Numerical Study of Bubble Train Flow in a Square Vertical Mini-Channel: Influence of Length of the Flow Unit Cell *

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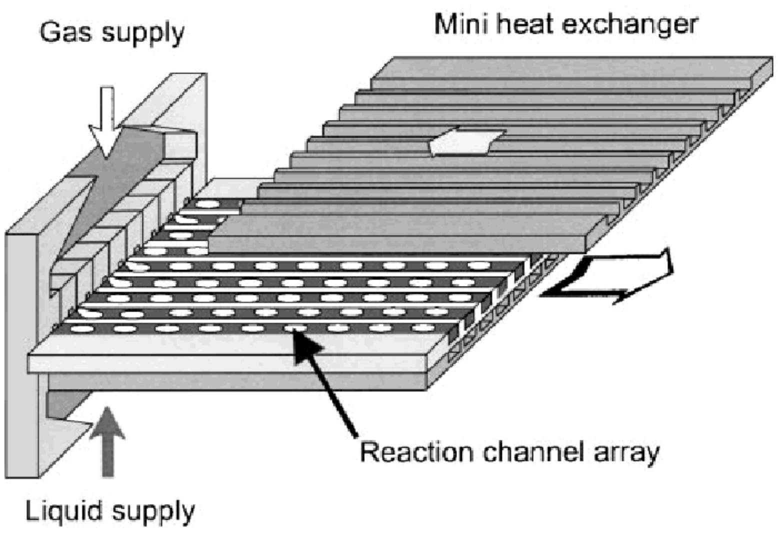
5th International Conference on Multiphase Flow
Yokohama, Japan, May 30 – June 4, 2004

* Oral presentation by E. Laurien, University of Stuttgart, Germany

Motivation

- Multi-phase chemical process engineering
  - Miniaturized devices offer certain advantages
    - High interfacial area per unit volume
      ⇒ Enhanced heat and
      mass transfer
    - Defined interface geometry
      ⇒ Numbering up instead
      of scaling up
    - Example:
      Micro bubble column*



- <u>Of interest:</u> gas-liquid flow in single channel

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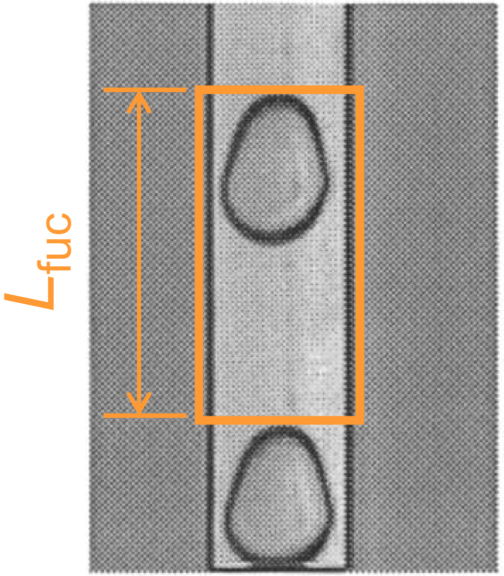
Objective

- Investigate gas-liquid flow in narrow channel numerically by volume-of-fluid method
- Verification by experiments of Thulasidas et al.*
  - Square vertical channel
    cross section: 2 mm × 2 mm ($W = 2$ mm)
  - Air bubbles in silicon oil
  - Bubbles of identical shape move with same velocity = “bubble train flow”
  - Flow is fully characterized by a single “flow unit cell” of length L_{fuc}



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* Thulasidas, Abraham, Cerro, Chem. Eng. Science 50 (1995) 183-199

In-house code TURBIT-VOF

- Volume-of fluid method for interface tracking
  - Interface is locally approximated by plane (PLIC method)
- Governing equations for two incompressible fluids (see paper)
- Solution strategy
  - Projection method resulting in pressure Poisson equation
  - Explicit third order Runge-Kutta time integration scheme
- Discretization in space
  - Finite volume formulation for regular staggered grid
  - Second order central difference approximations

Numerical set up

- Consideration of one flow unit cell
- Account for influence of trailing/leading unit cells by periodic boundary conditions in axial direction
- Length of flow unit cell, L_{fuc}, is input parameter
- Here: investigate influence of L_{fuc} / W
- Flow is driven in vertical direction (y) by specified axial pressure gradient and buoyancy

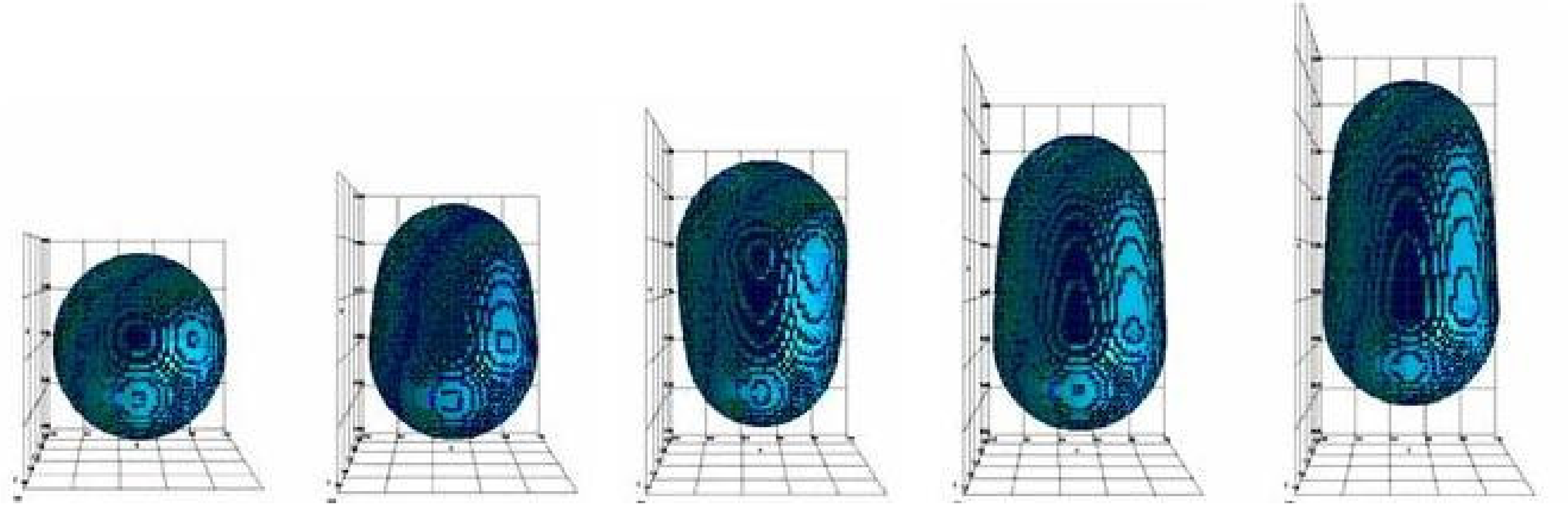
Physical parameters

- Fluid properties

Factor 10 higher than ρ and μ of air

ρ_l	ρ_g	μ_l	μ_g	σ
957 kg/m^3	11.7 kg/m^3	0.048 Pa s	1.84×10^{-4} Pa s	0.022 N/m

- Initial bubble shapes* (void fraction $\varepsilon = 33\%$)



- Simulations are started from gas and liquid at rest

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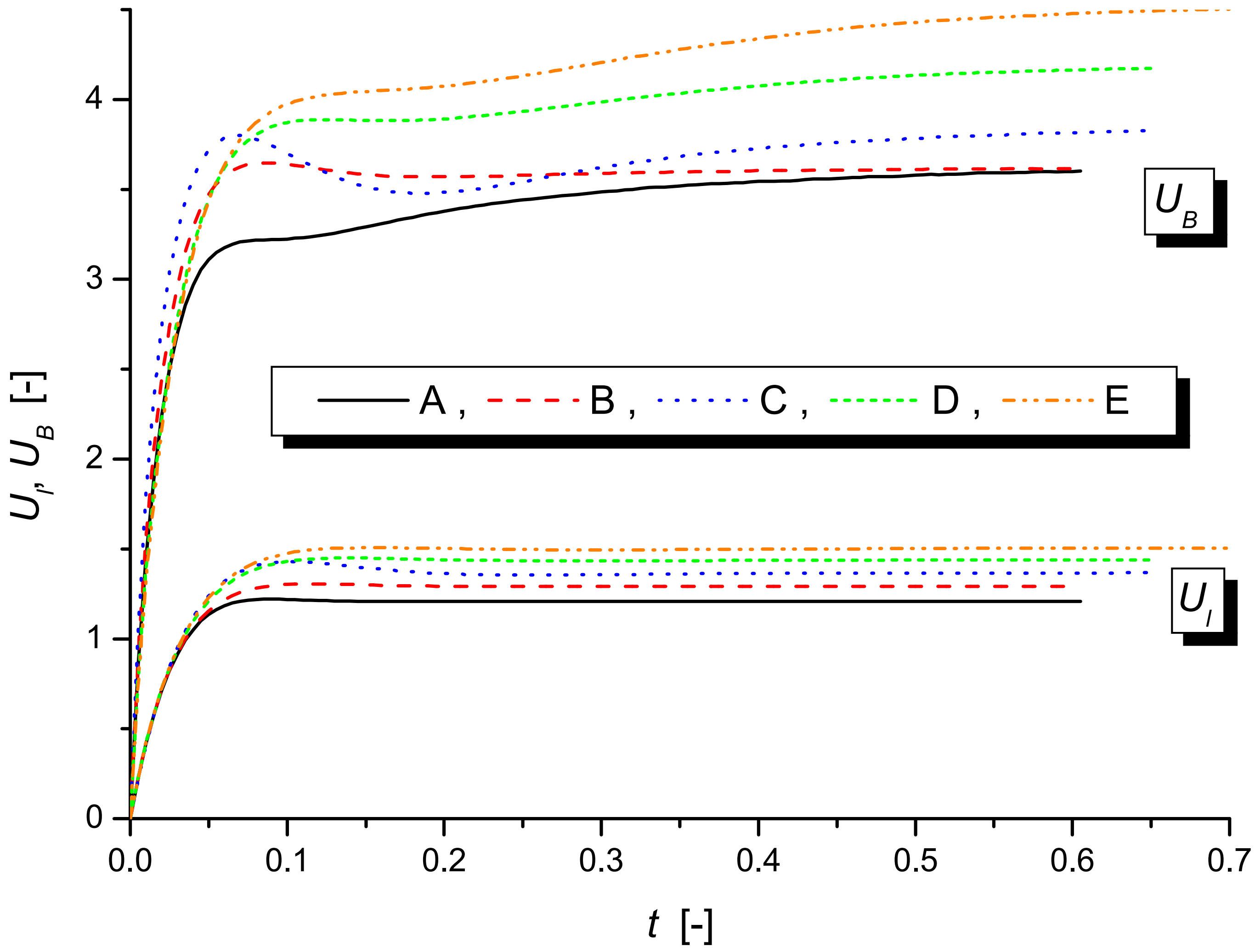
* Mathematical description see paper

Computational parameters

Case	L_{fuc} / W	Domain	Grid	Time steps
A1	1	1 × 1 × 1	48 × 48 × 48	24,000
A2	1	1 × 1 × 1	64 × 64 × 64	60,000
B	1.25	1 × 1.25 × 1	48 × 60 × 48	24,000
C	1.5	1 × 1.5 × 1	48 × 72 × 48	26,000
D	1.75	1 × 1.75 × 1	48 × 84 × 48	26,000
E	2	1 × 2 × 1	48 × 96 × 48	28,000

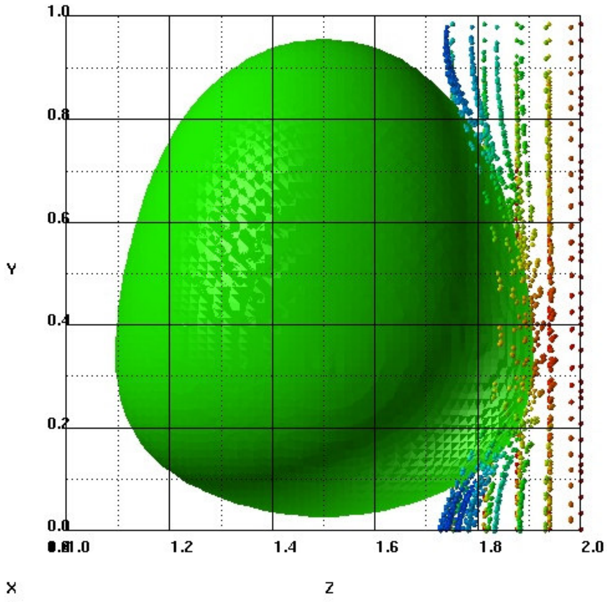
Results on both grids show only slight differences

Time history of mean velocities

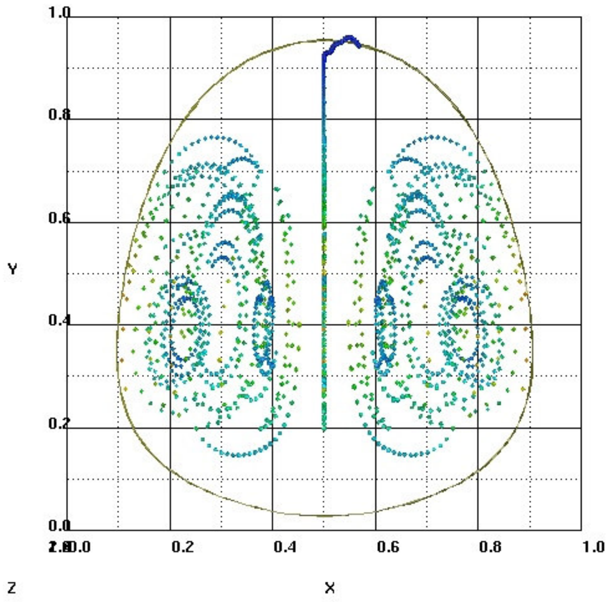


Steady state values of bubble velocity U_B and mean liquid velocity U_l increase with increasing length of the flow unit cell

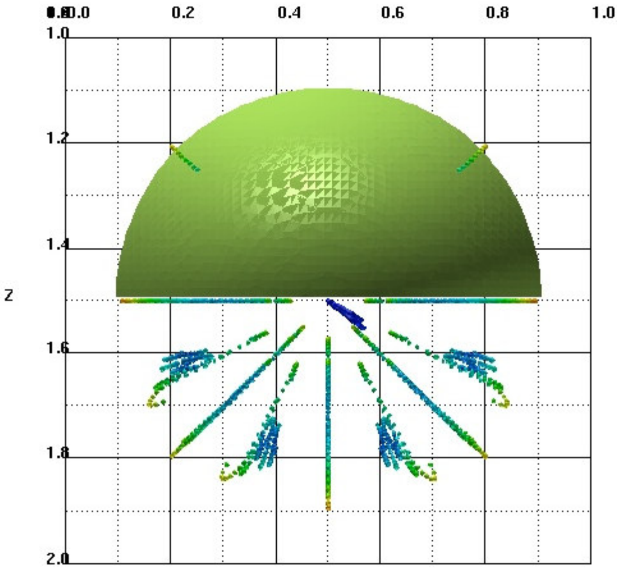
Bubble shape and trajectories of mass less particles for case A



View from side



View from side



View from top

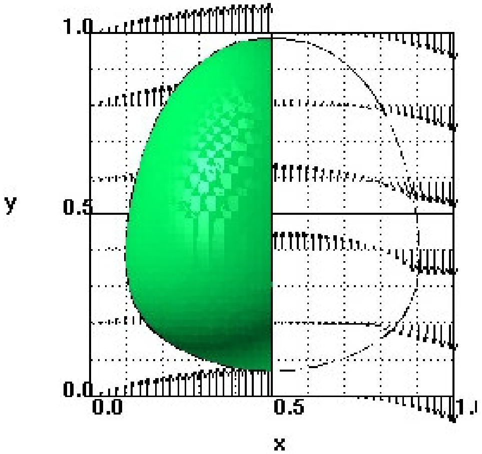
- Bubble has axisymmetric shape
- One large vortex inside the bubble
- Small azimuthal flow inside bubble

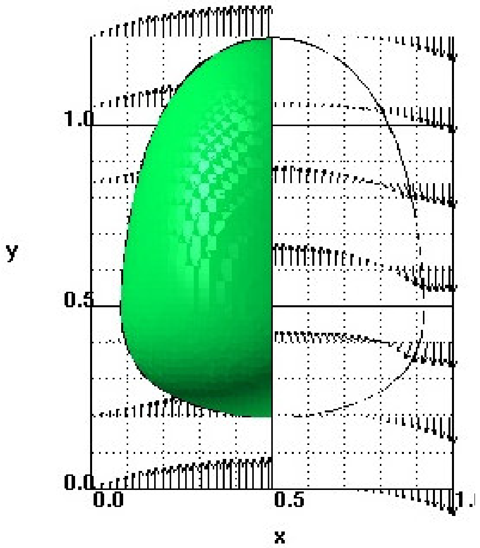
Bubble shape and velocity field

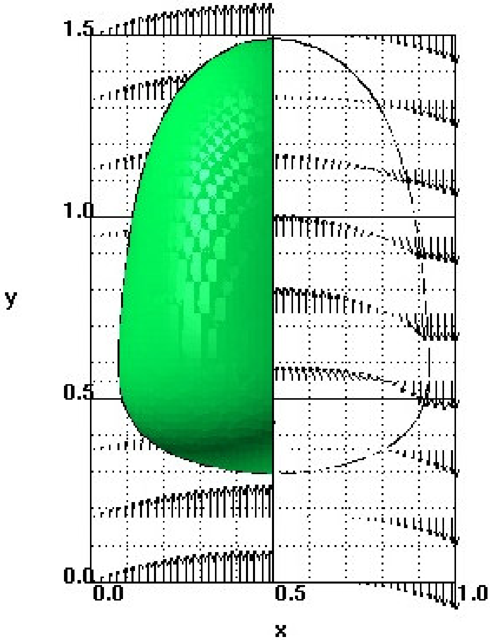
Velocity field in vertical mid-plane

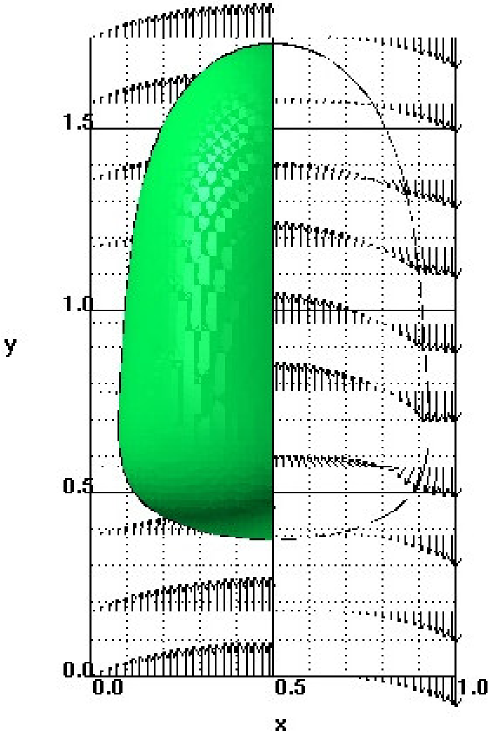
Right half: frame of reference moving with bubble

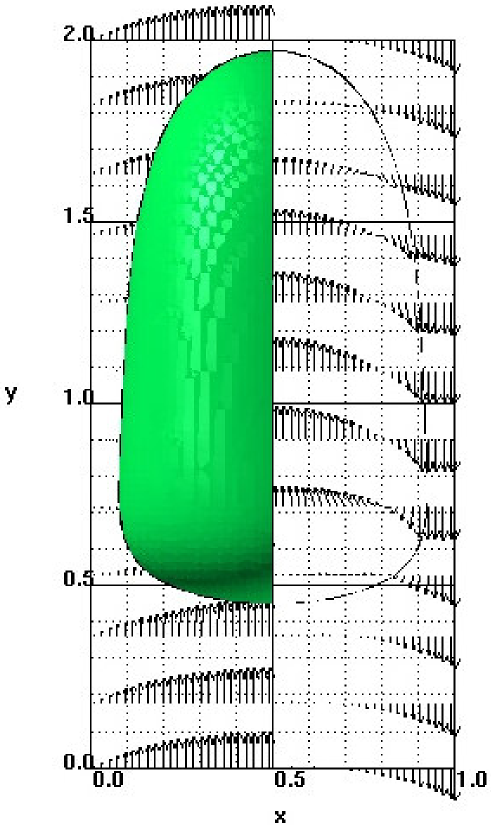
Left half: fixed frame of reference











Comparison with experiment

Non-dimensional bubble diameter

Relative velocity

Non-dimensional U_B

Case	L_{fuc} / W	Ca_B	D_B / W	$(U_B - J_{total})/U_B$	U_B/J_{total}
A	1	0.204	0.81	1.80	0.445
B	1.25	0.207	0.84	1.75	0.430
C	1.5	0.215	0.85	1.75	0.430
D	1.75	0.238	0.85	1.78	0.438
E	2	0.253	0.85	1.8	0.445
Experimental data[*] correlated in terms of Capillary number $Ca_B \equiv \mu_l U_B / \sigma$					
		0.2 – 0.25	0.82 – 0.86	1.68 – 1.84	0.435 – 0.475
			✓	✓	✓

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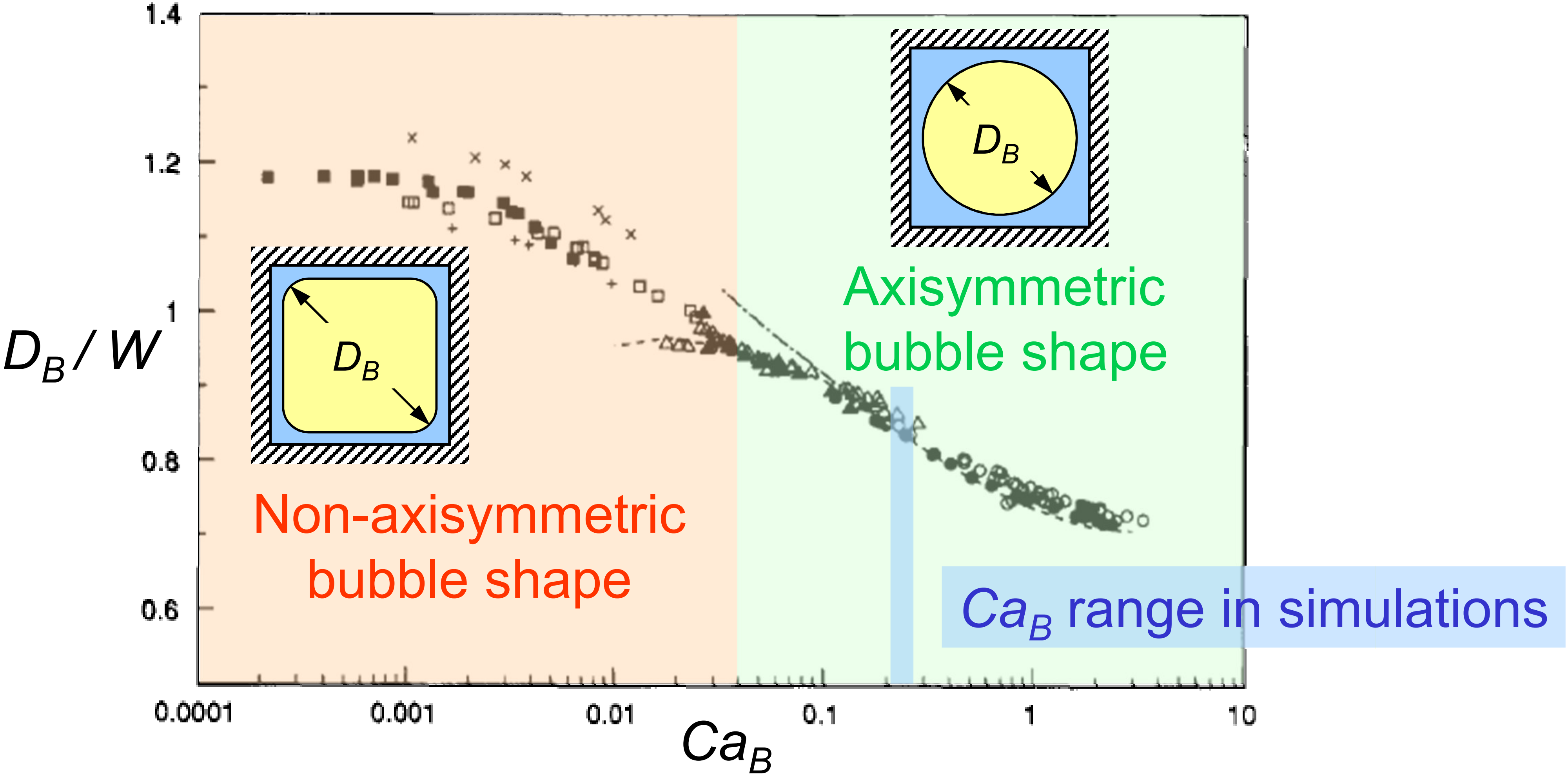
[*] Thulasidas, Abraham, Cerro, Chem. Eng. Science 50 (1995) 183-199

D_B measured along channel diagonal*



⇒ D_B / W decreases with increase of Ca_B

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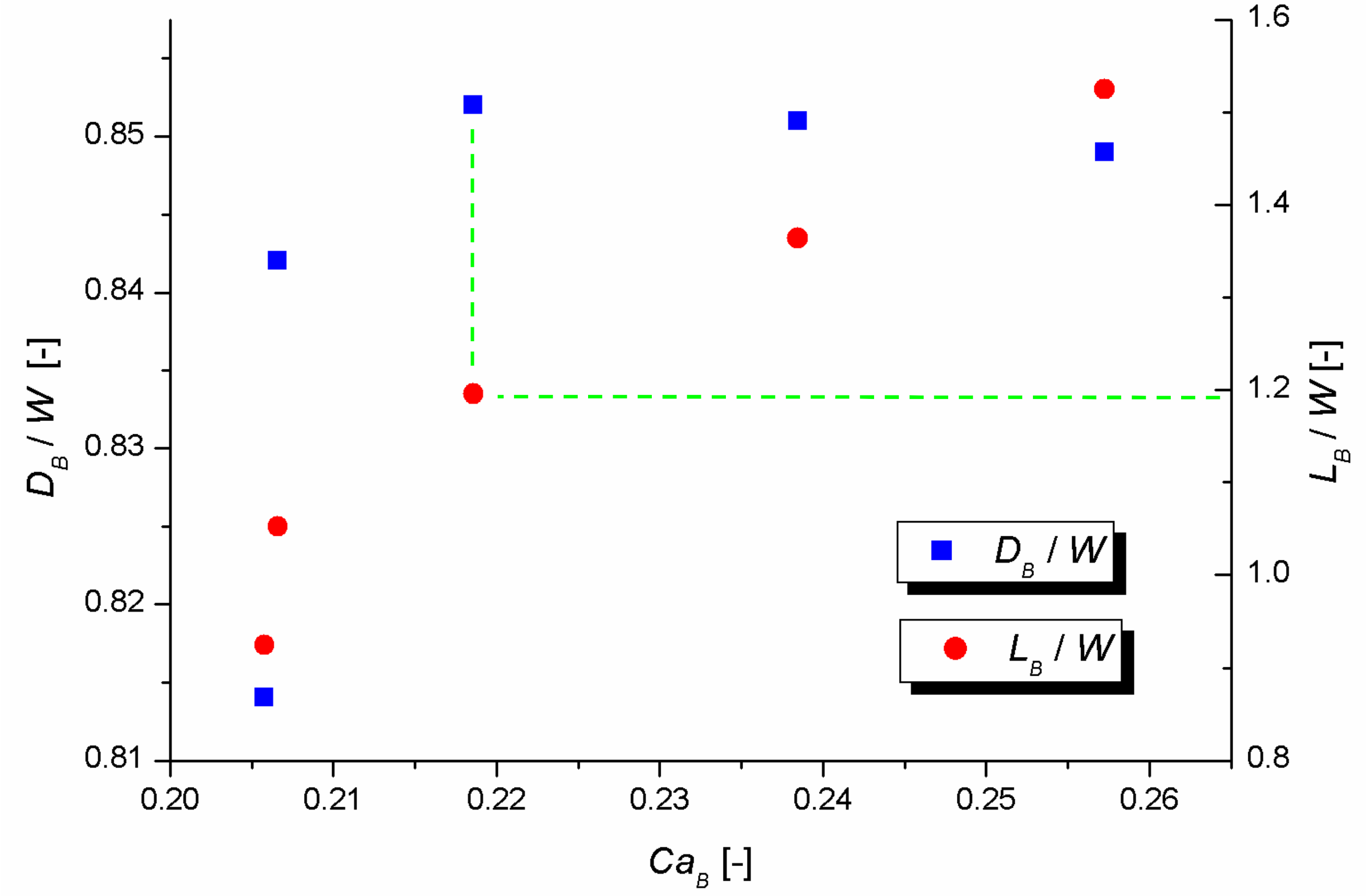
Bubble diameter in simulations



D_B / W decreases with increase of Ca_B <u>only</u> if the bubble length L_B is larger than about 1.2 the channel width (this is the case in the experiments by Thulasidas et al.)

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Conclusions

- Numerical simulation of bubble train flow
  - Square vertical mini-channel of width $W = 2$ mm
  - Investigation of influence of flow unit cell length
- Good agreement with experimental data from literature
- Dependence of bubble diameter on Capillary number
  - Regime I: increase of D_B with Ca_B for $L_B < 1.2\ W$
  - Regime II: decrease of D_B with Ca_B for $L_B > 1.2\ W$
  - From experiments so far only regime II is reported (long bubbles)