Analysis of bubble-induced turbulence and needs for model improvements

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Content

- Introduction
- Phenomena in bubble-turbulence interaction
- Direct numerical simulations of bubble swarm flows
- Analysis of transport equation of liquid phase turbulent kinetic energy (k_L) from DNS data
  - Budget of terms in k_L-equation
  - Assessment of closure assumptions
- Conclusions

Introduction

- For thermal-hydraulic design of innovative reactor and transmutation systems, computational fluid dynamics (CFD) is of great importance
  - Experiments at full scale and for realistic conditions (temperature, pressure, flow rates) are often hardly possible
  - The scale-up from laboratory experiments and the design and optimization of the reactor relies almost entirely on CFD
  - Due to large dimensions, the flow is usually in the turbulent regime, thus for reliable CFD results turbulence models play a critical role
  - Assessment and needs for turbulence models
    - Single phase heat transfer, see presentation A05 by G. Grötzbach (Monday)
    - Here: two-phase bubbly flows

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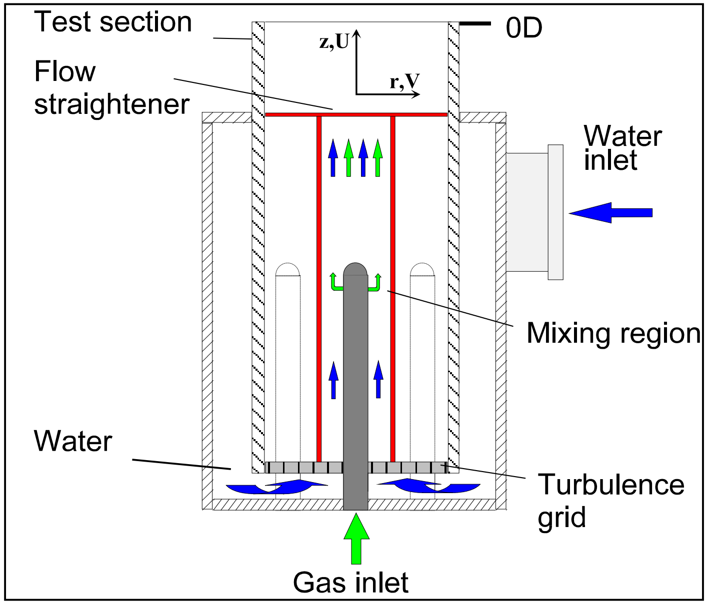
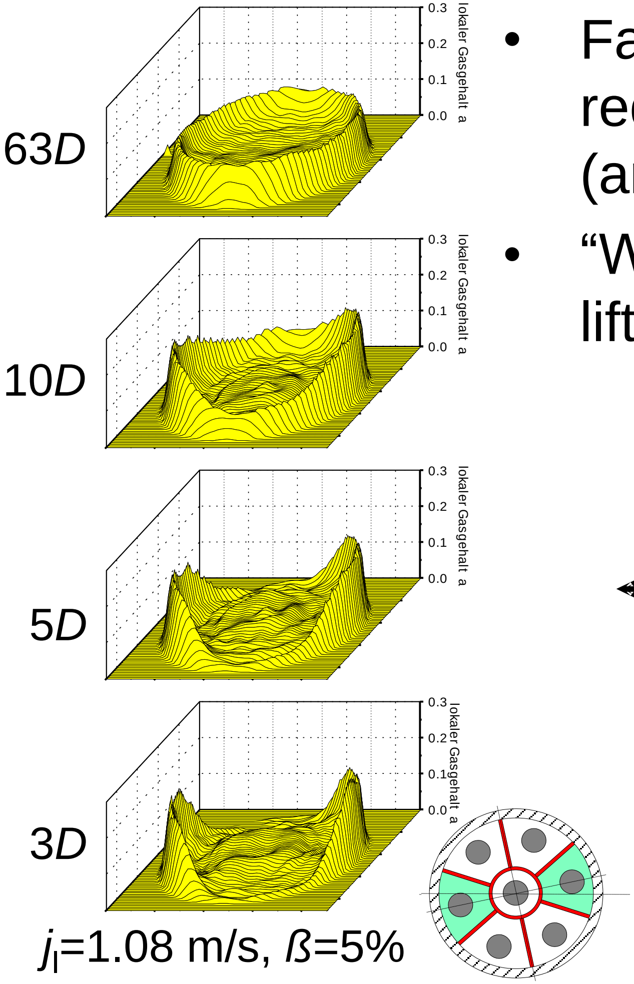
Bubble-turbulence interaction

Experiments on cocurrent upward air-water flow in a vertical pipe

(Samstag, FZKA 5662, 1996)

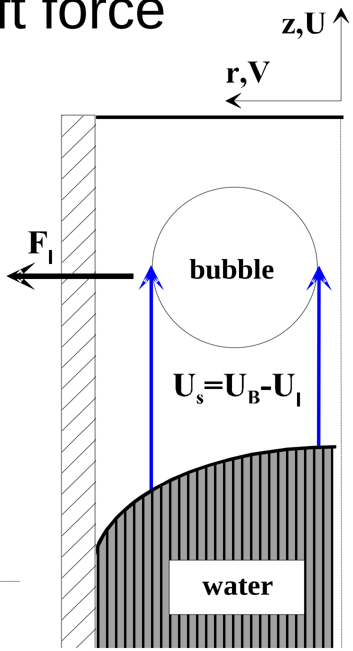
D=70mm
j_l=0.36, 1.08, 1.44 m/s
ß= j_l / (j_l + j_g) = 0, 5, 10%
1 – 7 nozzles , d_B ≈ 2 - 5 mm



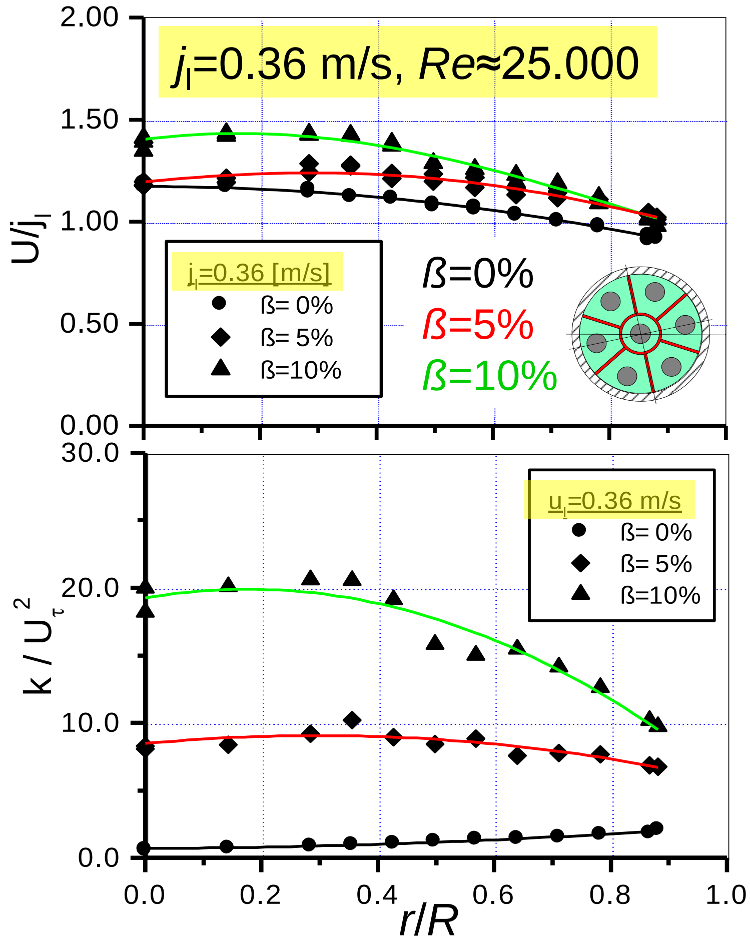


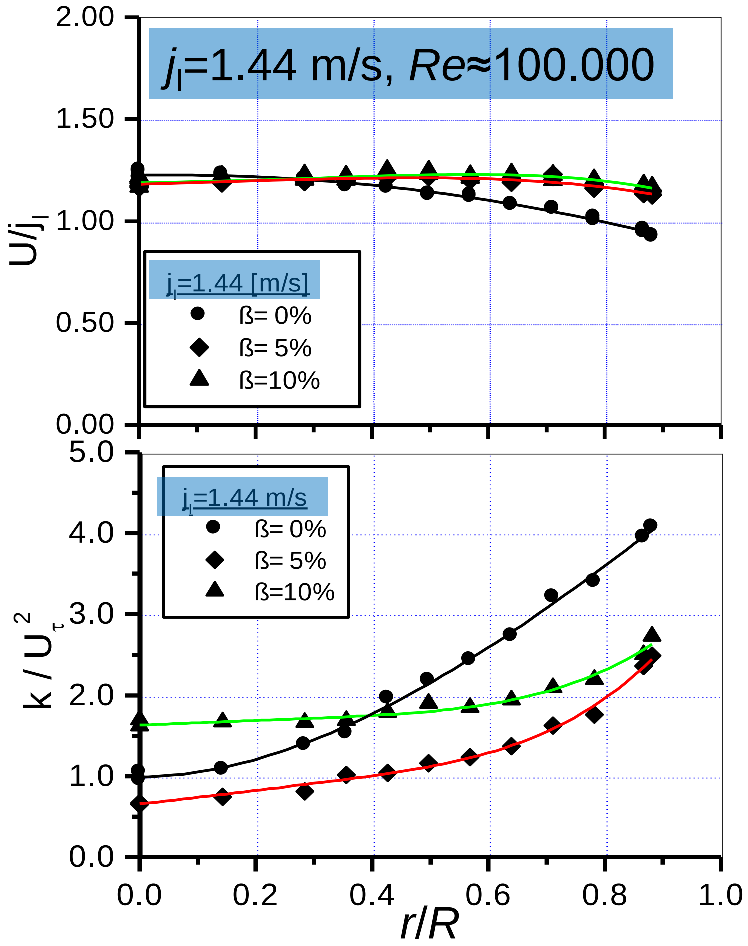
j_l=1.08 m/s, ß=5%

- Fast azimuthal gas redistribution (anisotropic)
- “Wall peaking” due to lift force



Bubble-turbulence interaction





Radial profile of mean axial liquid velocity

at 70*D*

Radial profile of liquid turbulent kinetic energy at 70*D*

Bubbles enhance turbulence for
0≤ *r*/*R*<1 for both, β=5% and β=10%

β=5%: bubbles damp turbulence for 0≤ *r*/*R*<1
β=10%: bubbles enhance turbulence for *r*/*R*<0.4
and damp it for *r*/*R*>0.4

Bubble-turbulence interaction

- Mechanisms of bubble-turbulence interaction
  - Direct
    - Gas bubbles displace liquid and induce velocity fluctuations
    - Vortices in bubble wake induce velocity fluctuations
    - Dissipation of liquid phase turbulence kinetic energy by disperse elements
  - Indirect
    - Modification of mean liquid velocity profile by presence of bubbles
    - Modification of production rate of turbulent kinetic energy by shear stresses
  - Nonlinear feedback
    - Turbulence has strong influence on breakup and coalescence of bubbles and thus determines bubble size distribution
    - Bubbles of different size have different rise velocity and experience different magnitude and direction of lift force (toward wall or toward pipe center)
    - Bubble size distribution influences radial void fraction profile
    - Radial void fraction profile influences mean liquid velocity profile

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Direct numerical simulations

- Background and motivation for DNS
  - Experiments show that bubbles may enhance turbulence or damp turbulence as compared to single phase flow
  - Experimental data in literature are not conclusive and contradictory*
  - Qualitatively, phenomena are partly understood, but not quantitatively
  - A reliable model to account for turbulence in bubbly flows in Euler-Euler CFD codes (two-fluid model) is missing
  - Model development is hindered by difficulty to measure relevant correlations between various fluctuating quantities
- Goal: use DNS data to analyze turbulence kinetic energy equation for liquid phase and to test closure assumptions

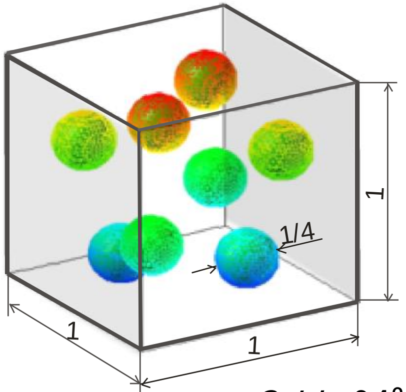
** For recent literature overview see Hu et al, CES 62 (2007) 1199*

In-house code TURBIT-VOF

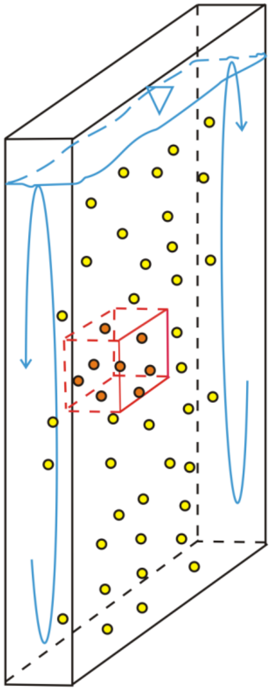
- Volume-of fluid method for interface tracking
  - Interface is locally approximated by a plane (PLIC method)
- Governing equations for two incompressible fluids
  - Single field momentum equation with surface tension term
  - Zero divergence condition for center-of-mass velocity
  - Advection equation for liquid volumetric fraction *f*
- Discretization in space and solution strategy
  - Projection method with 3rd order explicit Runge-Kutta time integration
  - Finite volume formulation for regular staggered grid
  - Second order central difference approximations
- Verification
  - Test problems with known analytical solution
  - Experimental results for single bubbles of various shape

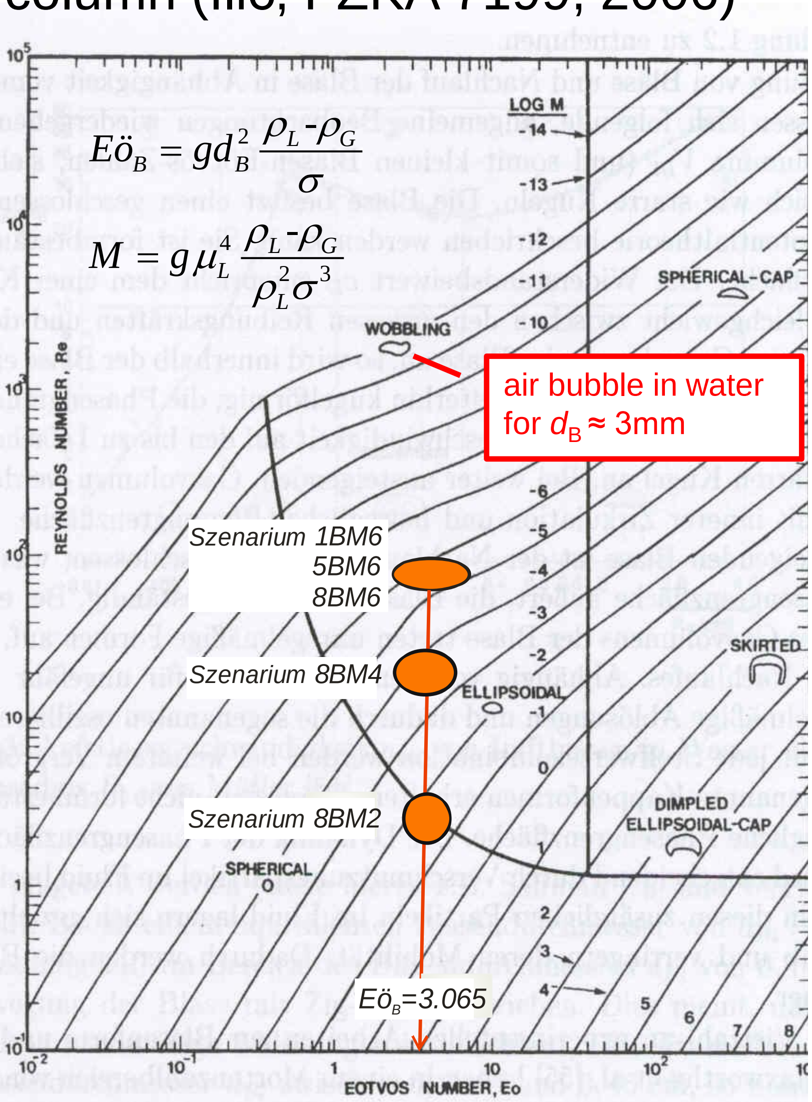
Bubble swarm simulations

- Simulations for central region of a flat bubble column (Ilić, FZKA 7199, 2006)
  - No-slip side walls and periodic b.c. in vertical and lateral direction
  - Bubbles drive liquid flow and induces “pseudo-turbulence”



Grid: 64^3 *and* 100^3





$$Eö_B = g d_B^2 \frac{\rho_L - \rho_G}{\sigma}$$

$$M = g \mu_L^4 \frac{\rho_L - \rho_G}{\rho_L^2 \sigma^3}$$

air bubble in water for $d_B \approx 3$mm

Szenarium 1BM6
5BM6
8BM6

Szenarium 8BM4

Szenarium 8BM2

$Eö_B = 3.065$

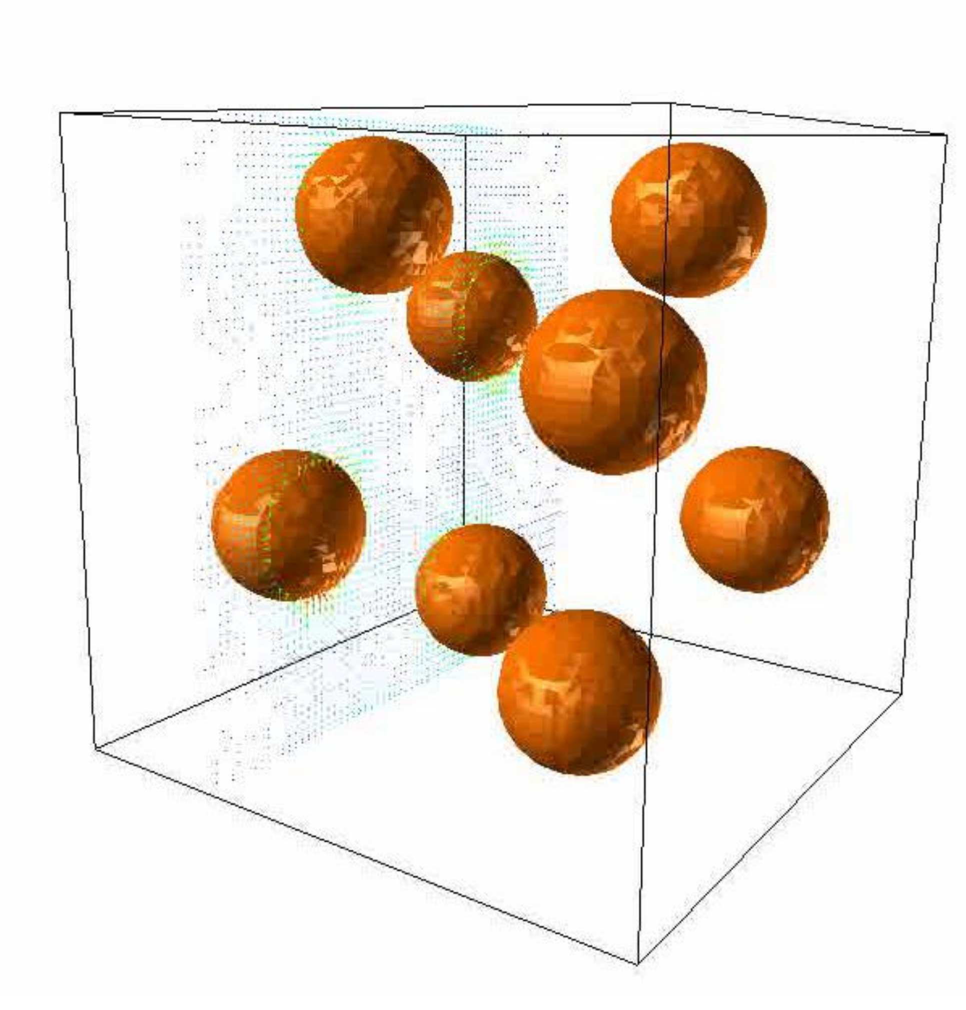
Influence of gas content

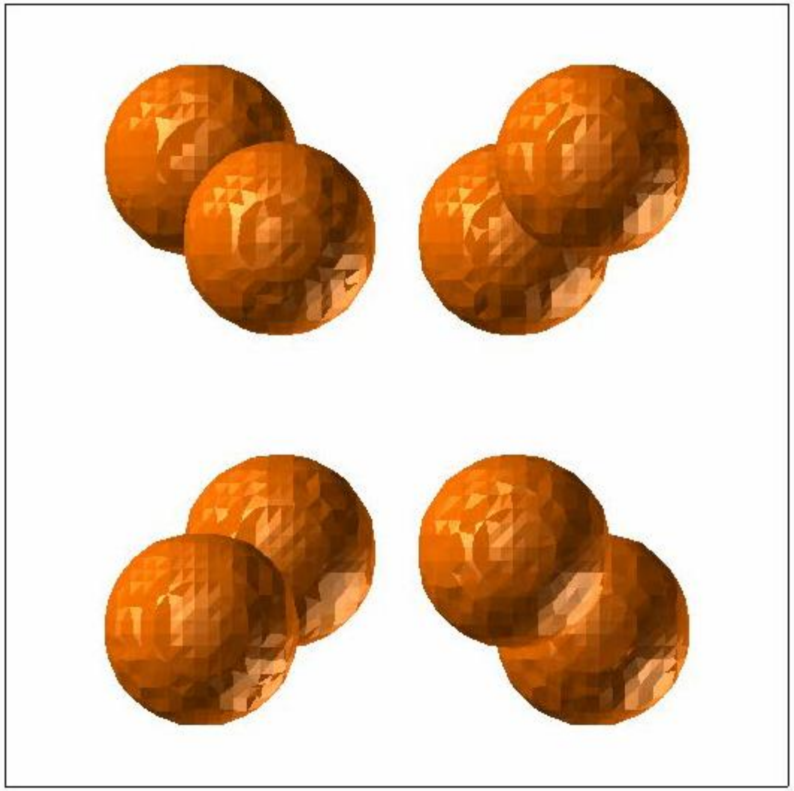
Scenario	*1BM6*	*5BM6*	*8BM6*	*8BM4*	*8BM2*
No. of bubbles	1	5	8	8	8
Gas content	0.818%	4.088%	6.544%	6.544%	6.544%
Morton number	$3.06\cdot10^{-6}$	$3.06\cdot10^{-6}$	$3.06\cdot10^{-6}$	$3.06\cdot10^{-4}$	$3.06\cdot10^{-2}$

$\rho_L/\rho_G = 2$, $\mu_L/\mu_G = 1$

Influence of bubble shape and velocity

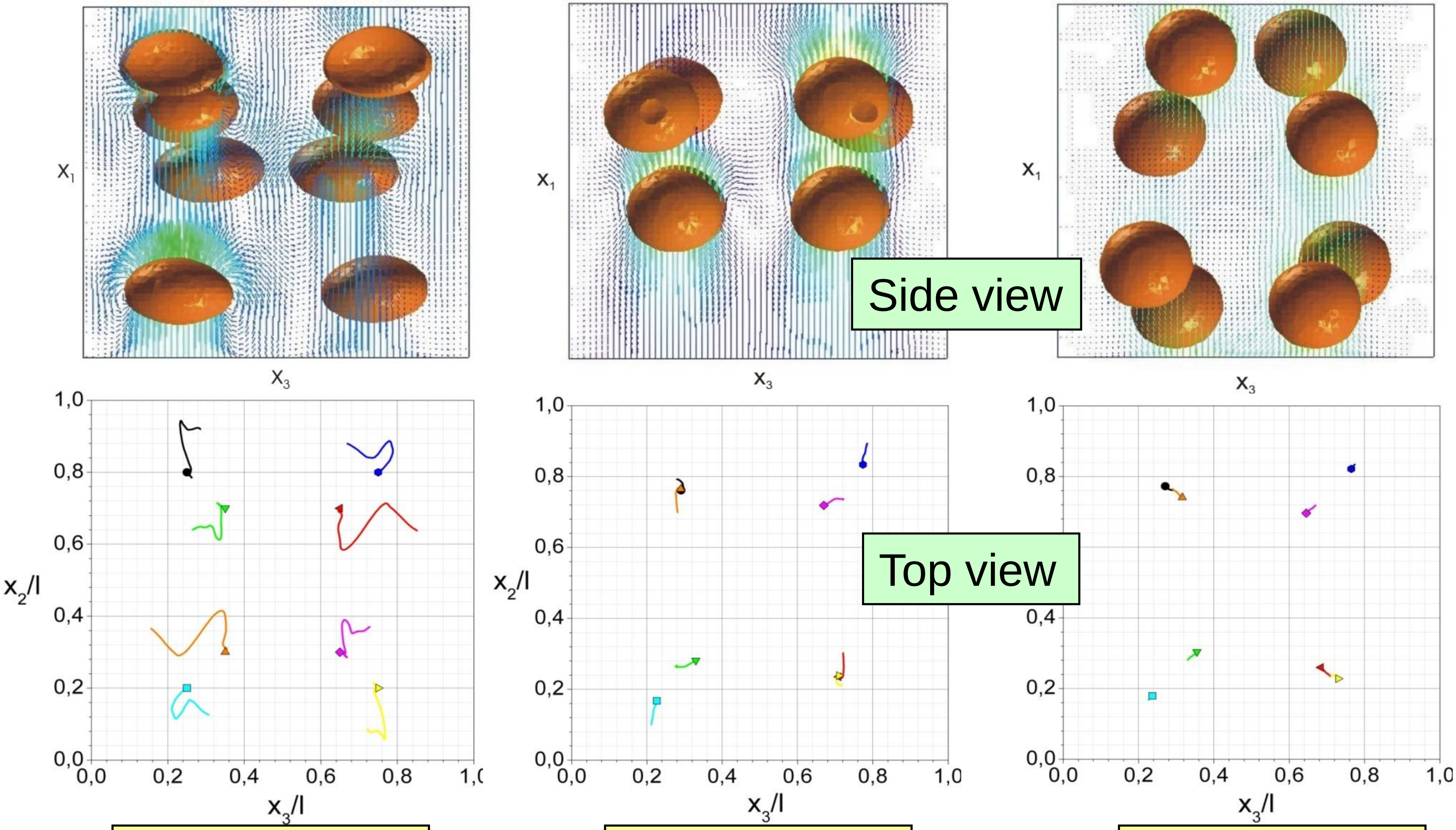
Visualization of bubble motion





8BM6: $M = 3\times10^{-6}$

Bubble shape and path



Side view

Top view

8BM6: $M = 3\times10^{-6}$

8BM4: $M = 3\times10^{-4}$

8BM2: $M = 3\times10^{-2}$

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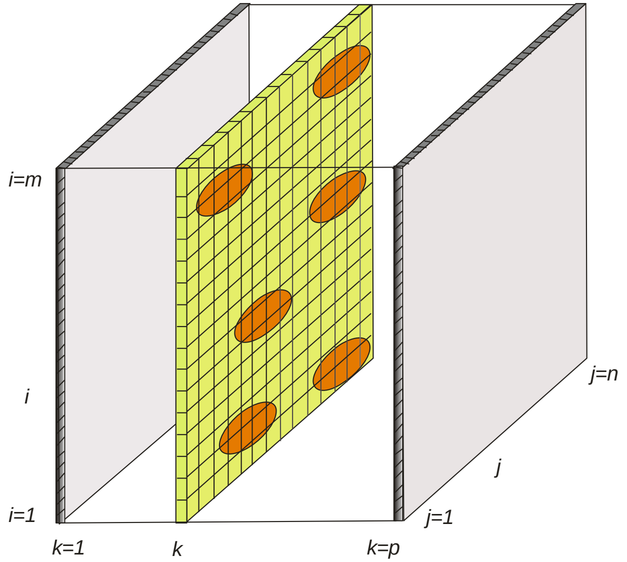
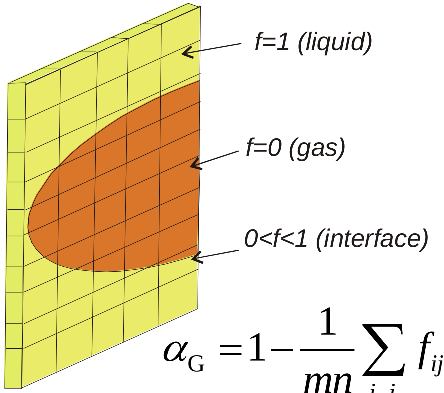
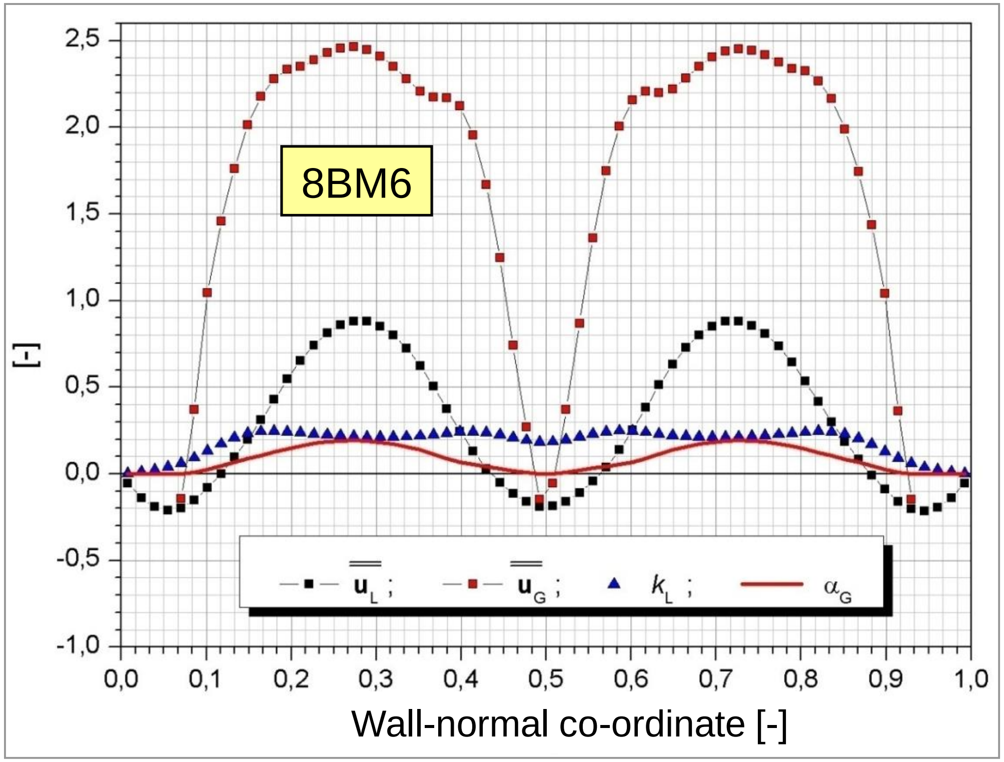
Averaging of simulation results

Averaging over planes parallel to the side walls





$$\alpha_G = 1 - \frac{1}{mn}\sum_{i,j} f_{ijk}$$



Mean quantities:

$$\overline{A}_{Lk} = \frac{1}{mn}\sum_{i,j} A_{Lijk}$$ average

$$\overline{\overline{A}}_{Lk} = \frac{1}{\alpha_{Lk}}\sum_{i,j} f_{ijk} A_{Lijk}$$ phase-average

Fluctuating quantities:

$$A'_{Lijk} = A_{Lijk} - \overline{\overline{A}}_{Lk}$$ in bulk

$$A'_{Lijk,in} = A_{Lijk,in} - \overline{\overline{A}}_{Lk}$$ at interface

Terms in exact k_L-equation and budget

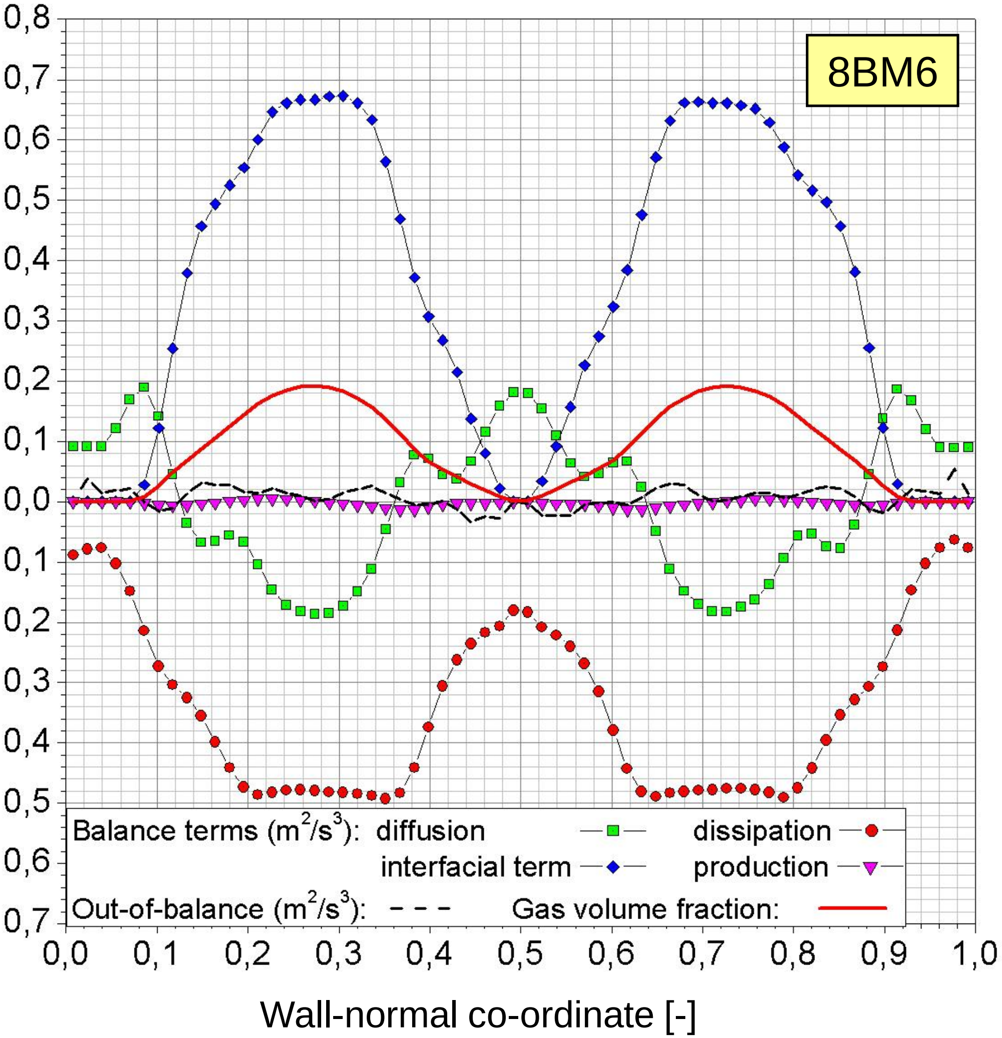
$$\frac{\partial}{\partial t}\left(\alpha_\mathrm{L} k_\mathrm{L}\right) + \nabla\cdot\left(\alpha_\mathrm{L} k_\mathrm{L} \overline{\overline{\mathbf{u}_\mathrm{L}}}\right) =$$

$$\underbrace{\frac{1}{Re_\mathrm{ref}}\nabla\cdot\left(\alpha_\mathrm{L}\overline{\mathbb{T}_\mathrm{L}^{'}\cdot\mathbf{u}_\mathrm{L}^{'}}\right) - \nabla\cdot\left[\alpha_\mathrm{L}\left(\overline{p_\mathrm{L}^{'}\mathbf{u}_\mathrm{L}^{'}} + \frac{1}{2}\overline{(\mathbf{u}_\mathrm{L}^{'}\cdot\mathbf{u}_\mathrm{L}^{'})\mathbf{u}_\mathrm{L}^{'}}\right)\right]}_{DIFFUSION}$$

$$\underbrace{-\alpha_\mathrm{L}\overline{\mathbf{u}_\mathrm{L}^{'}\mathbf{u}_\mathrm{L}^{'}} : \nabla\overline{\overline{\mathbf{u}_\mathrm{L}}}}_{PRODUCTION}$$

$$\underbrace{-\frac{1}{Re_\mathrm{ref}}\alpha_\mathrm{L}\overline{\mathbb{T}_\mathrm{L}^{'} : \nabla\mathbf{u}_\mathrm{L}^{'}}}_{DISSIPATION}$$

$$\underbrace{+\overline{\left[\frac{1}{Re_\mathrm{ref}}\mathbb{T}_\mathrm{L;in}^{'} - p_\mathrm{L;in}^{'}\mathbb{I}\right]\cdot\mathbf{u}_\mathrm{L;in}^{'}\cdot\mathbf{n}_\mathrm{L;in} a_\mathrm{in}}}_{INTERFACIAL\ \ TERM}$$



Balance terms (m^2/s^3): diffusion —🟩— dissipation —●—
interfacial term —◆— production —▼—
Out-of-balance (m^2/s^3): – – – Gas volume fraction: ——

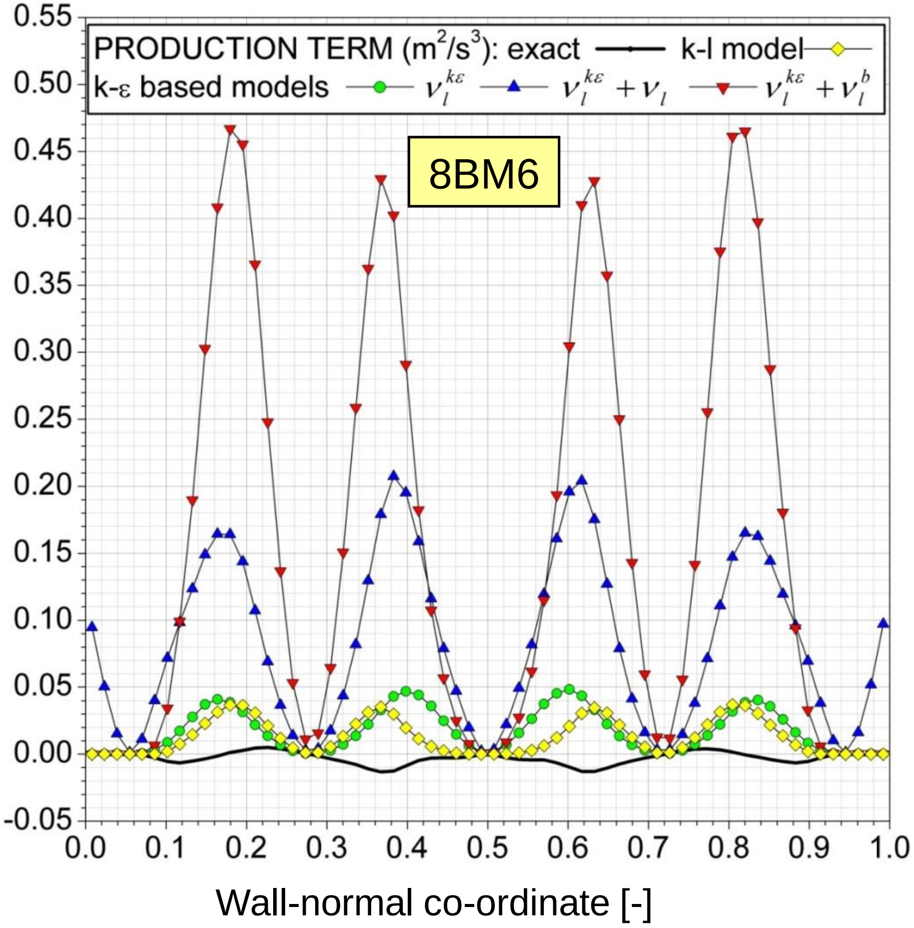
All terms on right hand side of k_L-equation must be modeled

$$\underbrace{\alpha_L \overline{\overline{u_L' u_L'}} : \nabla \overline{\overline{u_L}}}_{EXACT} \Rightarrow \underbrace{\alpha_L \nu_L^t (\nabla \overline{\overline{u_L}} + \nabla \overline{\overline{u_L}}^T) : \nabla \overline{\overline{u_L}}}_{MODELLED}$$

Boussinesq ansatz

Modeling of eddy viscosity:

extension of single phase concepts



***k–l* model:**

$$\nu_L^t = 0.56 \underbrace{\alpha_G d_B / 3}_{\text{turbulence length scale}} \sqrt{\overline{\overline{k_L}}}$$

turbulence velocity scale

α_G = gas content

d_B = bubble diameter

Two–equation models:

$$\nu_L^t = \nu_L^{k\varepsilon} = 0.09 \frac{\overline{\overline{k_L}}^2}{|\varepsilon_L|}$$

$$\nu_L^t = \nu_L^{k\varepsilon} + \nu_L$$

$$\nu_L^t = \nu_L^{k\varepsilon} + \underbrace{0.6 \alpha_G d_B \left|\overline{\overline{\mathbf{u}_r}}\right|}_{\nu_L^B}$$

$\mathbf{u}_r$ = relative velocity

ν_L = molecular viscosity of liquid phase

ν_L^B = bubble–induced eddy viscosity (Sato)

All models overestimate production by shear stresses!

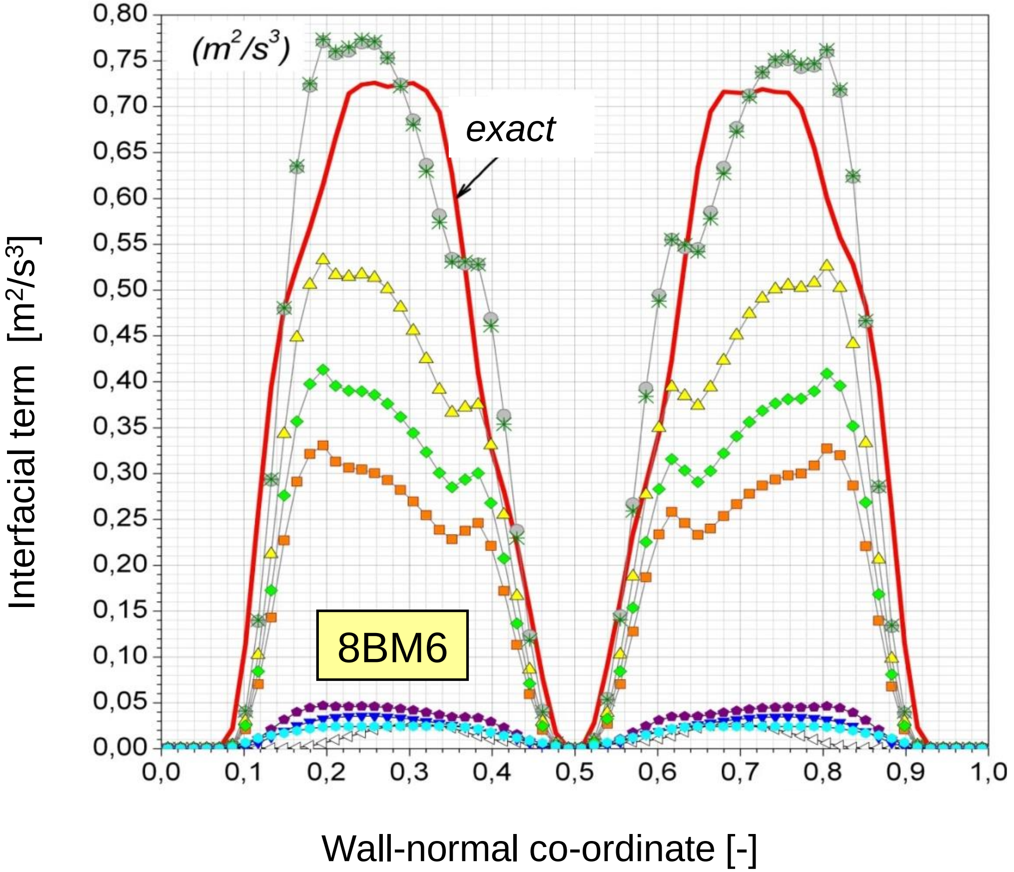
Models for interfacial term

exact: $-\overline{p'_{L,in}u'_{Li,in}}\,n_{Li}a_{in}+\overline{\tau'_{Lij,in}u'_{Li,in}}\,n_{Lj}a_{in}$

CLOSURE ASSUMPTIONS		
DRAG CONTRIBUTION *Defined in the form of:*	*Other contributions*	*Model of:*
Mean quantities:		
As power of drag force		
$W_D=0.75C_D\alpha_G\rho_L\lvert\overline{\overline{\mathbf{u}}}_r\rvert^3/d_B$	$M_{vm}\overline{\overline{\mathbf{u}}}_r$	*Morel* 📪
	none	*Troshko&Hassan* ⑥
As part of power of drag force		
$0.05\alpha_G W_D$	*none*	*Boisson et al.* ③
$0.75W_D$	*none*	*Olmos et al.* ⌨
$1.44W_D$	*none*	*Pfleger et al.* ✏
$0.075W_D$	$\alpha_G\rho_L k_L^{2/3}/d_B$	*Kataoka et al.* ✠
Drag force not explicitly included:		
$0.25\alpha_L\alpha_G\rho_L\left(1+C_D^{4/3}\right)\lvert\overline{\overline{\mathbf{u}}}_r\rvert^3/d_B$	*none*	*Lahey et al.* ☹
Mean and turbulent quantities:		
Only liquid turbulence properties		
$0.45C_D\alpha_G\rho_L k_L\lvert\overline{\overline{\mathbf{u}}}_r\rvert/d_B$	$2.53\alpha_G\alpha_L\Pi$	*Sheng et al.* 👌
Turbulence properties of both phases		
$\frac{3}{4}C_D\frac{\lvert\overline{\overline{\mathbf{u}}}_r\rvert}{d_B}\left\{2\alpha_G\rho_L(C_t-1)k_L-\frac{\nu_L^{k\varepsilon}\overline{\overline{\mathbf{u}}}_r\nabla\alpha_G}{\alpha_L\alpha_G}\right\}$	*none*	*Hill et al.* 📪

C_D = drag coefficient (different formulations used)

$$C_t=\overline{u'_G u'_G}\Big/\overline{u'_L u'_L}\propto f\left(l_e,Re_t,\alpha_G,d_B,\overline{\overline{\mathbf{u}}}_r,C_D\right)$$



- *Modeling as power of drag force gives good results (non-drag forces are insignificant here)*
- *Which correlation to use for C_D?*

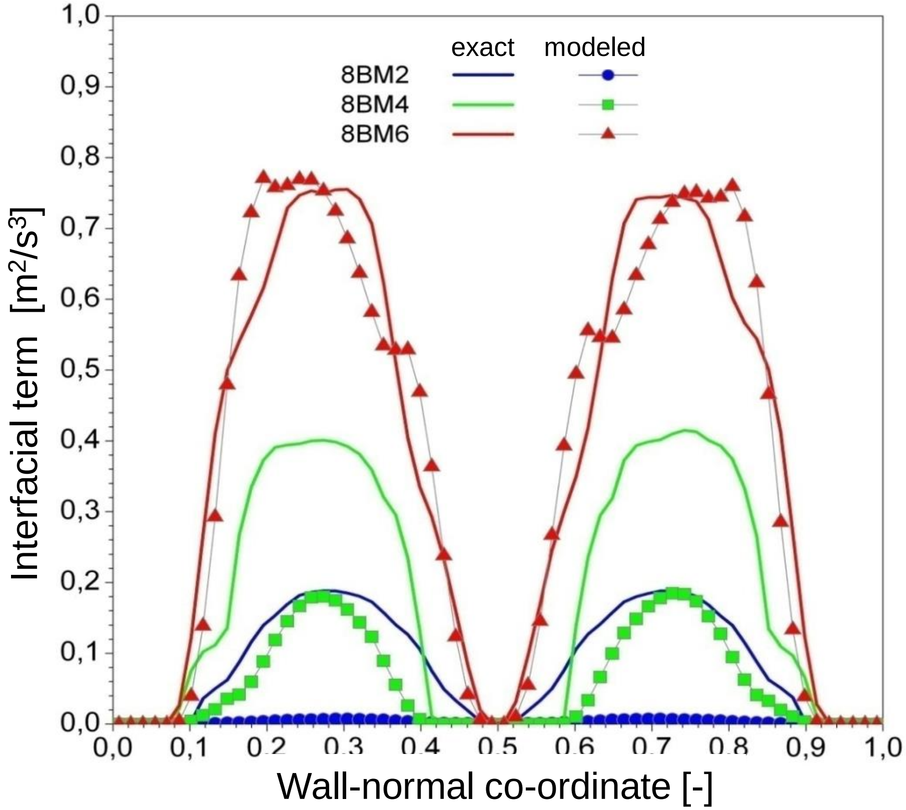
Models for interfacial term

Model of Morel (1997), Troshko&Hassan (2001):

$$W_{\mathrm{D}} = 0.75 (C_{\mathrm{D}} / d_{\mathrm{B}}) \alpha_{\mathrm{G}} \rho_{\mathrm{L}} \left| \overline{\overline{\mathbf{u}}}_{\mathrm{r}} \right| \overline{\overline{\mathbf{u}}}_{\mathrm{r}} \cdot \overline{\overline{\mathbf{u}}}_{\mathrm{r}}$$

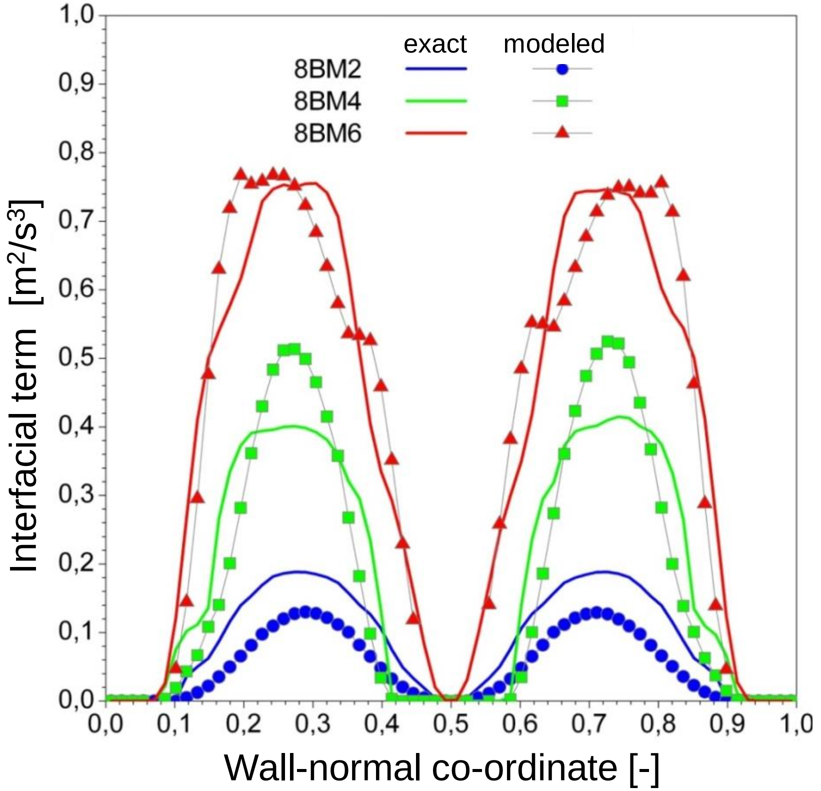
Correlation of Ishii for air-water ($M \approx 10^{-10}$)

$$C_{\mathrm{D}} = \frac{2}{3} \sqrt{E\ddot{o}_{\mathrm{B}}}$$



Correlation of Tomiyama (valid for $M = 10^{-14} - 10^{7}$)

$$C_{\mathrm{D}} = \max \left\{ \min \left[\frac{16}{Re_{\mathrm{B}}} (1 + 0.15 Re_{\mathrm{B}}^{0.687}), \frac{48}{Re_{\mathrm{B}}} \right], \frac{8}{3} \frac{E\ddot{o}_{\mathrm{B}}}{E\ddot{o}_{\mathrm{B}} + 4} \right\}$$



Conclusions

- Experimental data reveal complex bubble-turbulence interaction (enhancement/damping of shear turbulence)
- DNS of bubble driven liquid flow and analysis of transport eq. for liquid turbulence kinetic energy for pseudo-turbulence
  - Production by shear stresses is negligible (as expected)
  - Importance of interfacial term and diffusion term
- Evaluation of model assumptions
  - Production term and diffusion term: poor performance of standard single-phase type models (PT is over-, DT is underestimated)
  - Interfacial term: modeling as work of drag force together with Tomiyama correlation for C_D shows good performance
- Turbulence models for bubbly flows have strong deficiencies
  - Combined theoretical, experimental and numerical efforts are required to develop physically sound and general models for CFD