Numerical simulation of bubble-train flow in a small channel of square cross-section

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Motivation

- Problem
  - ***small channels***: compact heat exchangers, small-sized refrigeration systems, chemical processing
- Subject
  - gas-liquid two-phase flows in small channels
  - flow channels with hydraulic diameters of the order of 1 mm

    $\Rightarrow$ ***continuum model***
- Objectives:
  - local characteristics: velocities and temperature profiles; flow structure;

    $\Rightarrow$ better understanding of the basic hydrodynamics

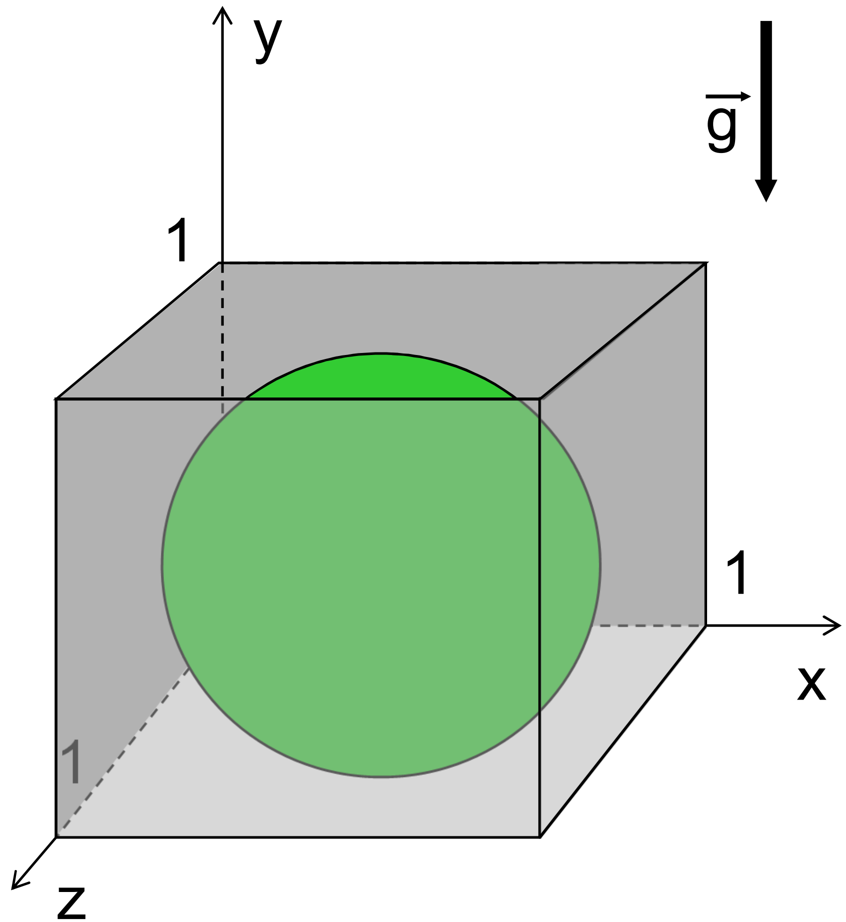
TURBIT-VoF

- In-house code: bubbly flow in large channels
- Applicability:
  - incompressible single and two-phase flows
  - plane and rectangular channels
  - spatially periodic flows: fully developed regime
- Features
  - dimensionless equations
  - finite volume + 3-rd order Runge-Kutta method
  - volume tracking method: Volume-of-Fluid procedure (VoF)
  - piecewise linear interface reconstruction: EPIRA algorithm
  - heat transport equation (passive scalar)

Bubble flow in capillaries of square cross section

Numerical setup

- Channel: $L \times L$; flow cell: L
  - $\Rightarrow$ Computational domain: 1x1x1
- Initial bubble diameter: d = 0.858
  - $\Rightarrow$ void fraction α = 33%
- Walls: x = 0, x = 1; z = 0, z = 1;
- Periodic b.c. in y-direction
- Mesh: 64x64x64
- Constant pressure drop in y-direction
  - $\Rightarrow$ determine the liquid/gas flow rates



Comparison with experiments

- T.C. Thulasidas *et al* (1995)*
  - vertical channel 2×2mm
  - silicone oil and air

	$\rho_{liquid}/\ \rho_{gas}$	$\mu_{liquid}/\ \mu_{gas}$
Case A	775.8	249.1
Case B	813.2	2599.7

  - Measurements for:
    - ➢ bubble diameter : D_b,
    - ➢ bubble velocity : U_b,
    - ➢ relative bubble velocity : $W=(U_b-v_{ls})/U_b$ (v_{ls} : liquid slug velocity)

*Thulasidas, Abraham & Cerro, Chem. Eng. Sci., 50, pp 183, 1995

Simulation parameters

	ρ_l / ρ_g	μ_l / μ_g	J_l [cm/s]	J_g [cm/s]	Re	Ca	Eö
Case A	78	25	6.52	6.87	75.8	0.043	1.35
Case B	81	260	2.82	3.72	1.35	0.205	1.06

- Capillary number: $Ca = \mu_l U_b / \sigma$
- Reynolds number: $Re = \rho_l U_b D_b / \mu_l$
- Eötvös number: $Eö = (\rho_l - \rho_g) g D_b^2 / \sigma$

Dimensionless bubble diameter D_b

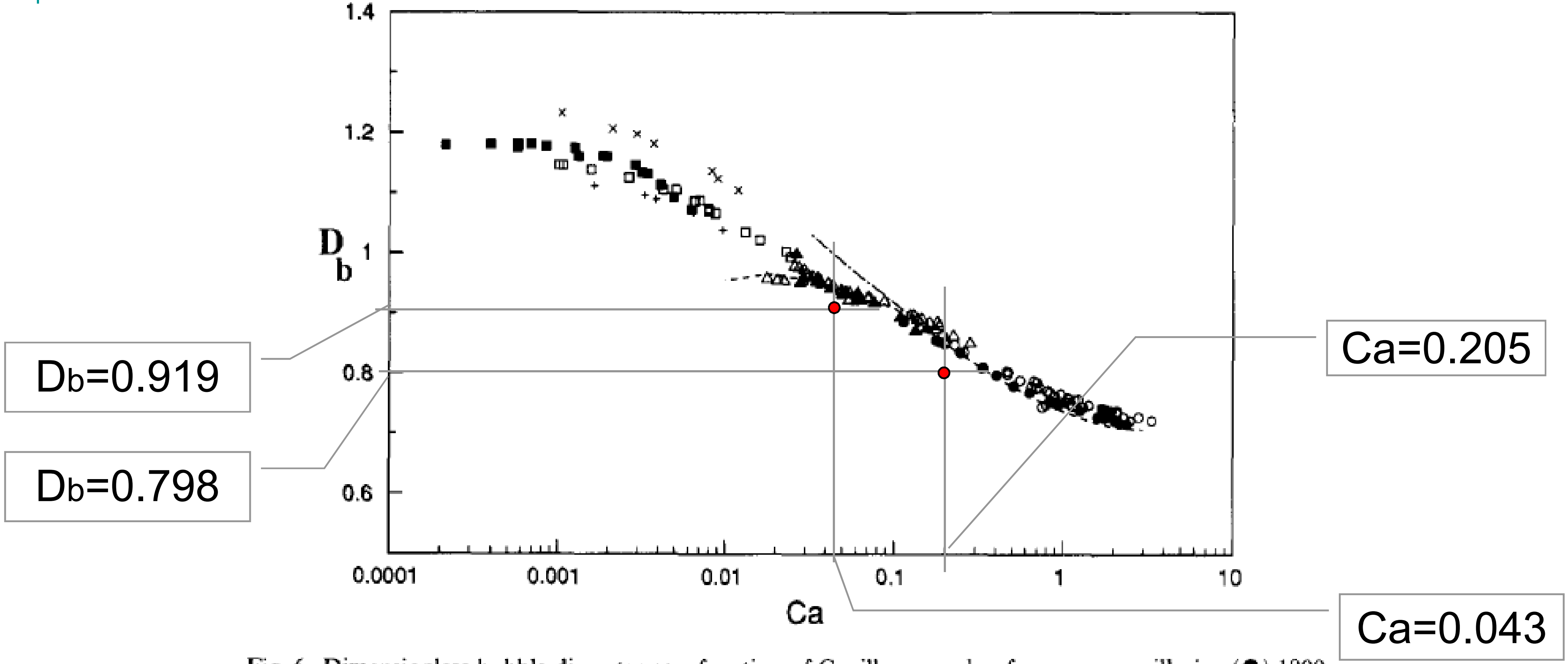


Fig. 6. Dimensionless bubble diameter as a function of Capillary number for square capillaries; (●) 1000 centistokes silicone oil, downward flow. (○) 1000 centistokes silicone oil, bubble-train flow; (▲) 50 centistokes silicone oil, upward flow; (△) 50 centistokes silicone oil, bubble-train flow; (+) 5 centistokes silicone oil, upward flow; (×) 5 centistokes silicone oil, downward flow; (□) 5 centistokes silicone oil, bubble-train flow; (■) water, bubble-train flow; (– –) Kolb and Cerro (1991) experimental results in the axial plane. (—) Kolb and Cerro (1991) experimental results in the diagonal plane.

Dimensionless bubble velocity

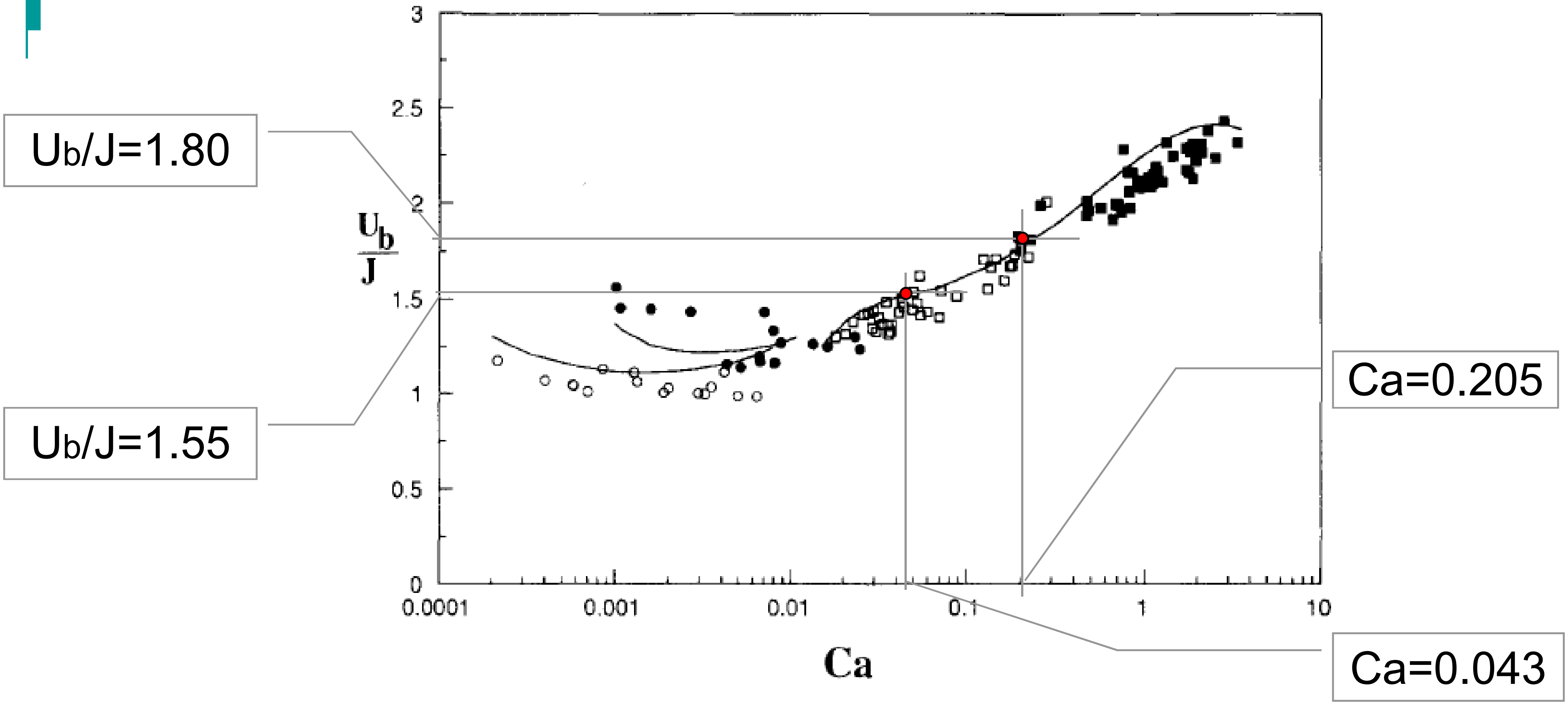


Fig. 10. Dimensionless bubble velocity defined as the ratio of bubble velocity to total superficial velocity for square capillaries: (■) 1000 centistokes silicone oil, bubble-train flow; (□) 50 centistokes silicone oil, bubble-train flow; (●) 5 centistokes silicone oil, bubble-train flow; (○) water, bubble-train flow. The solid line represents solution obtained from eq. (15).

Total superficial velocity: $J = J_l + J_g$

Relative bubble velocity

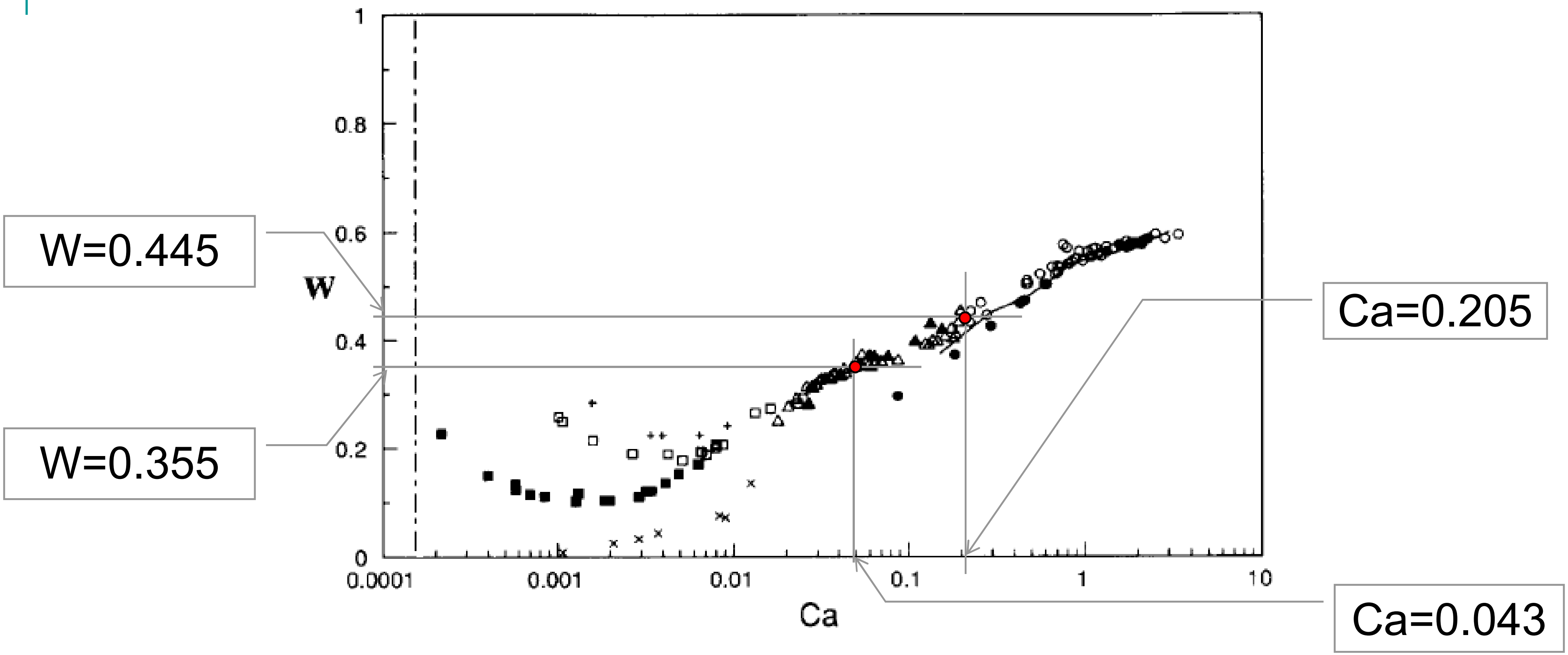
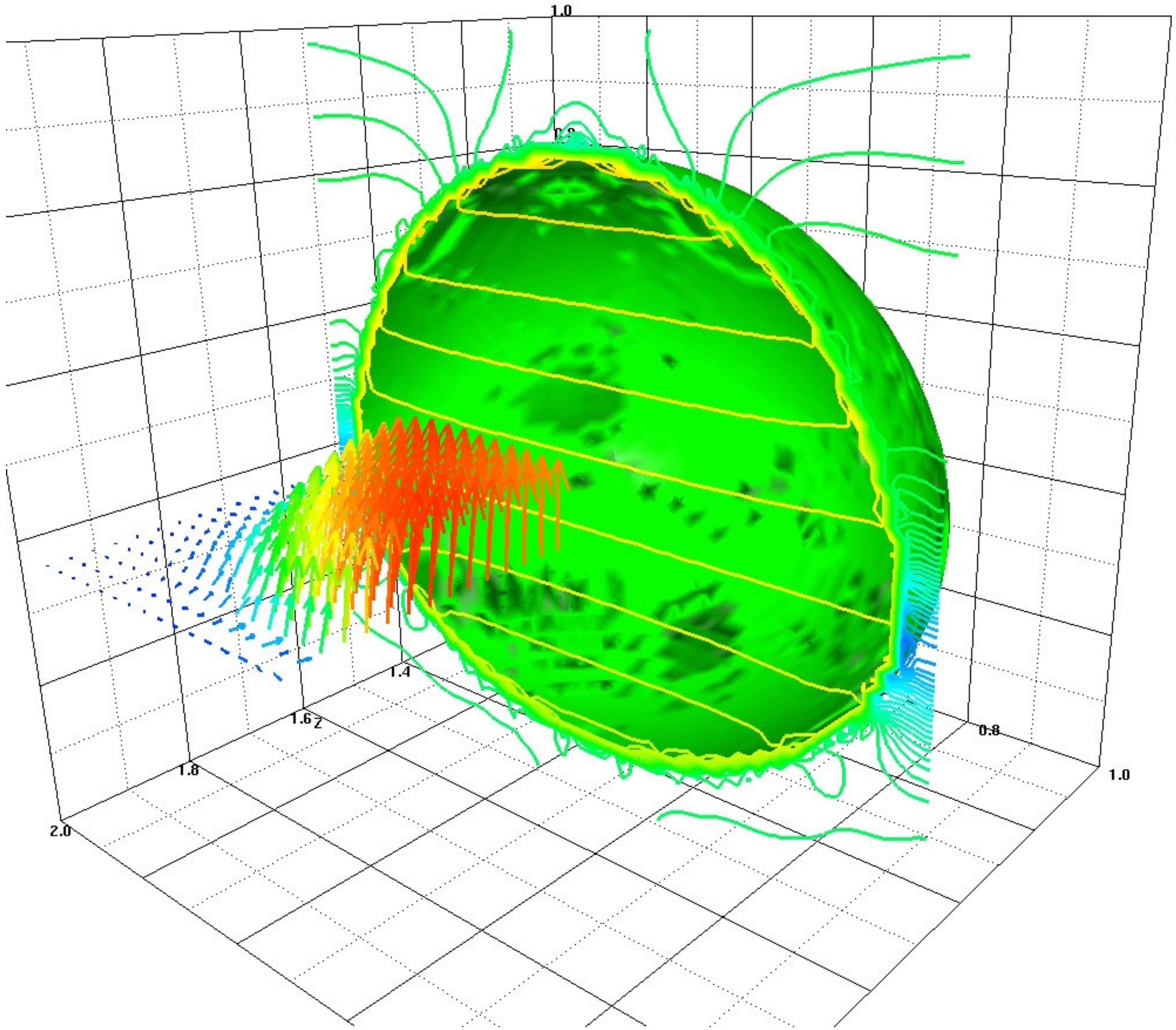
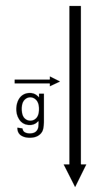


Fig. 8. Relative bubble velocity, W as a function of Capillary number for square capillaries: (●) 1000 centistokes silicone oil, downward flow; (○) 1000 centistokes silicone oil, bubble-train flow; (▲) 50 centistokes silicone oil, upward flow; (△) 50 centistokes silicone oil, bubble-train flow; (+) 5 centistokes silicone oil, upward flow; (×) 5 centistokes silicone oil, downward flow; (□) 5 centistokes silicone oil, bubble-train flow; (■) water, bubble-train flow. The solid line represents Kolb and Cerro (1991) experimental results for downward flow. The broken line represents the limiting Ca of 1.5×10^{-4} of a bubble inside a stagnant fluid in the square capillary.

Velocity field and reduced pressure field

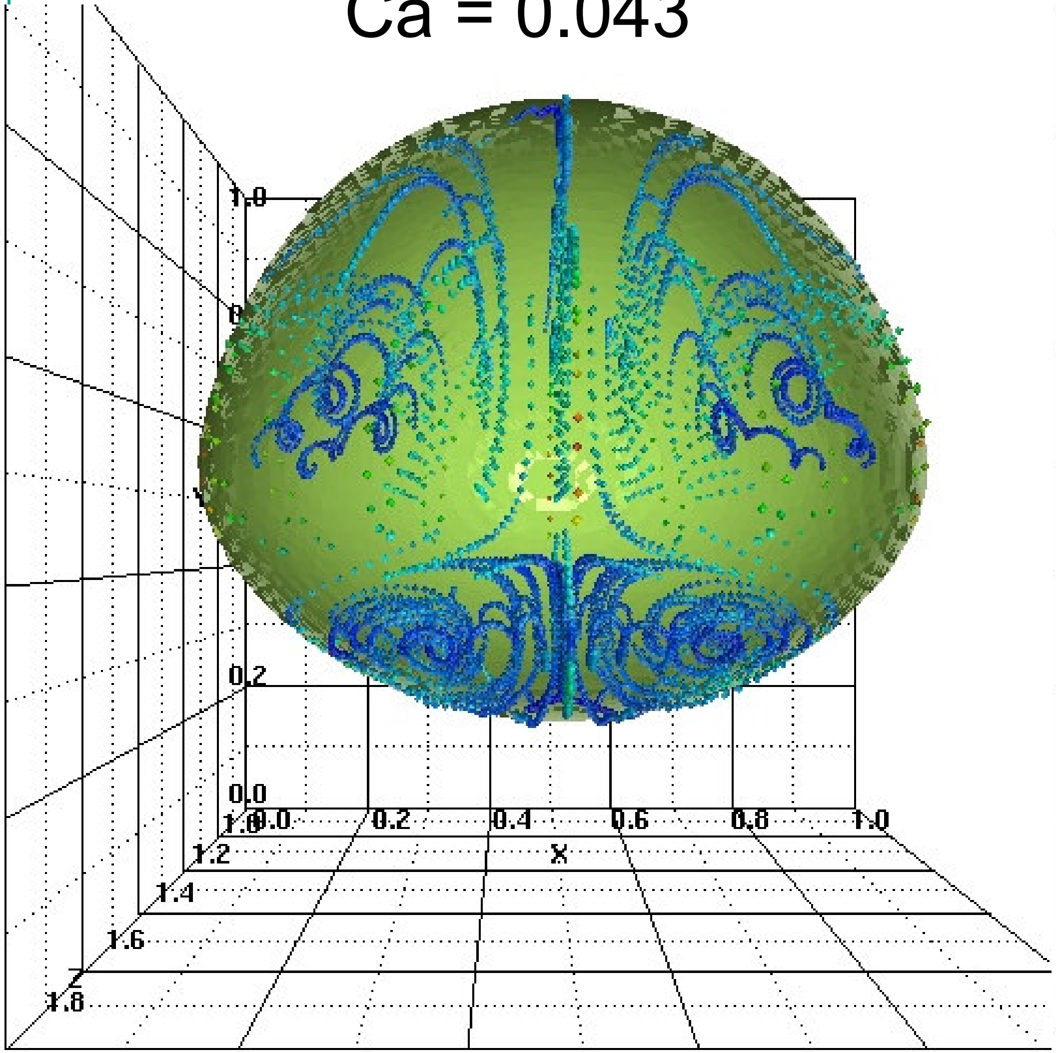




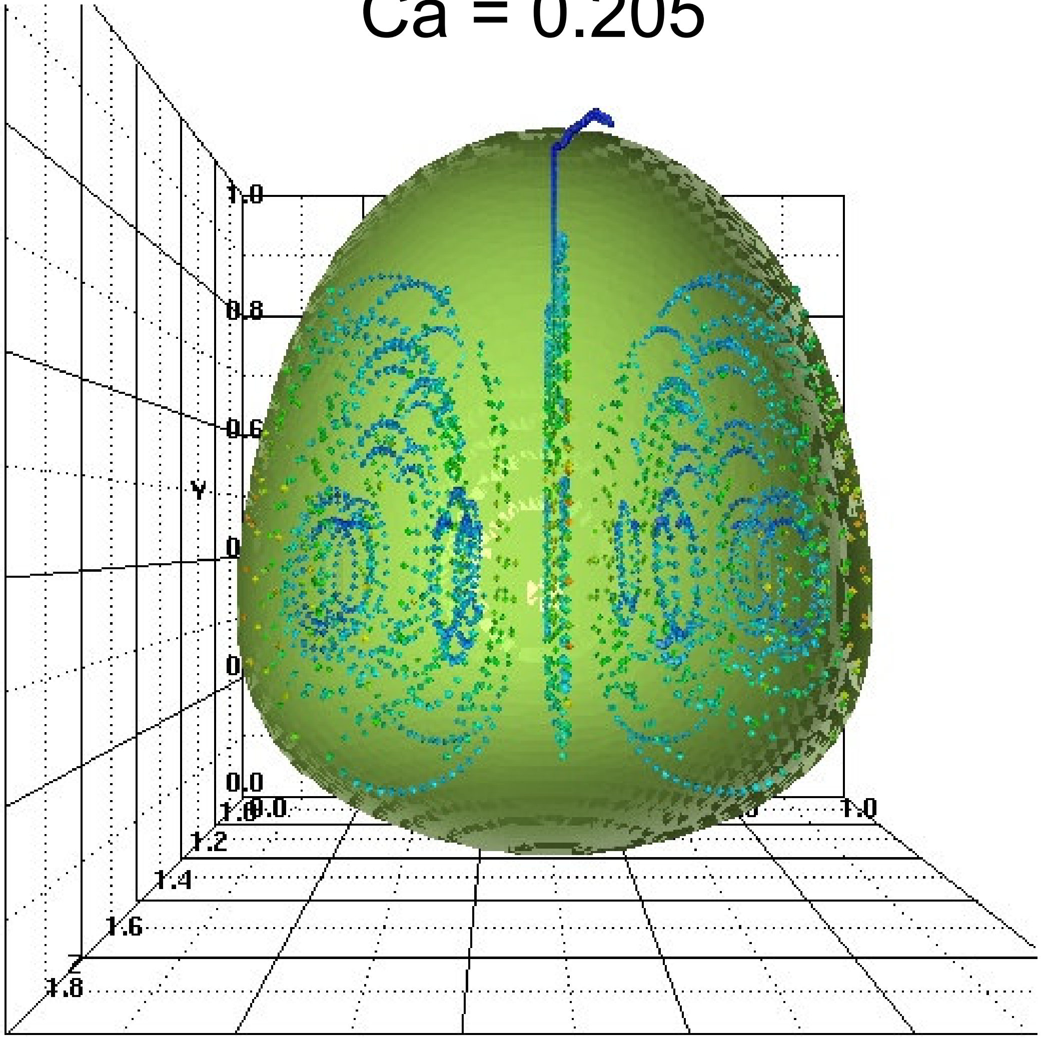
Flow structure inside the bubble

- lateral view (perspective)-

Ca = 0.043



Ca = 0.205

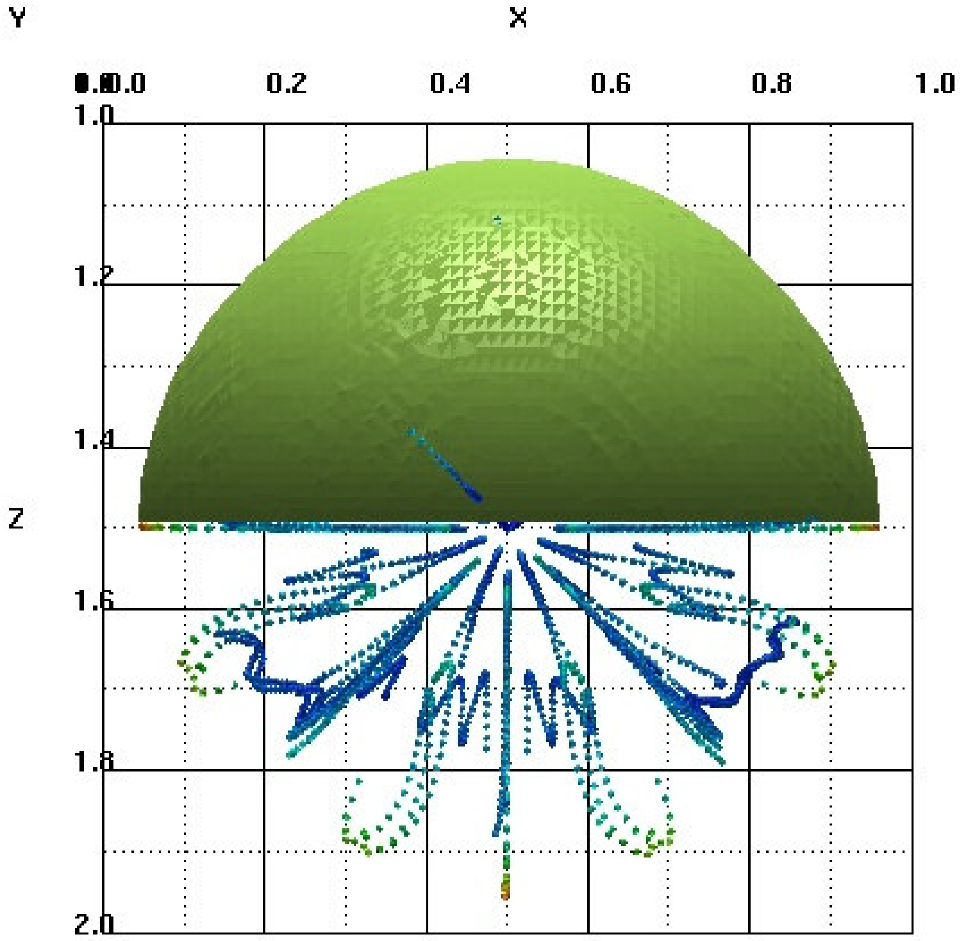


- referential linked to the bubble center of mass

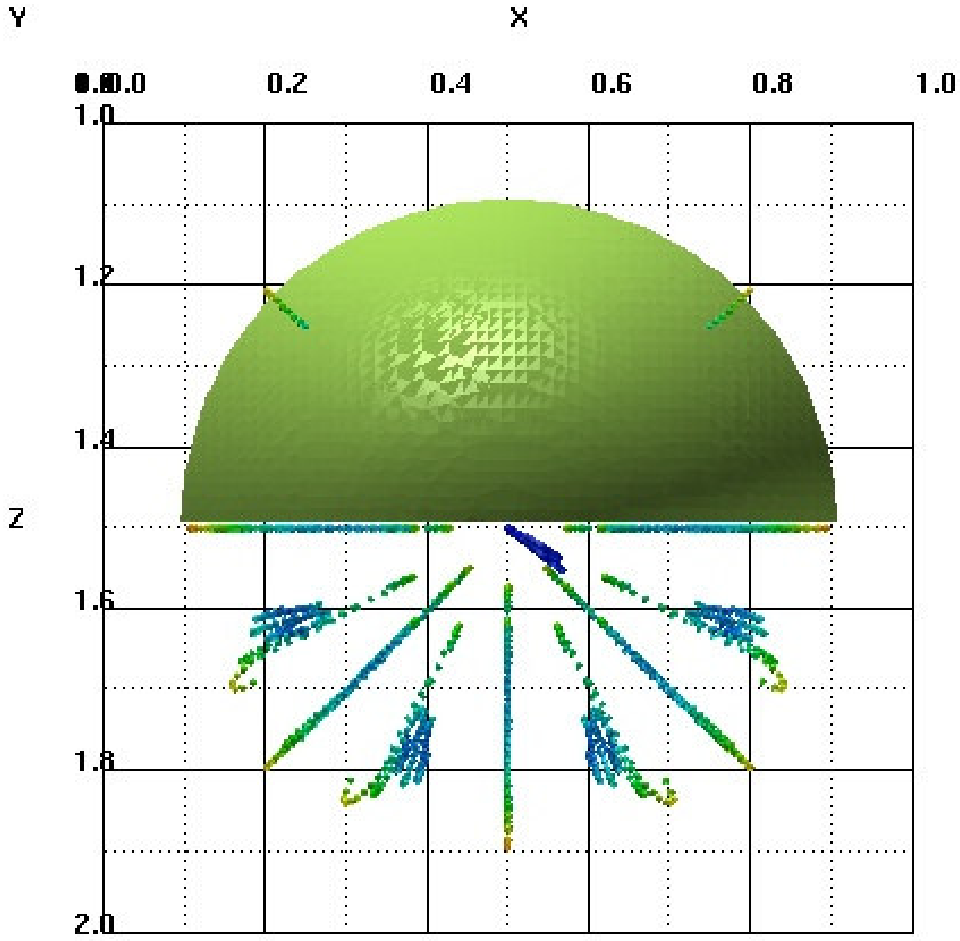
Flow structure inside the bubble

-top view-

Ca = 0.043

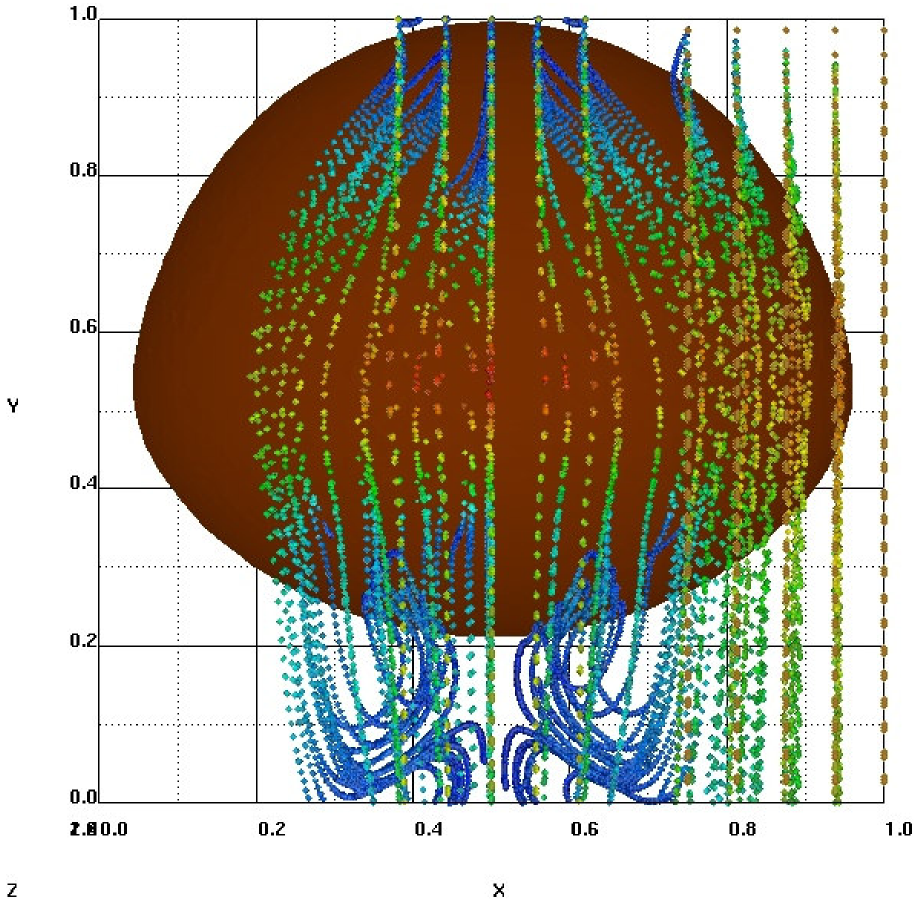


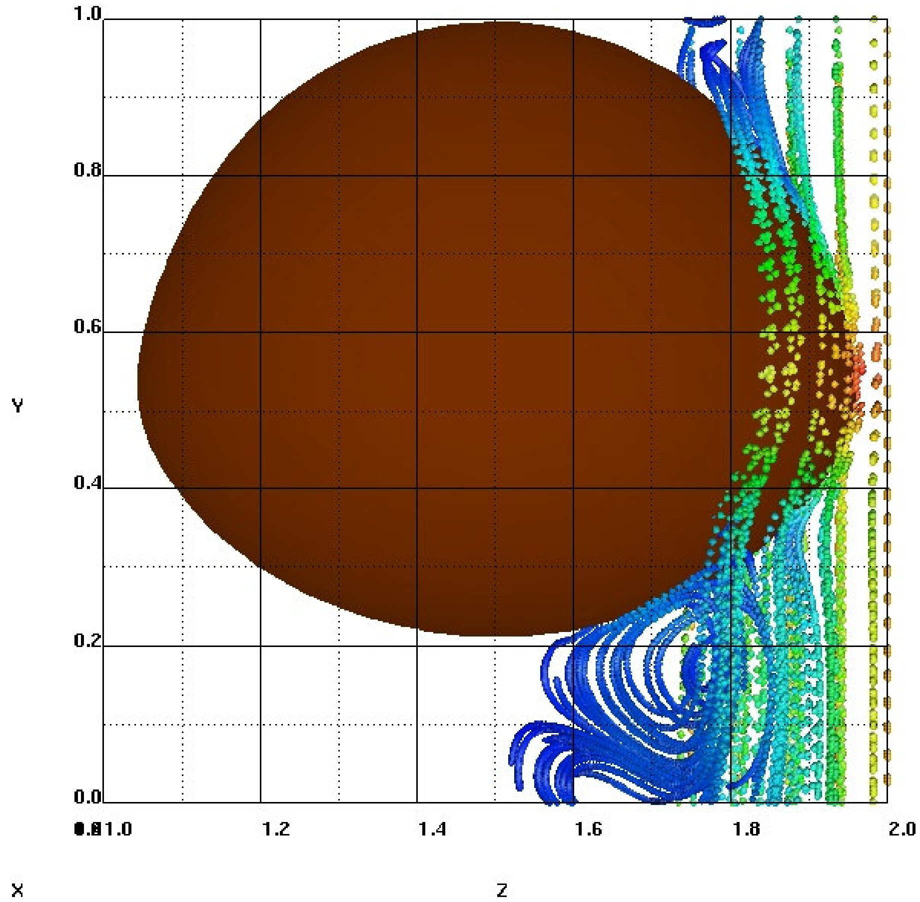
Ca = 0.205



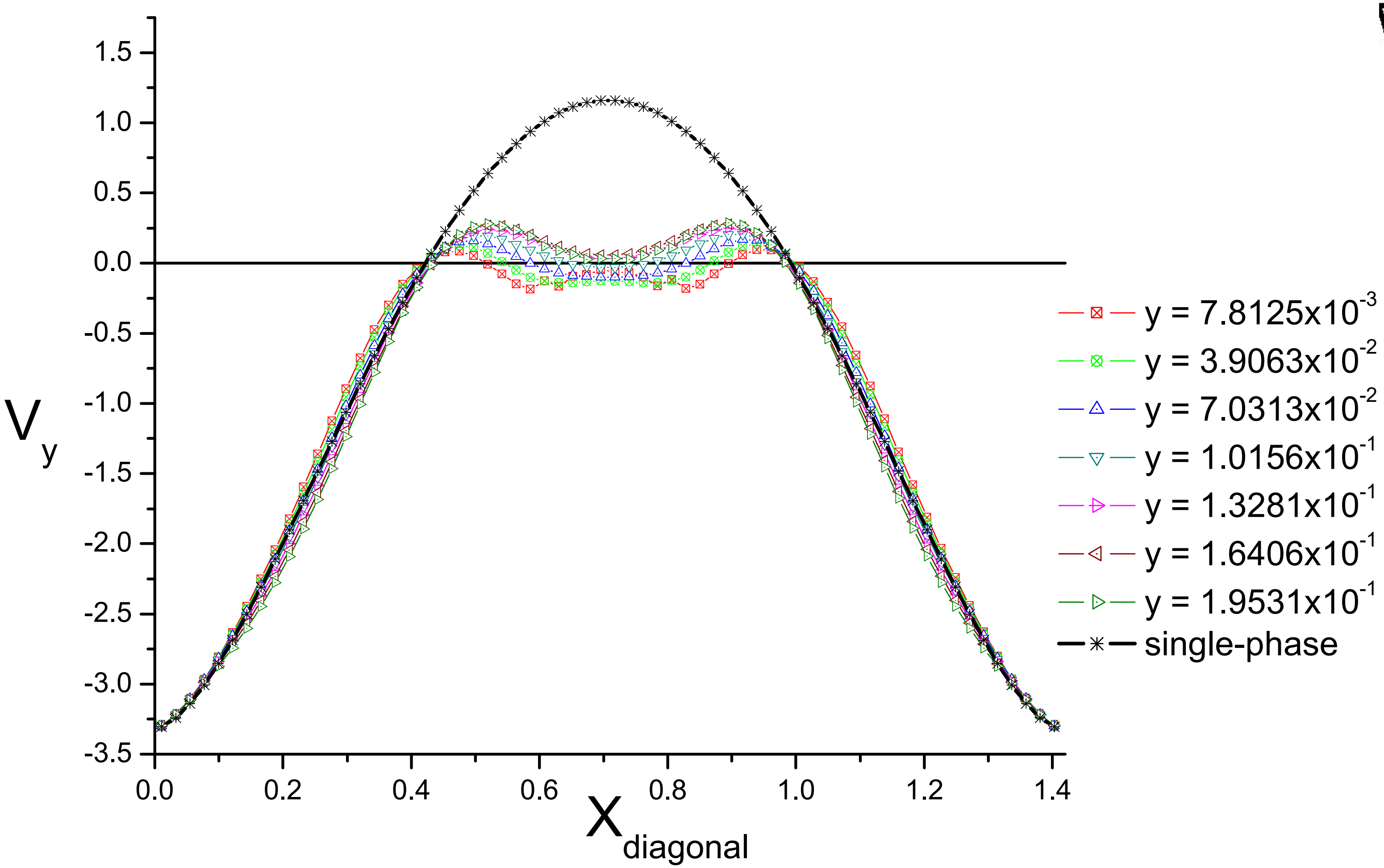
Liquid flow structure visualization

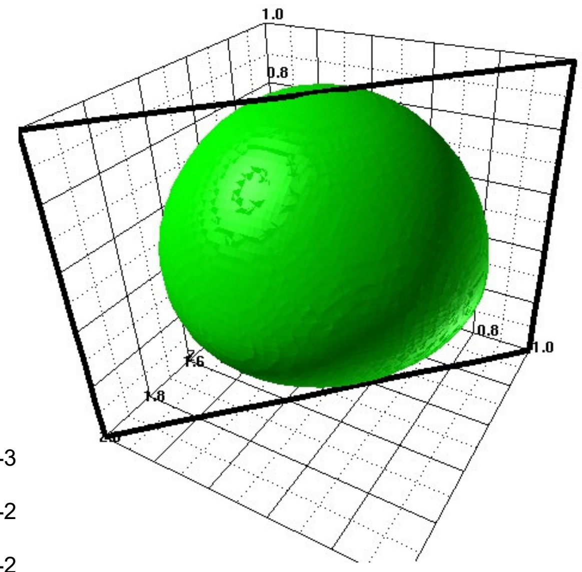
Ca=0.043



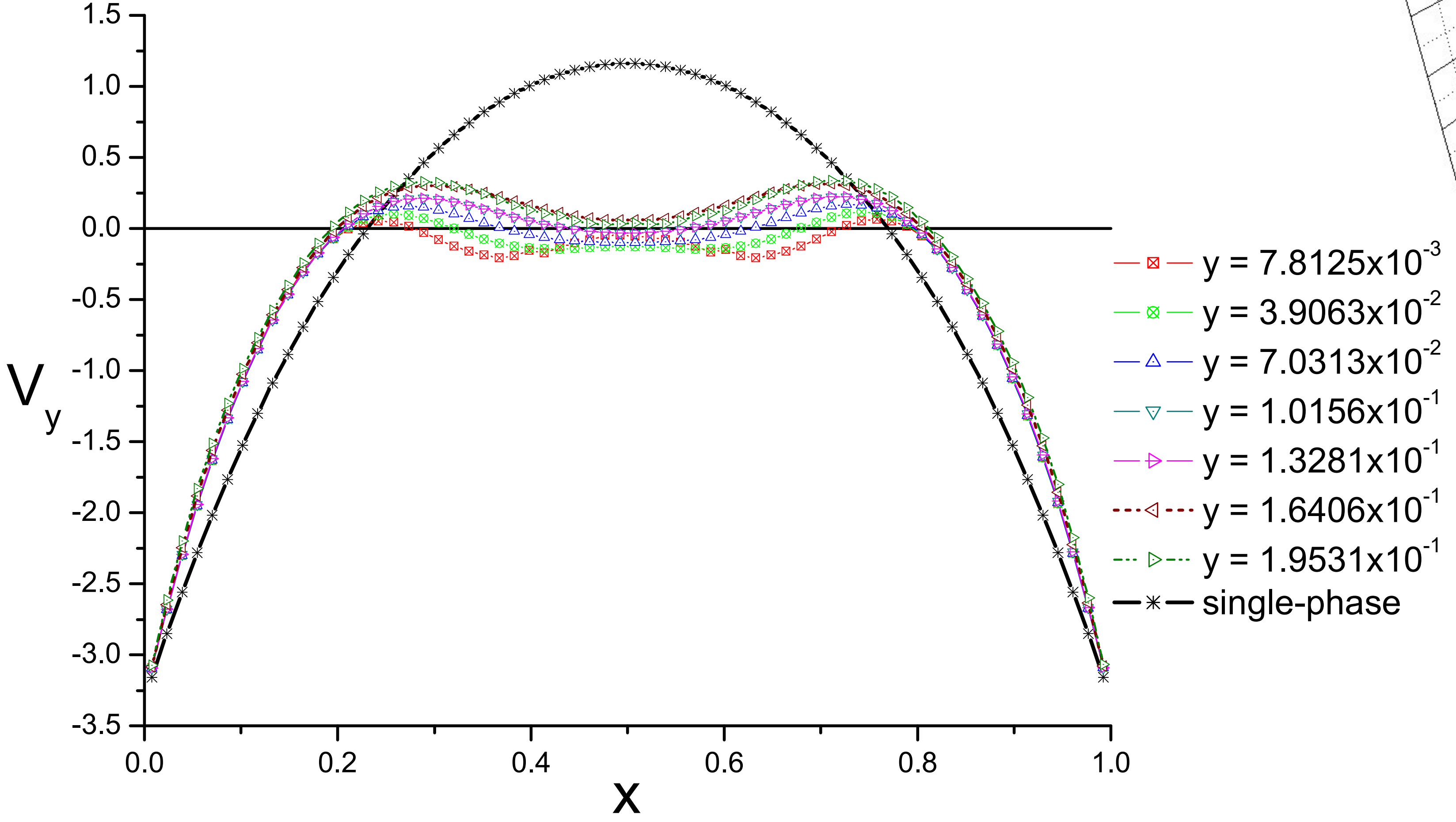


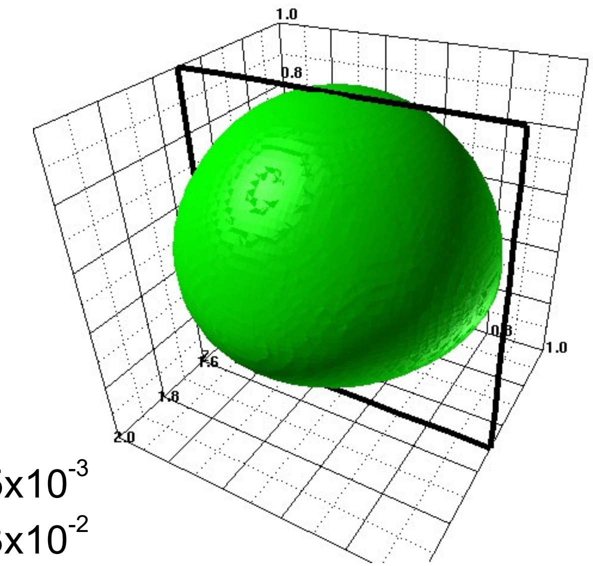
Velocity profiles in the slug
- diagonal plane profiles -





Velocity profiles in the slug
- axial plane profiles -





Conclusions

- **3D** numerical simulation of a bubble-train flow in a square channel at **low Ca** and **Eö** numbers
- Use global parameters as input in order to get local information about the flow
- Good agreement with experimental data
- Structure of the flow in the bubble / liquid slug
  - lower Ca:
    - ⇨ intense mixing inside the bubble and in the liquid slug;
    - ⇨ larger bubble diameter : thin liquid layer between the bubble and the wall;

Future work

- Further validation of the numerical method
- Assessment of the limits of method
- Computation of heat/mass transfer
- *Chemical reaction*