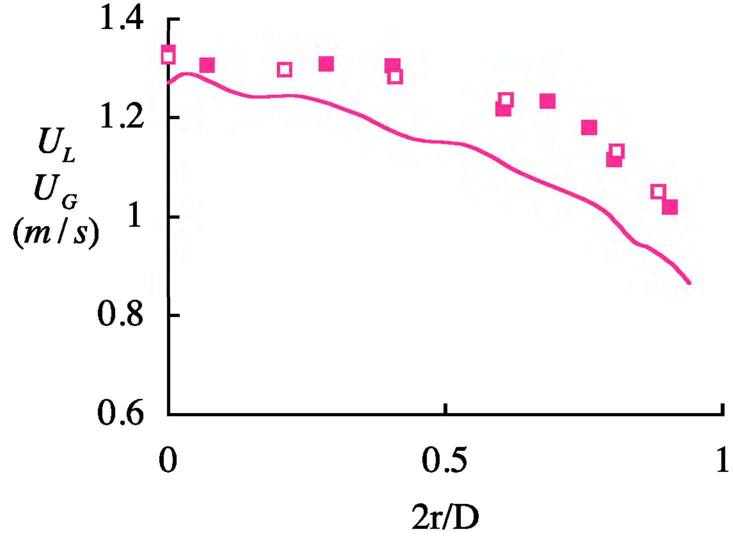


- Flattening of the mean velocity profiles
- Bubble drift velocity - 20 to - 30 cm/s decreases near the wall
- Increase or decrease of turbulence in two-phase flow
- RMS velocities of gas depend on the flow conditions

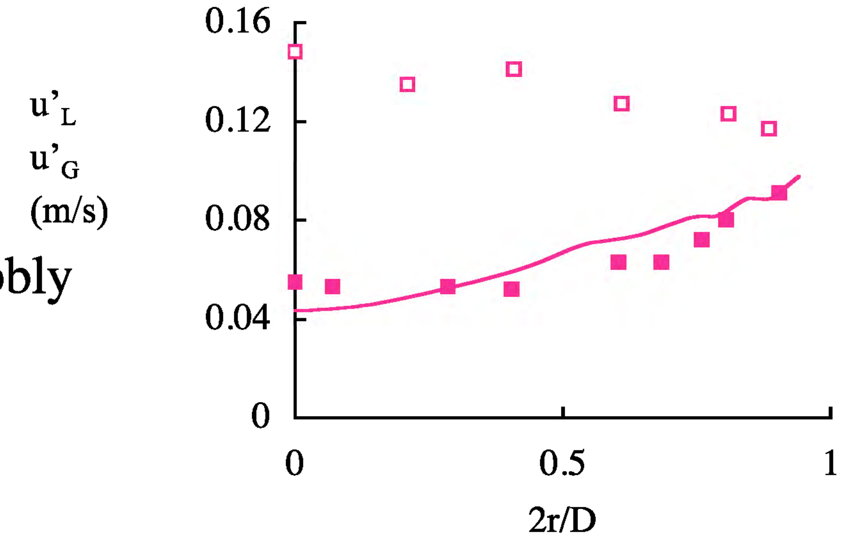
Micro-gravity flows

M4





- Small bubbles (surfactant)
- Flat profile of void fraction
- Mean bubble drift velocity near 0
- No significant increase of turbulence in bubbly flow

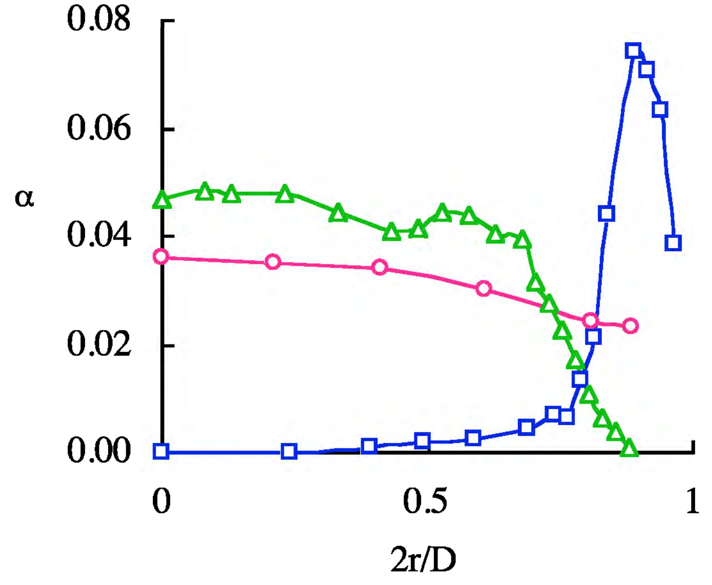


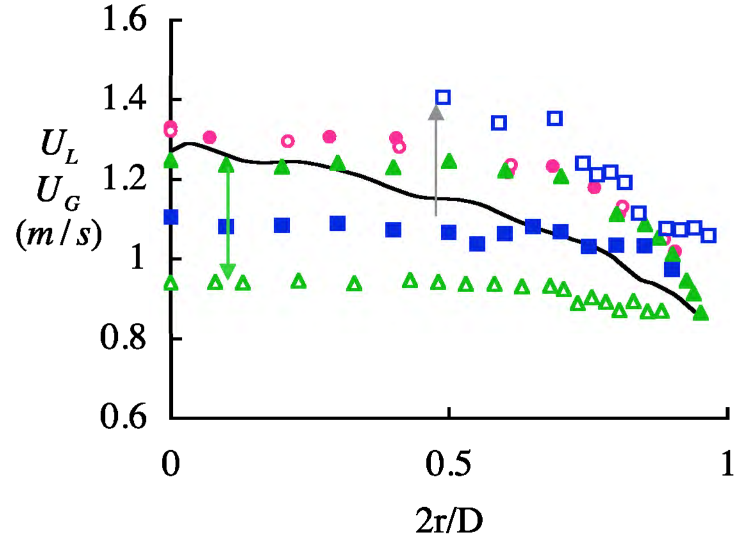
- $\sqrt{u'^2_G}/\sqrt{u'^2_L} \approx 2$ to 3

good agreement with the Tchen's Theory

Influence of gravity on the structure of bubbly flow:

Migro gravity, 1-g upward flow, downward flow





Microgravity Bubbly flows similar to single-phase flow

In normal gravity, upward flow or downward flow:

2 regions in the flow: wall region and a core region

Void fraction, velocity distribution and turbulence strongy depend on gravity

Turbulence can be reduced or enhanced /single-phase flow

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- Experimental set-up and measurement techniques
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    - microgravity flow
- **Wall friction and logarithmic law**
- Turbulence in bubbly flows
- Void fraction distribution
- Conclusion and perspectives

Wall friction

Very few measurements reported in bubbly flows

- determined from pressure drop: requires very good accuracy on void fraction measurements (Liu, IJMF 1997):

$$\frac{dP}{dx} = \rho_L g(1 - <\alpha>) + \frac{4}{D}\tau_w = \rho_L g(1 - <\alpha>) + \frac{4}{D}\rho_L u_*^2$$

- direct method as electrochemical method (Nakoryakov et al., 1999)

- indirect methods: log law fitting (validity?) or extrapolation of the turbulent shear stress (difficult not linear in bubble flow)

Some correlations or models

- $\tau_w/\tau_{w0} = f(Re, <\alpha>)$ by Herringe et Davis (1978) and Beyerlein et al., (1985)

- Including void fraction distribution by Sato et al. (1981) or Marié (1987)

Wall friction

Wall shear stress is obtained from measurements of pressure drop and mean void fraction

$$\frac{dP}{dx} = \rho_L g < \alpha > + \frac{4}{D}\tau_w = \rho_L g < \alpha > + \frac{4}{D}\rho_L u_*^2$$

Ratio of buoyancy over wall friction

Run	g	j_L (m/s)	j_G (m/s)	$<\alpha>$	u_{*0} (m/s)	u_* (m/s)	d mm	Re	Ri_*
U1	-1	0.27	0.023	0.043	0.017	0.039	3.3	11720	2.77
U3	-1	0.77	0.046	0.043	0.043	0.053	3.5	32640	1.5
U4	-1	1	0.023	0.019	0.053	0.056	3.4	40920	0.59
D3	1	0.77	0.053	0.075	0.044	0.064	4.2	32920	1.8
D4	1	1	0.024	0.024	0.053	0.059	3.1	40960	0.68
M1	0	0.27	0.030	0.055	0.017	0.019	1.8	12000	0
M3	0	0.78	0.046	0.041	0.043	0.047	2.0	33040	0
M4	0	1	0.028	0.025	0.053	0.052	1.2	41120	0

$$Ri_* = \frac{|g| < \alpha > D}{4 u_*^2}$$

when $Ri_* > 1$ $u_* > u_{*0}$

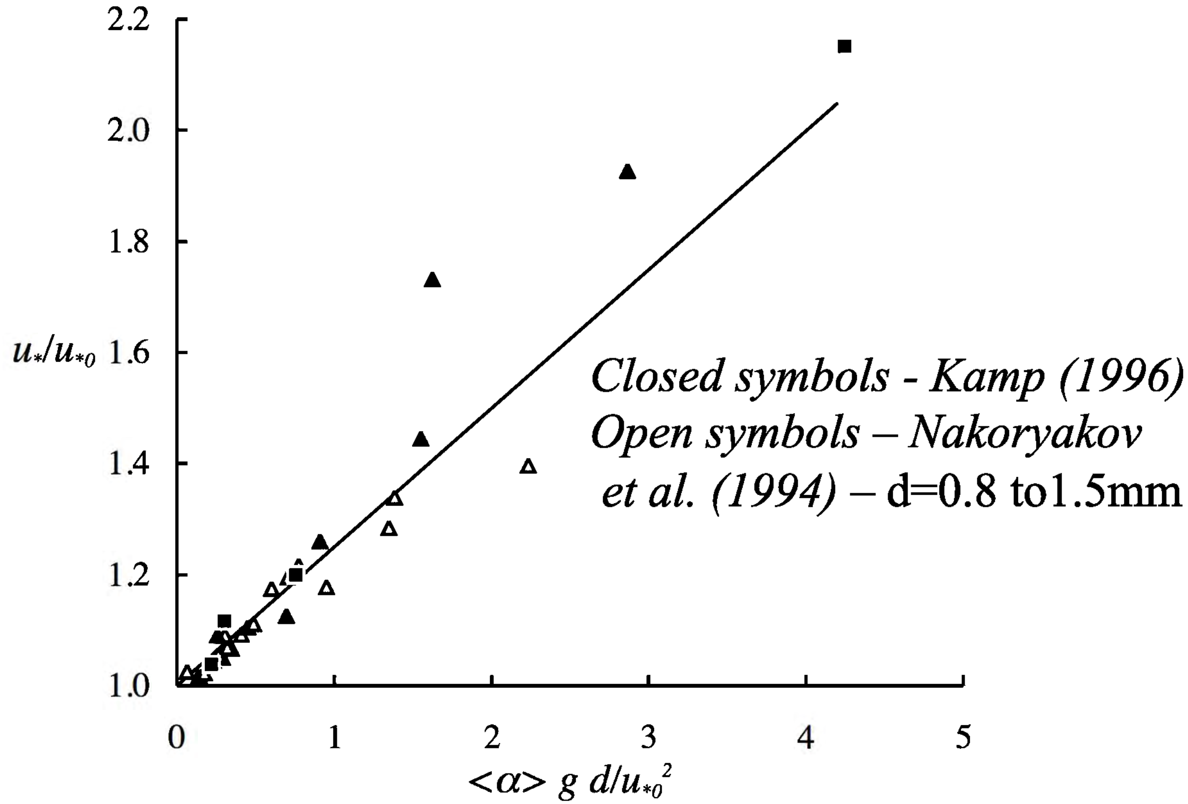
Wall friction in bubbly flow

Marié *et al.* (1997) : analysis of the turbulent bubbly boundary layer, estimation of u_* approximated expression :

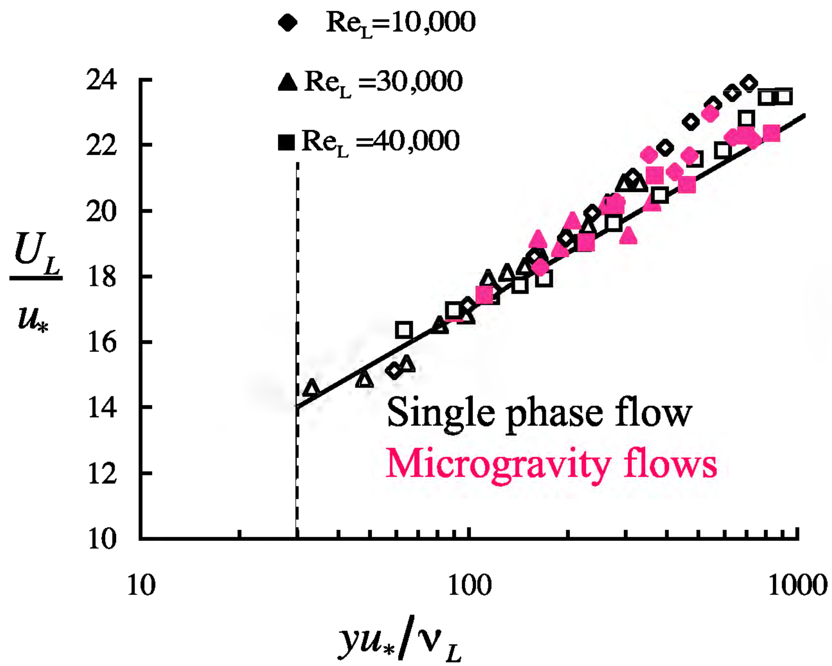
$$\frac{u_*}{u_{*0}} \approx 1 + \underbrace{\frac{1}{2}\left(1 - 10.6\frac{u_{*0}}{<U_L>}\right)}_{0.5} Ri_{*d} \quad \text{with} \quad Ri_{*d} = \frac{(\alpha_w - \alpha_c)gd}{u_{*0}^2}$$

Simple expression

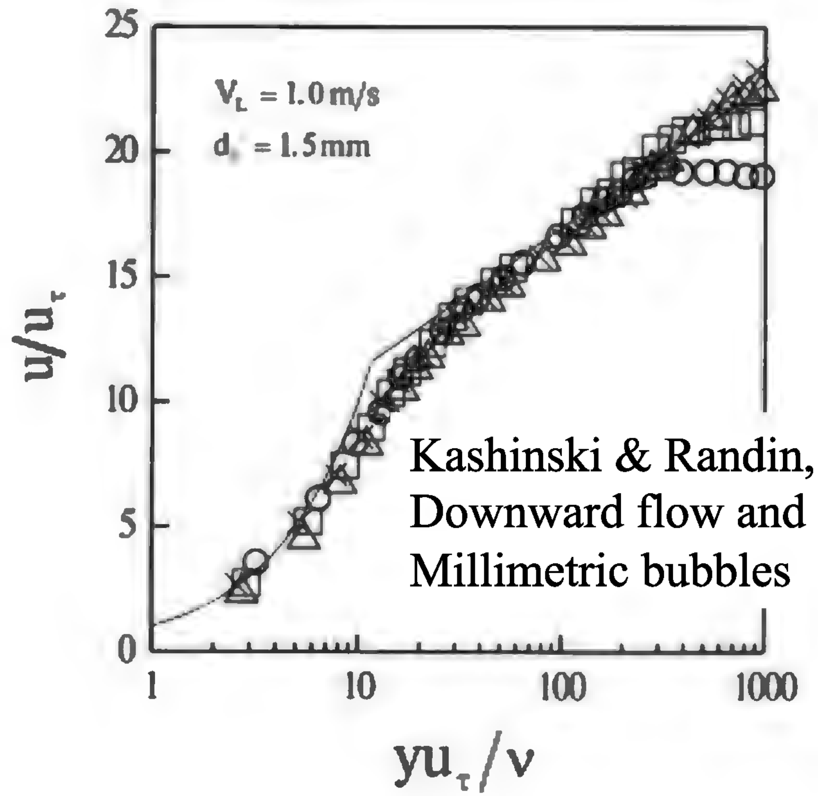
$$\frac{u_*}{u_{*0}} = \sqrt{\frac{\tau_w}{\tau_{w0}}} = 1 + \frac{<\alpha> g\,d}{4\,u_{*0}^2}$$



Liquid Mean velocity



$$\frac{U_L}{u_*} = \frac{1}{\kappa} \mathrm{Ln}\left(\frac{yu_*}{\nu_L}\right) + B$$

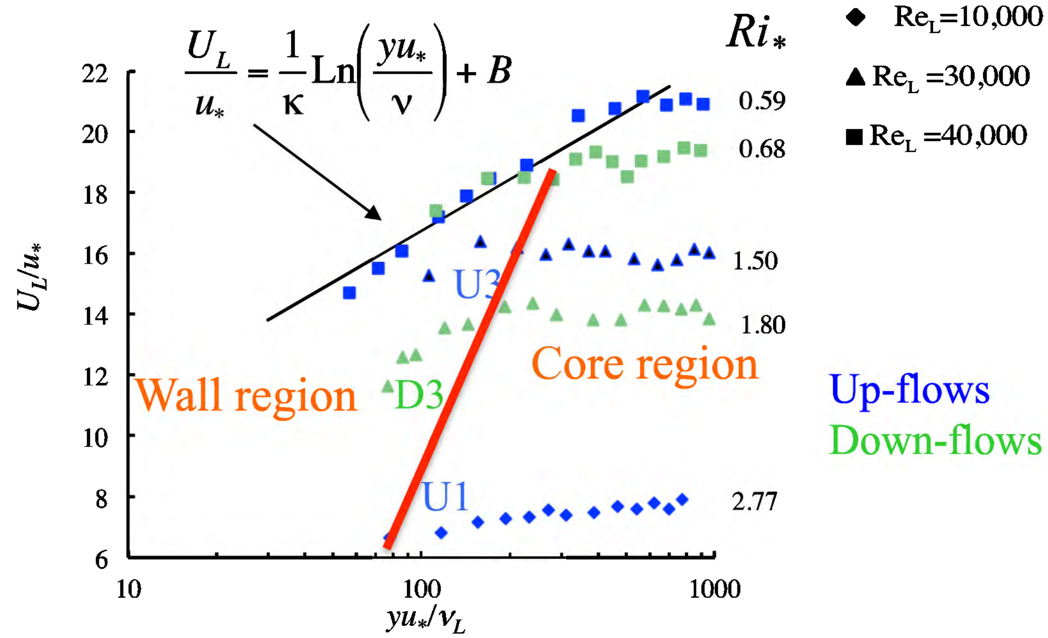


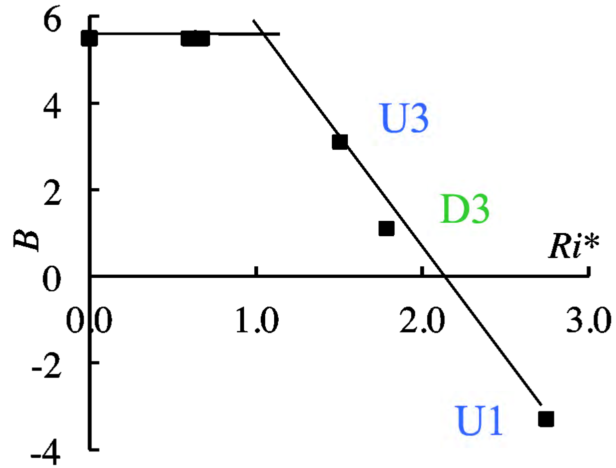
Kashinski & Randin, 1999
Downward flow and
Millimetric bubbles

In agreement *with A. Soldati*

Logarithmic law valid without change of κ=0.41 and B=5.5

Liquid Mean velocity





•In gravity-depend flows: departure from the log-law in the inertial region (U1, U3, D3) – the constant B<5.5

•Presence of an homogeneous region farther from the wall (flat velocity profile)

$$\delta/D = 0.48/Ri_*$$

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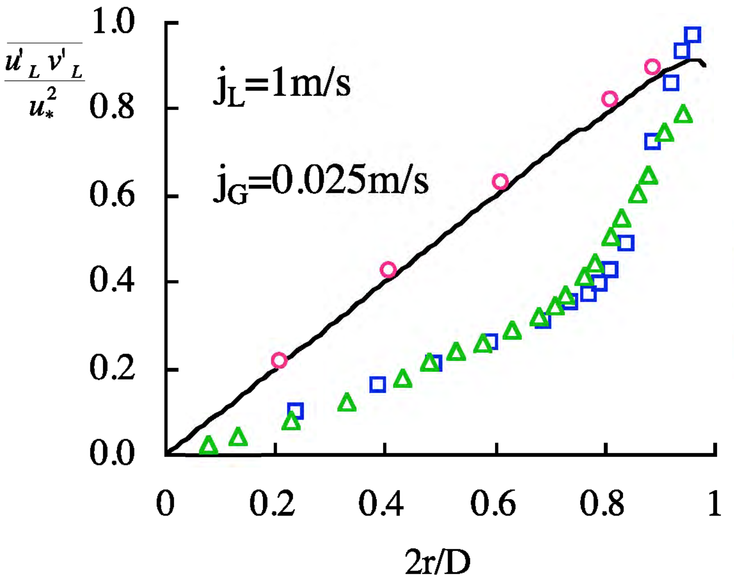
Turbulent shear stress

Axial Momentum Bal. Eq. of the mixture $-\frac{dP}{dx}+\frac{1}{r}\frac{d}{dr}\left[r(1-\alpha)\tau_L\right]-\rho_L(1-\alpha)g=0$

Turbulent shear stress is calculated from the measurements of α

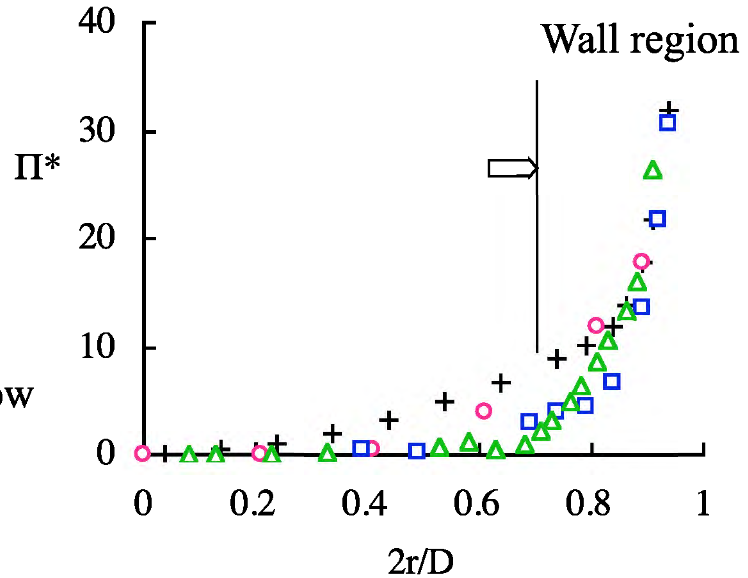
$$-\rho_L\overline{u_L' v_L'}=\left[\frac{dP}{dz}+\rho_L g\right]\frac{r}{2(1-\alpha)}-\frac{\rho_L g}{(1-\alpha)r}\int_0^r \alpha r'\,dr'-\mu_L\frac{\partial U_L}{\partial r}$$



Upflow,
Downflow
Microgravity
Single-phase flow

Production

$$\Pi^*=-(1-\alpha)\overline{u_L' v_L'}\frac{\partial U_L}{\partial r}\frac{D}{2u_*^3}$$



Production of turbulence is smaller in up and down flows than in single-phase flow

Turbulent kinetic energy of the liquid

$$k_L = \frac{1}{2}\left(u_L^2 + v_L^2 + w_L^2\right)$$

For very low void fractions
k_L is splitted into 2 contributions = k_{LS} + k_{LB}

(Lopez de Bertodano et al., 1994, Chahed et al., 2003)

Shear-induced turbulence (steady axi-symetric flow):

$$\underset{(a)}{-\rho_L(1-\alpha)\overline{u_L v_L}\frac{dU_L}{dr}} \underset{(b)}{-\rho_L(1-\alpha)\varepsilon_{LS}} + \underset{(c)}{\frac{1}{r}\frac{d}{dr}\left[\rho_L(1-\alpha)\frac{\nu_L^t}{\sigma_k} r \frac{dk_{LS}}{dr}\right]} = 0$$

Production Dissipation Diffusion

Bubble-induced turbulence: $k_{LB} \approx \alpha U_{LG}^2$

(Lance & Bataille, 1991 Garnier et al., 2001)

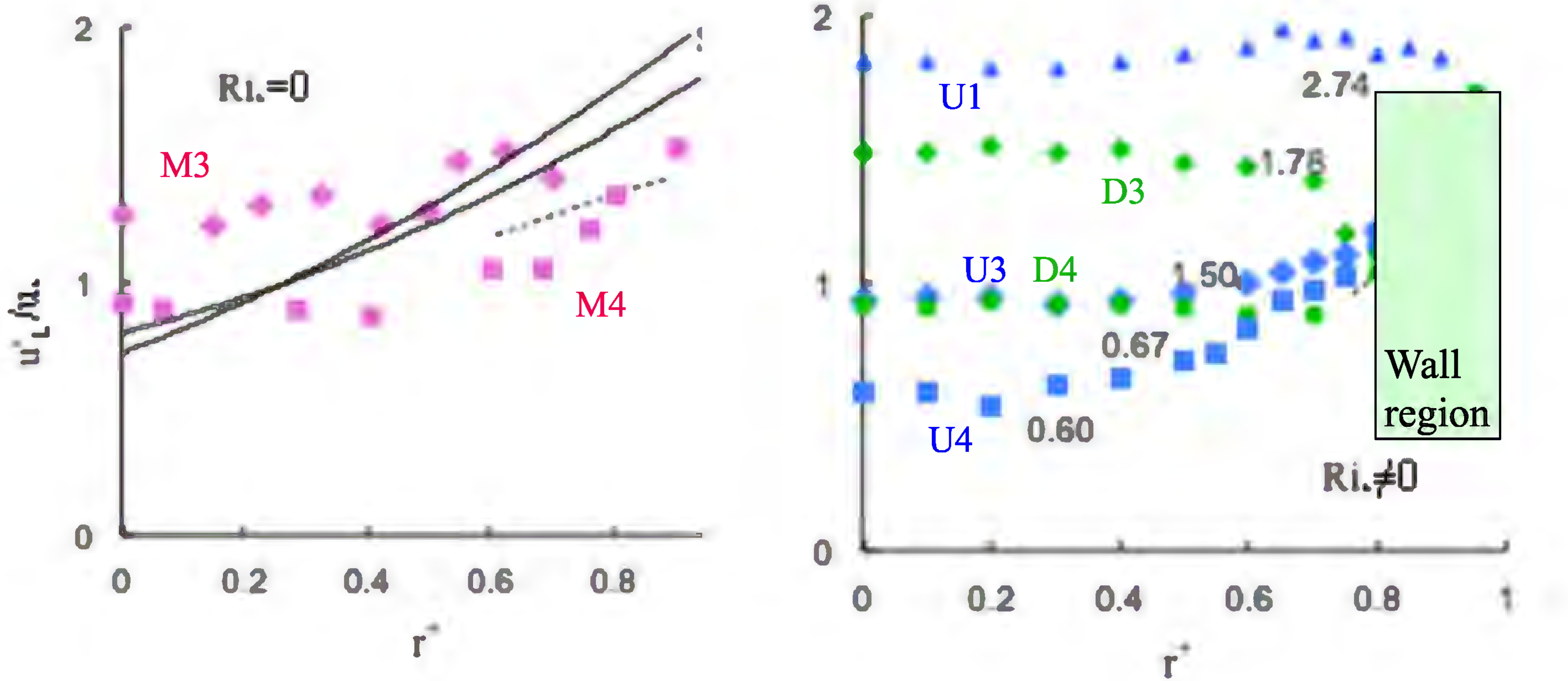
Asymptotiques solutions :

If diffusion is negligible: Prod=Diss

$\nu_{Lt} = C_\mu k_{LS}^2 / \varepsilon_{LS}$ and $k_{LS} = \frac{\overline{u_L v_L}}{\sqrt{C_\mu}}$

$$\Longrightarrow \frac{k_{LB}}{k_{LS}} \approx \frac{\alpha U_{LG}^2}{\overline{u_L v_L}} \approx \frac{d}{D} Ri_* = Ri_{*d} = \frac{\alpha g d}{u_*^2}$$

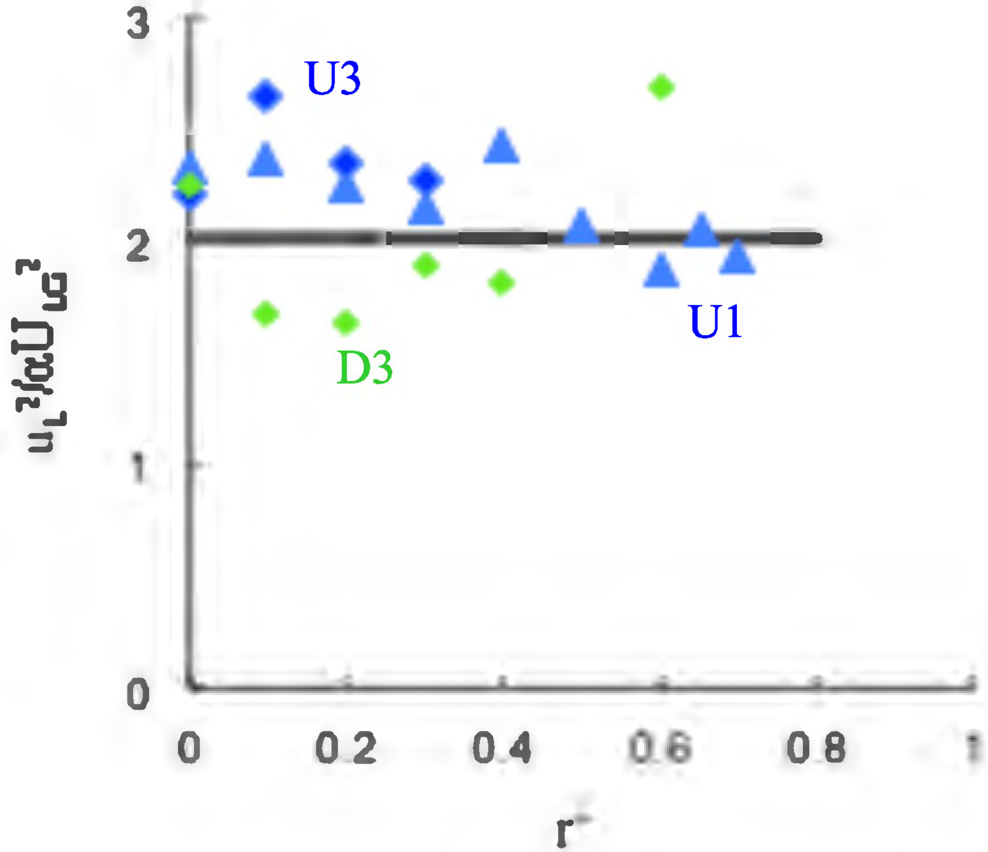
Turbulent kinetic energy of the liquid



Dashed lines $k_{LS} = \dfrac{\overline{u_L v_L}}{\sqrt{C_\mu}}$ equilibrium between production and dissipation in the wall region

good estimation of the turbulence level near the wall, when an inertia region does exist.

Bubble induced turbulence



$$\frac{k_{LB}}{k_{LS}} \approx \frac{\alpha U_{LG}^2}{\overline{\overline{u_L v_L}}} \approx Ri_{*d} \approx \frac{\alpha |g| d}{u_*^2}$$

In the core region, when $k_{LB} >> k_{LS}$

$$\Rightarrow \quad u_L^2 \approx 2\alpha U_{LG}^2$$

(Lance & Bataille, 1991 Garnier et al., 2001)

Homogeneous core region dominated by bubble induced turbulence, if $Ri_* \; d/D > 1$

Conclusion: Mean velocity and turbulence

- Simple expression to predict the wall friction velocity in bubbly flow u_*
- Relevant number to predict the buoyancy effect Ri_* or Ri_{*d}

- Logarithmic law still valid in bubbly flow for Ri_*=0 (S and M) and Ri_*<1. When Ri_*>1 the inertia region becomes smaller and the additive constant B decreases.

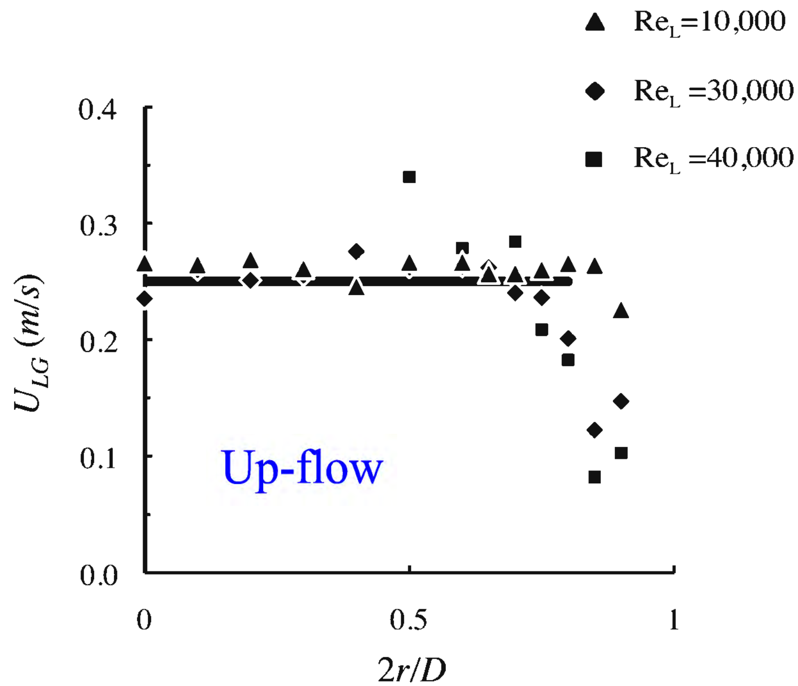
- The turbulent shear stress can be calculated from the streamwise momentum balance eq.

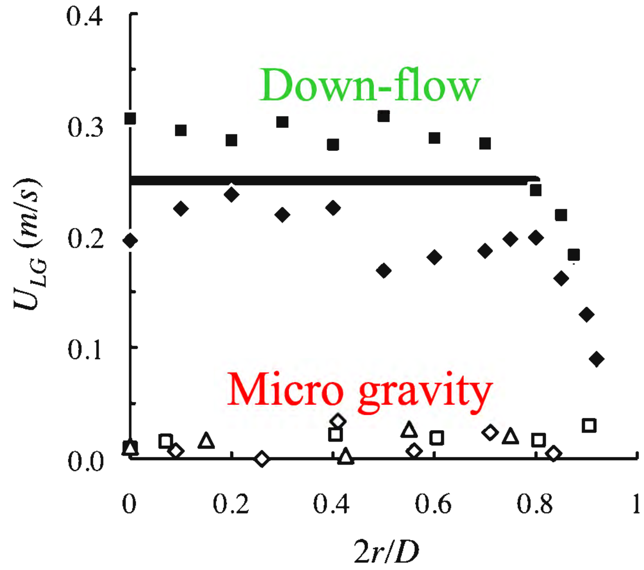
Two regions exist in the flow:

- a wall region where the log. Law is still valid. Even when Ri_*>1, k_L can be estimated from a balance between its production and its dissipation. In this region a maximum value of the void fraction is obtained in upflow and this region is free of bubble in downward flow

- A core region where the wall is homogeneous and where the bubble induced turbulence dominates when Ri_{*d}>1. The production of shear induced turb. is negligible .

Bubble slip velocity $U_{LG}=U_G - U_L$





Bubble slip velocity in the inertia-capillaro regime (*Mendelson*)

$$U_\infty = \left[2.14\frac{\sigma}{\rho_L d} + 0.505 g d\right]^{1/2} \quad \text{if} \quad d > 0.44\sqrt{\sigma/\rho_L g}$$

In microgravity, bubble slip velocity of 2mm/s due to Coriolis acceleration

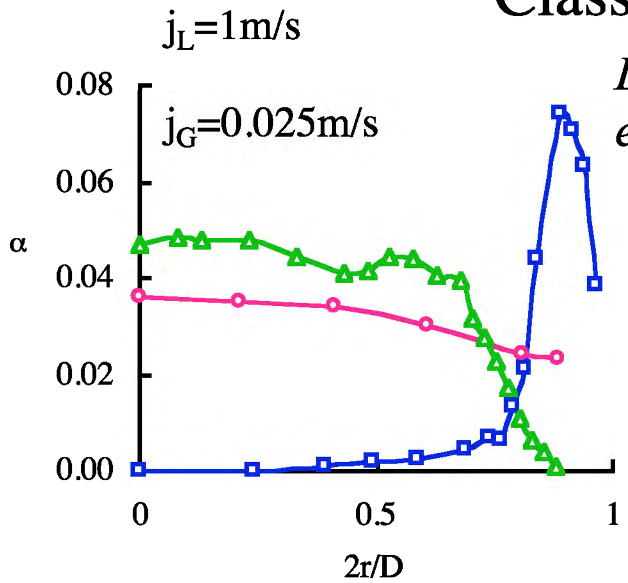
$$U_\infty = \frac{1}{18}\frac{g d^2}{\nu} \quad \textit{with} \;\; g/g_0 = 0.002$$

Bubble slip velocity decreases near the wall: in agreement with numerical simulations of Adoua (2009)➔increase in the drag coefficient for an ellipsoidal bubble in a shear flow

Outline

- Experimental set-up and measurement techniques
- Main results on:
  - vertical upward flow
  - downward flow
  - microgravity flow
- Wall friction and logarithmic law
- Turbulence in bubbly flows
- Void fraction distribution
- Conclusion and perspectives

Void fraction distribution



Classical analysis based on Eulerian two-fluid models

Lance & Lopez de Bertodano, 1994; Chahed et al., 1999; Lucas et al. 2007, Hosokawa and Tomiyama., 2009…)

$$0 = \rho_L \alpha \frac{\partial (1-\alpha)\overline{v'^2_L}}{\partial r} + M_{Gr}$$

M_G is the interfacial momentum transfer : average of the forces acting on the bubbles

Bubble-turbulence interactions

Wall effect

$$v'^2_L \frac{\partial \alpha}{\partial r} = (1-\alpha)\frac{\partial v'^2_L}{\partial r} - C_L (U_G - U_L)\frac{\partial U_L}{\partial r} + M_{Grt} + F_{wr}$$

Vertical upflow	>0	>0	>0
Vertical downflow	<0	>0	<0
Microgravity	>0?	>0	~0

Non-linear terms needed especially in microgravity (added mass, *Chahed et al 1999*)

Void fraction distribution

Classical analysis based on Eulerian two-fluid models

$$v'^2_L \frac{\partial \alpha}{\partial r} = (1-\alpha)\frac{\partial v'^2_L}{\partial r} - C_L\left(U_G - U_L\right)\frac{\partial U_L}{\partial r} + M_{Grt} + F_{wr}$$

$$M_{GTr} = -C_{DT}\,\rho_L k_{LS}\frac{\mathrm{d}\alpha}{\mathrm{d}r}$$

Lance et Lopez de Bertodano (1994)

$$M_{GTr} = \frac{3}{4}\frac{C_D}{d}|U_{LG}|V_d - \frac{C_M}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left[r\alpha(v_G'^2 - v_L'^2)\right]$$

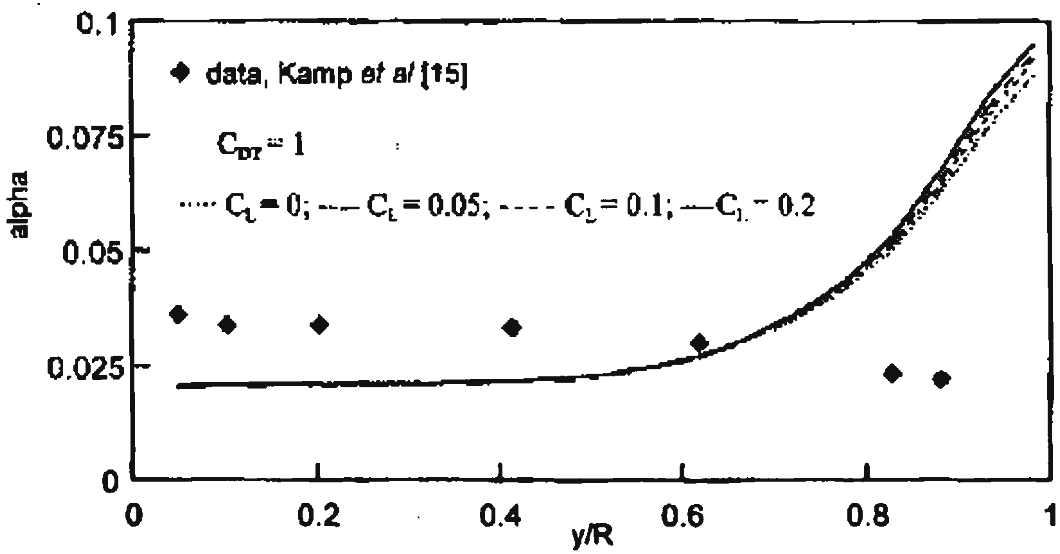
Chahed et al. (2002)

$$\left[\alpha v_G'^{+2} + C_M(v_G'^{+2} - v_L'^{+2}) - \frac{3}{4}C_D C_{DT} C_\mu v_t^+ \frac{U_{LG}}{u_*}\right]\frac{\mathrm{d}\alpha}{\mathrm{d}r^+}$$

$$= \alpha(1-\alpha)\frac{\mathrm{d}v_L'^{+2}}{\mathrm{d}r^+} - \alpha C_L \frac{U_{LG}}{u_*}\frac{\mathrm{d}U_L^+}{\mathrm{d}r^+} - C_M\frac{\alpha}{r^+}\frac{\mathrm{d}}{\mathrm{d}r^+}\left[r^+(v_G'^{+2} - v_L'^{+2})\right]$$

Vertical upflow	>0	>0	<0
Vertical downflow	>0	<0	<0
Microgravity	>0	~0	<0

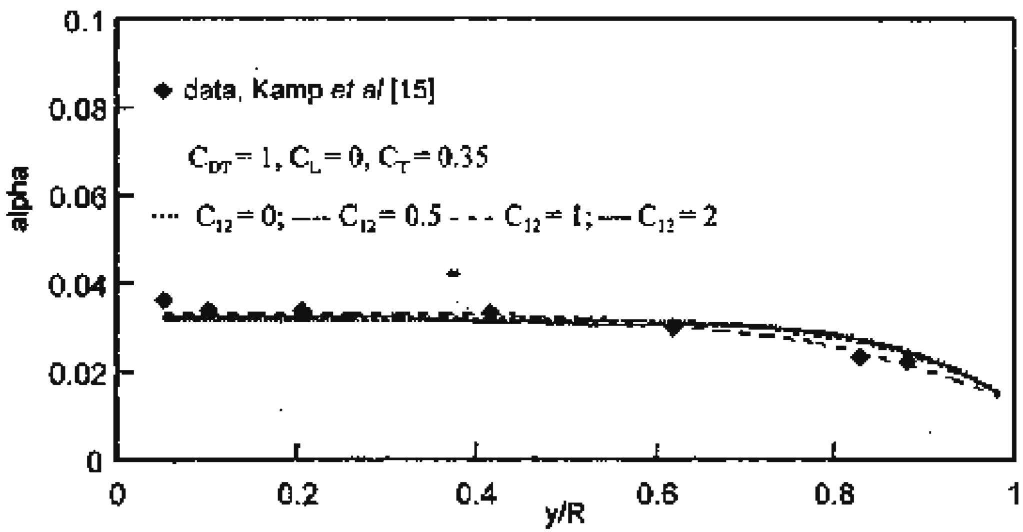
Computation of the void fraction distribution in microgravity with a two-fluid model *(Chahed, Colin, Masbernat , JFE, 2002)*



Without the turbulent term in the added mass force

j_L=1m/s

j_G=0.025m/s



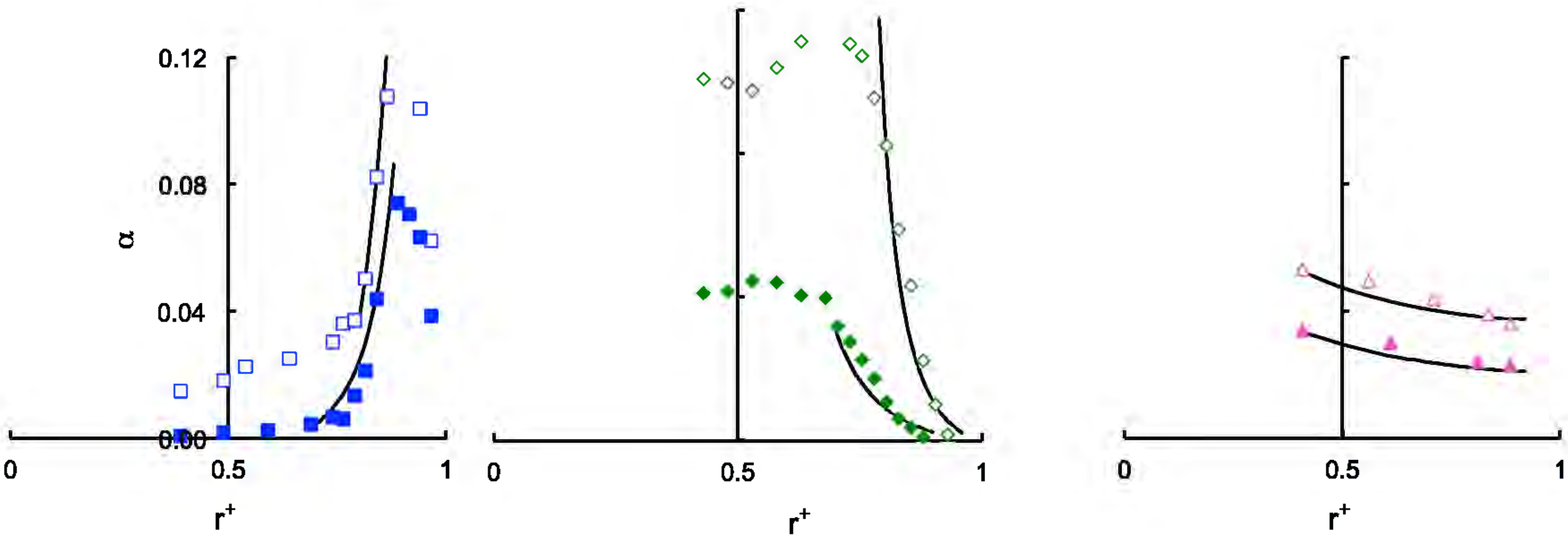
With the turbulent terms in the added mass force

Void fraction distribution

ODE for the void fraction distribution can be integrated in the transition region between the core and the wall region, neglecting the interaction of the bubbles with the wall

$$\frac{\alpha}{\alpha_c} = \frac{f(r^+)}{f(r_c^+)} \quad \text{where } r^+ = r/R \; ; \; f(r^+) = \frac{(ar^+ + b)^{(C_0 - 1)}}{r^+} \left(\frac{ar^+ + b}{1 - r^+} \right)^{C_g \frac{U_{LG}}{u_*}} \quad \text{with } \frac{u'v'}{u_*^2} = ar^+ + b$$

C_0 and C_g are 2 constantes depending on C_L=0.288, C_M=0.4, Ct=1.8



Conclusion

- Experiments on a turbulent bubbly pipe flow are performed in normal and microgravity conditions with the same set-up
- The wall shear stress in bubbly flow can be predicted versus Ri_{*d}
- From local measurements, the effect of gravity on the flow structure has been highlighted with a dimensionless number Ri_*
- When $Ri_* = 0$ (microgravity), the flow structure is similar to single-phase flow (validity of the log law, linear shear stress)
- When $Ri_* > 1$, buoyancy effects dominate (modification of the log law, reduction of the turbulent shear stress)
- The bubbly flow in upward and downward configuration displays two regions: a homogeneous core region and a wall region
- Void fraction distribution can be calculated from a radial momentum balance, but the non linear term in the interfacial momentum transfer have to be taken into account to explain the void fraction distribution in microgravity.

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More details in *Colin, Fabre, Kamp, Journal Fluid Mech. 2012*
doi:10.1017/jfm.2012.401 and experimental data available on line