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3D volume-of-fluid simulation of a wobbling bubble in a gas-liquid system of low Morton number

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Background and motivation

- Bubbly two-phase flow
  - enhancement of turbulence by bubbles (bubble-induced turbulence = BIT, pseudo-turbulence)
  - phenomenon is not fully understood
  - no general models available for engineering CFD codes
- Goal: “direct” simulations with volume of fluid (VOF) method
  - achieve low Morton numbers to realize “wobbling” bubbles
  - extend basic understanding of BIT
  - use simulation results to develop improved models for BIT

Non-dimensional volume-averaged equations*

$$\nabla \cdot \mathbf{u_m} = 0$$

$$\frac{\partial}{\partial t}\rho_m \mathbf{u_m} + \nabla \cdot (\rho_m \mathbf{u_m} \mathbf{u_m}) = -\nabla p + \frac{1}{\mathrm{Re_{ref}}} \nabla \cdot \left[\mu_m \left(\nabla \mathbf{u_m} + \nabla \mathbf{u_m}^{\mathrm{T}}\right)\right] - (1-f)\frac{\mathrm{Eo_{ref}}}{\mathrm{We_{ref}}}\frac{\mathbf{g}}{g} + \frac{a_{int}\kappa \vec{n}}{\mathrm{We_{ref}}}$$

$$\rho_m \equiv \frac{f\rho_1^* + (1-f)\rho_2^*}{\rho_{ref}^*} \qquad \mu_m \equiv \frac{f\mu_1^* + (1-f)\mu_2^*}{\mu_{ref}^*} \qquad f \equiv \alpha_1$$

$$\mathbf{u_m} \equiv \frac{f\rho_1^* \overline{\mathbf{u}_1^*}^1 + (1-f)\rho_2^* \overline{\mathbf{u}_2^*}^2}{\rho_m^* U_{ref}^*} \qquad \mathbf{u_r} \equiv \frac{\overline{\mathbf{u}_2^*}^2 - \overline{\mathbf{u}_1^*}^1}{U_{ref}^*}$$

here: $\mathbf{u_r} = \mathbf{0}$

*see presentation # 245 in session DK this afternoon

Volume-of-fluid interface tracking

$$\frac{\partial f}{\partial t} + \nabla \cdot (f\,\mathbf{u_m}) = 0$$

- New algorithm for interface reconstruction:

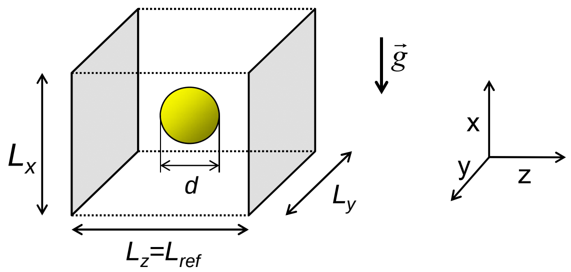
  EPIRA = Exact Plane Inferface Reconstruction Algorithm

  always reconstructs a 3D plane interface correctly, regardless of its orientation (see paper)
- Advection step by naive unsplit method

Computer code TURBIT-VOF

- Finite volume method on regular staggered grid
- Explicit Runge-Kutta time integration scheme (3rd O.)
- Central difference scheme (CDS) for diffusive terms (2nd O.)
- CDS or W-ENO scheme (3rd O.) for convective terms
- Surface tension:
  - use of normal vector of VOF reconstruction
  - use of a_{int} instead of delta function
- Conjugate gradient solver for Pressure-Poisson-equation

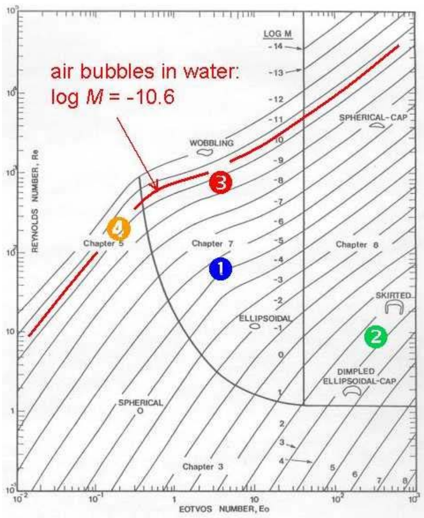
Computational domain and boundary conditions



- *x*-, *y*-direction: periodic boundary conditions
- *z*-direction: rigid walls
- present simulations: domain = 1 x 1 x 1 (64 x 64 x 64 cells)
  d / L_{ref} = 0.25 (=16 cells per bubble diam.)

Relevant non-dimensional groups

Group	type	value
$\mathrm{Re_B} = \rho_1^* U_B^* d_B^* / \mu_1^*$	result	10 - 1000
$\mathrm{Eo_B} = (\rho_1^* - \rho_2^*) g^* d_B^{*2} / \sigma^*$	input	3.07 - 243
$\mathrm{Mo} = \dfrac{g^* \mu_1^{*4} (\rho_1^* - \rho_2^*)}{\rho_1^{*2} \sigma^{*3}} = \dfrac{\mathrm{EoWe}^2}{\mathrm{Re}^4}$	input	$2.5 \cdot 10^{-10}$ - 266
ρ_2^* / ρ_1^*	input	0.5
μ_2^* / μ_1^*	input	1



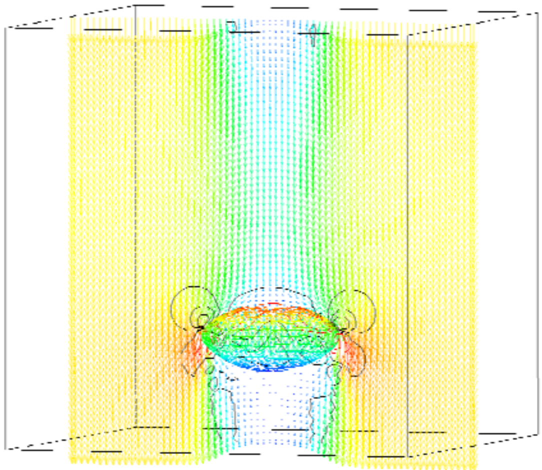
Case ❶ : ellipsoidal bubble

(Eo_B=3.07, M=3.1*10^{-6}

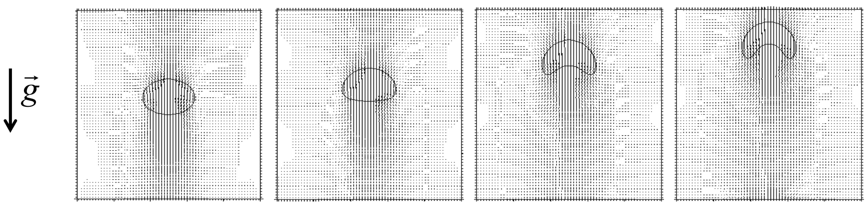
- rectilinear path
- steady shape

	Exp.	Sim.
axis-ratio	0,72	0,71
Re_B	50...70	61,5

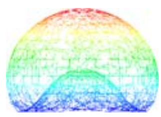
initial cond. for ❷+❸



Case ❷: spherical cap bubble (Eo_B=243, M=266)



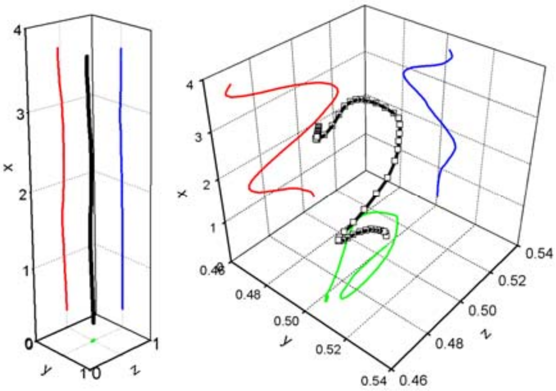
- Rectilinear path
- Steady bubble shape:



Exp. Bhaga&Weber Simulation

Case ❸: "wobbling" bubble (Eo_B=3.07, M=2.5*10^{-10})

- stepwise decrease of Morton number
- computation of 2050 time steps
- rectilinear path of case ❶ becomes unstable
- bubble shape becomes unsteady and irregular



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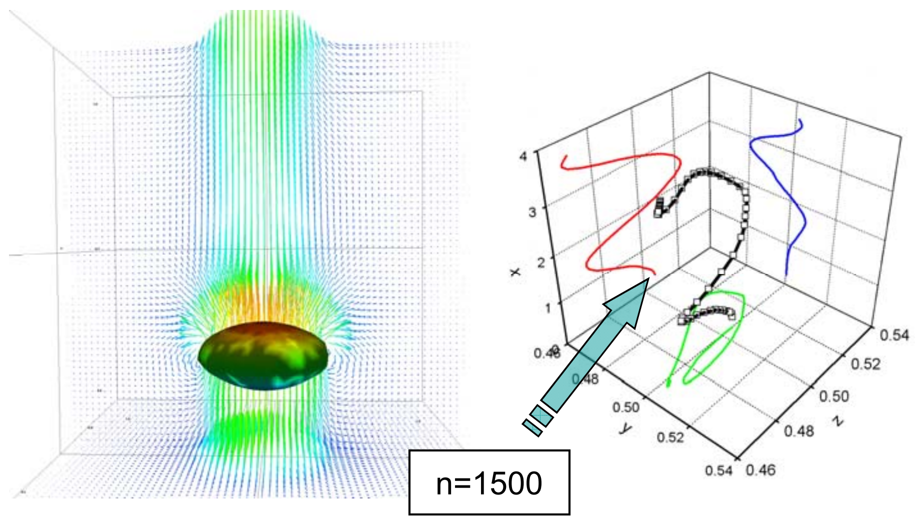
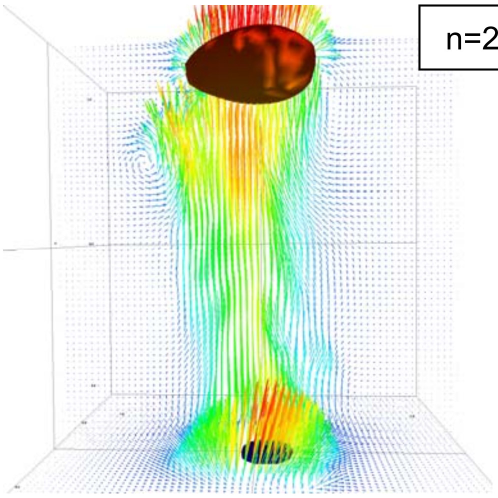
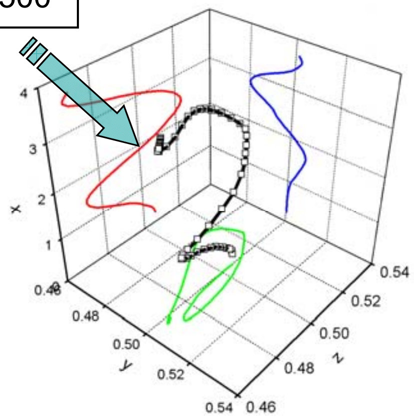




n=2500



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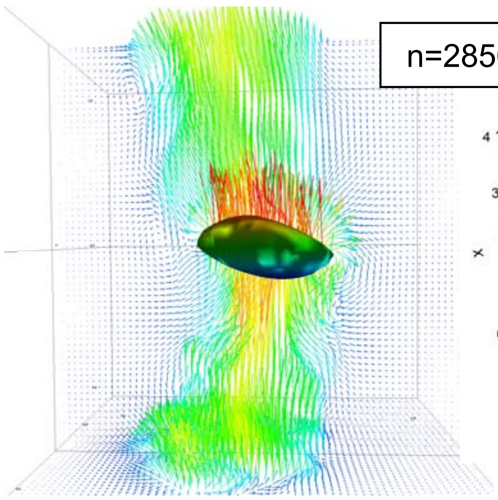
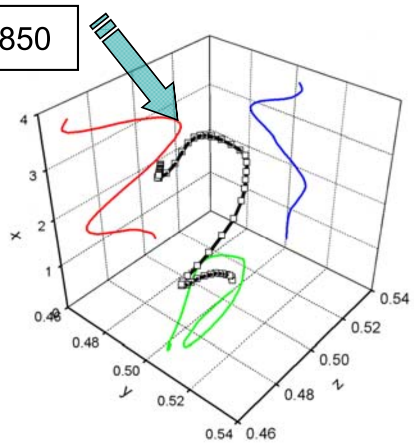
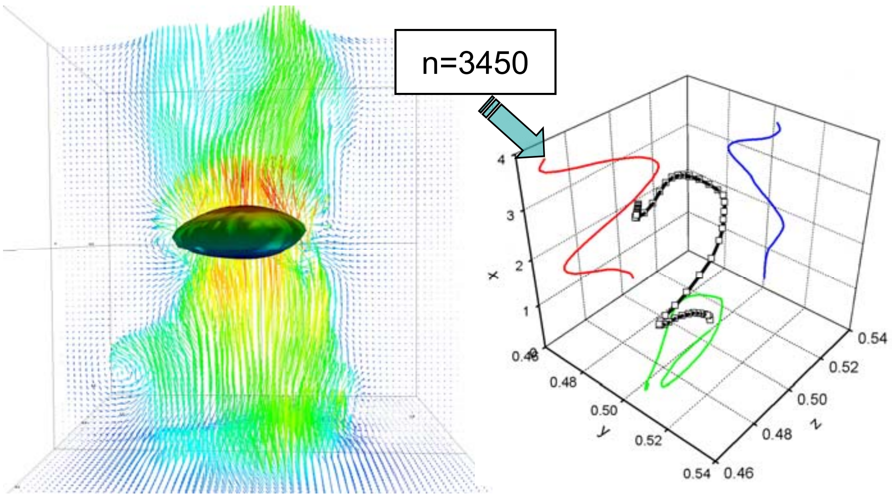


n=2850





Conclusions

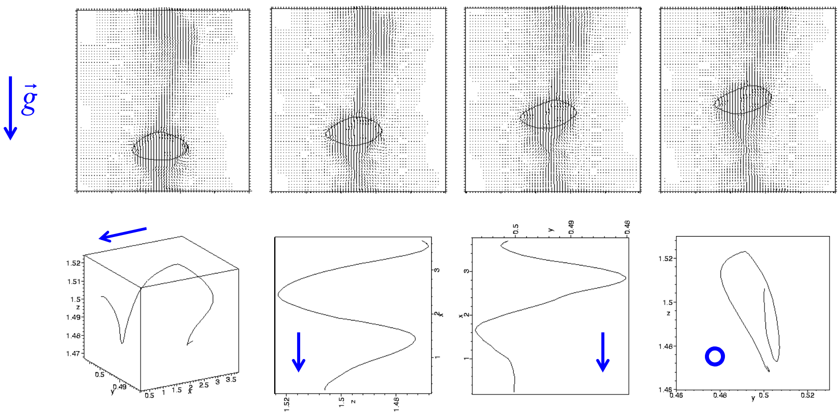
- present results for case ❶ and ❷ with $\rho_2/\rho_1 = 0.5$ compare well with experimental results for air-water systems
- bubble ❸ behaves as to be expected from CGW diagram
- bubble shape, wake, and path
  - depend mainly on Eötvös and Morton number
  - density ratio and viscosity ratio are of minor importance
- ⇒ use O(0.1) density ratio for efficient VOF simulations for bubble swarms in g/l systems of low Morton number
- ⇒ use results to develop models for bubble induced turbulence

Simulation parameters

$\rho_2 / \rho_1 = 1/2$
$\mu_2 / \mu_1 = 1$

	Case	Eo_b	Log *M*	Grid	Domain	*d / L*	Initial C.	Shape
	1BLc	0,2	-10,6	64*64*64	1x1x1	1 / 4	1BLa	Spherical
1	1BLa	3,07	-5,51	64*64*64	1x1x1	1 / 4	*U=0*	Ellipsoidal
·	1BLaa	3,07	-5,51	64*64*128	1x1x2	1 / 8	*U=0*	Ellipsoidal
·	1Blab	3,07	-5,51	128*64*64	2x1x1	1 / 4	*U=0*	Ellipsoidal
·	1Blac	3,07	-5,51	128*128*128	1x1x1	1 / 4	*U=0*	Ellipsoidal
1	5BLa	3,07	-5,51	64*64*64	1x1x1	1 / 4	*U=0*	Ellipsoidal
2	1BLb	243	2,42	64*64*64	1x1x1	1 / 4	1BLa	Ellips.-cap
3	1BLd	3,07	-9,6	64*64*64	1x1x1	1 / 4	1BLa	„Wobbling“

Case 3: wobbling bubble



Normalisation and non-dimensional numbers

$$\mathbf{u} = \frac{\mathbf{u}^*}{U^*_{ref}}$$

$$\rho = \frac{\rho^*}{\rho^*_{ref}}, \qquad \rho^*_{ref} = \rho^*_1$$

$$\mu = \frac{\mu^*}{\mu^*_{ref}}, \qquad \mu^*_{ref} = \mu^*_1$$

$$\mathbf{x}^* = \frac{\mathbf{x}^*}{L^*_{ref}}, \qquad t = \frac{t^* U^*_{ref}}{L^*_{ref}}$$

$$p^* = \frac{p^* + \rho^*_{ref}\mathbf{g}^* \cdot \mathbf{x}^*}{\rho^*_{ref} U^{*\,2}_{ref}}$$

$$\mathrm{Re}_{\mathrm{ref}} = \frac{\rho^*_{ref} U^*_{ref} L^*_{ref}}{\mu^*_{ref}}$$

$$\mathrm{Eo}_{\mathrm{ref}} = \frac{(\rho^*_1 - \rho^*_2) g^* L^{*\,2}_{ref}}{\sigma^*}$$

$$\mathrm{We}_{\mathrm{ref}} = \frac{\rho^*_{ref} U^{*\,2}_{ref} L^*_{ref}}{\sigma^*}$$

$$\mathrm{Mo} = \frac{g^* \mu^{*\,4}_{ref} (\rho^*_1 - \rho^*_2)}{\rho^{*\,2}_{ref} \sigma^{*3}} = \frac{\mathrm{Eo}_{\mathrm{ref}} \mathrm{We}^2_{\mathrm{ref}}}{\mathrm{Re}^4_{\mathrm{ref}}}$$

Verification of TURBIT-VoF

- single phase flow (Taylor-Green vortices)
- bubble at rest (pressure jump due to surface tension)
- Rayleigh-Taylor instability (2D and 3D)
- gravity wave (comparison with analytical solution)
- capillary wave (comparison with analytical solution)

Case ❸: "wobbling" bubble (Eo_B=3.07, M=2.5*10^{-10})

- stepwise decrease of Morton number
- computation of 2050 time steps
- rectilinear path of case ❶ becomes unstable
- bubble shape becomes unsteady and irregular