Simulation of Turbulent Disperse Bubbly Flows

Dr.-Ing. Josef Hasslberger and Prof. Dr.-Ing. habil. Markus Klein
Institute for Numerical Methods in Aerospace Engineering
Werner-Heisenberg-Weg 39, 85577 Neubiberg

Universität der Bundeswehr München

Introduction

- High technical relevance of bubbly flows
  - Boiling water reactors (nuclear industry)
  - Air lift pumps (oil industry)
  - Chemical reactors (process industry)
- Largely empirical design to date due to complex flow physics
- Direct Numerical Simulation (DNS), resolving the full spectrum of turbulent scales, now possible for reduced-complexity configurations at moderate Reynolds number
- Computationally less expensive **Large Eddy Simulation** (LES) applicable to technically relevant cases
- **Goal**: Development of LES sub-grid scale closures for two-phase flows
- Working program
  - Creation of DNS database
  - Sub-grid term order of magnitude analysis
  - A-priori analysis of several existing and new LES models
  - A-posteriori assessment of most promising approaches
  - Comparison with experiment (Haase et al. [1])

Computational Fluid Dynamics (CFD)

- Parallel Robust Interface Simulator (PARIS) finite-volume solver (Zaleski et al. [2])
- Unsteady incompressible Navier-Stokes equations
- One-fluid formulation (density and viscosity jump at interface)
- Geometrical Volume-Of-Fluid (VOF) method with Piece-wise Linear Interface Calculation (PLIC) for interface propagation
- Curvature calculation by height function method
- Third-order QUICK convection scheme and time integration by second-order explicit Heun scheme
- Digital filter method for synthetic inflow turbulence (Klein et al. [3])
- SuperMUC high performance cluster

LES methodology

- Favre-filtered governing equations (Labourasse et al. [4])

$$\frac{\partial \bar{\rho}}{\partial t} + \nabla \cdot (\bar{\rho}\tilde{\boldsymbol{u}}) = 0$$

$$\frac{\partial \bar{\rho}\tilde{\boldsymbol{u}}}{\partial t} + \nabla \cdot \left(\bar{\rho}\tilde{\boldsymbol{u}} \otimes \tilde{\boldsymbol{u}} + \bar{p}\mathbf{I} - \bar{\mu}\tilde{\mathbf{S}}\right) - \bar{\rho}\boldsymbol{g} - \sigma \bar{\boldsymbol{n}}\bar{\kappa}\delta_S = -\nabla \cdot \left(\tau_{\rho uu} + \tau_{\mu S}\right) + \tau_{nn}$$

$$\frac{\partial \bar{\alpha}}{\partial t} + \tilde{\boldsymbol{u}} \cdot \nabla \bar{\alpha} = \tau_{u\alpha}$$

- Sub-grid scale contributions which need to be modeled

$$\tau_{\rho uu} = \overline{\rho \boldsymbol{u} \otimes \boldsymbol{u}} - \bar{\rho}\tilde{\boldsymbol{u}} \otimes \tilde{\boldsymbol{u}}$$

$$\tau_{\mu S} = \overline{\mu \mathbf{S}} - \bar{\mu}\tilde{\mathbf{S}}$$

$$\tau_{nn} = \overline{\sigma \boldsymbol{n}\kappa\delta_S} - \sigma \bar{\boldsymbol{n}}\bar{\kappa}\delta_S$$

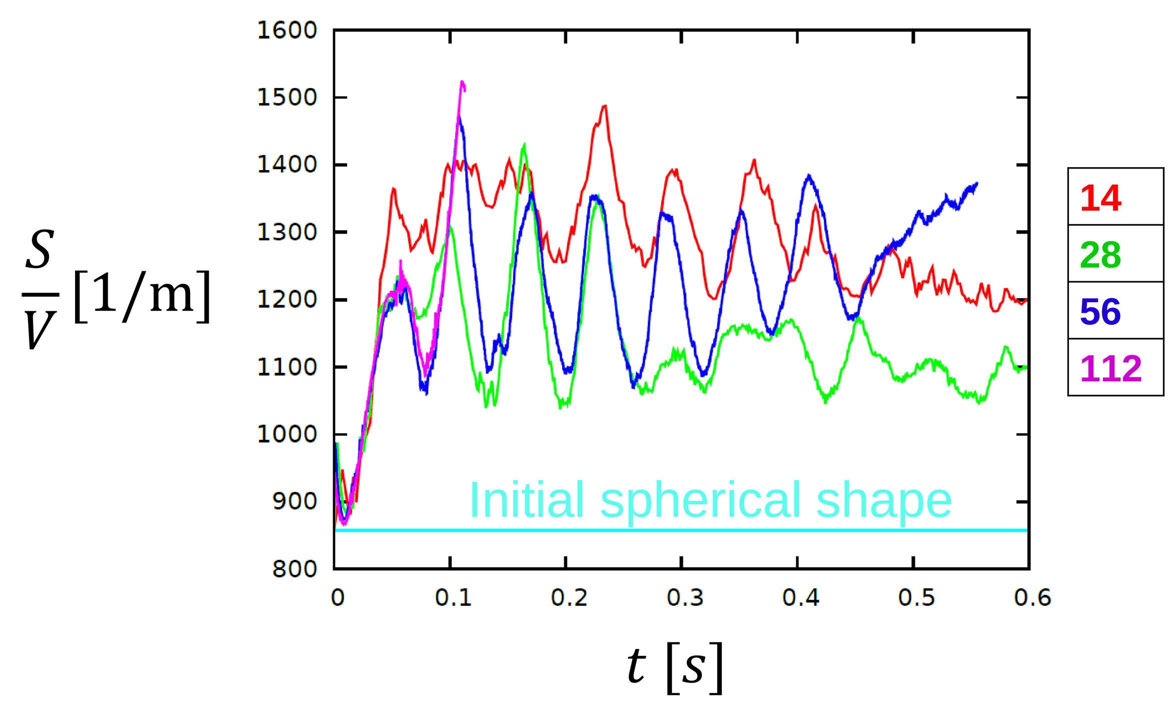
$$\tau_{u\alpha} = \tilde{\boldsymbol{u}} \cdot \nabla \bar{\alpha} - \overline{\boldsymbol{u} \cdot \nabla \alpha}$$

Acknowledgment

Deutsche Forschungsgemeinschaft (DFG)
Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften (lrz)

Bubble dynamics and bubble-induced turbulence

- Three sources of fluctuation/unsteadiness
  - Bubble trajectory
  - Bubble deformation
  - Vortex shedding in the bubble wake



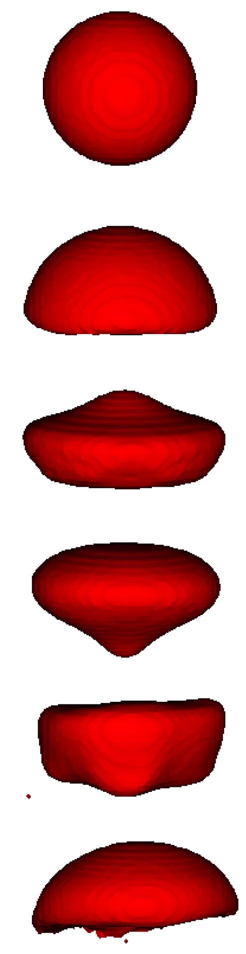


Fig. 1: Bubble shape oscillations evaluated by means of the surface-to-volume ratio; Including grid resolution sensitivity (colored numbers represent the number of cells per initial bubble diameter)

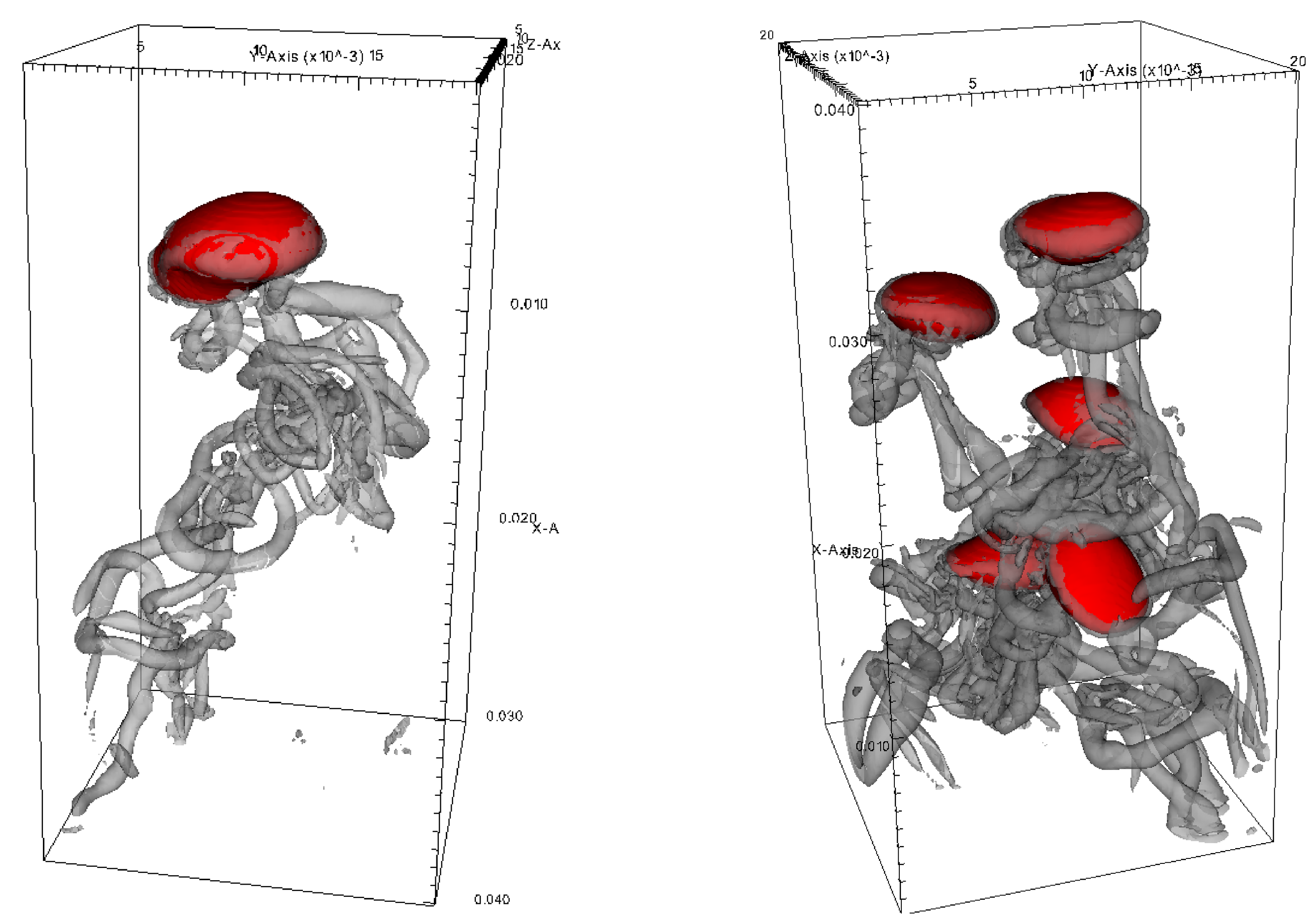


Fig. 2: Coherent structures visualized by the Q-criterion; Single bubble (1 x 7 mm) on the left, bubble cluster (5 x 5 mm) on the right

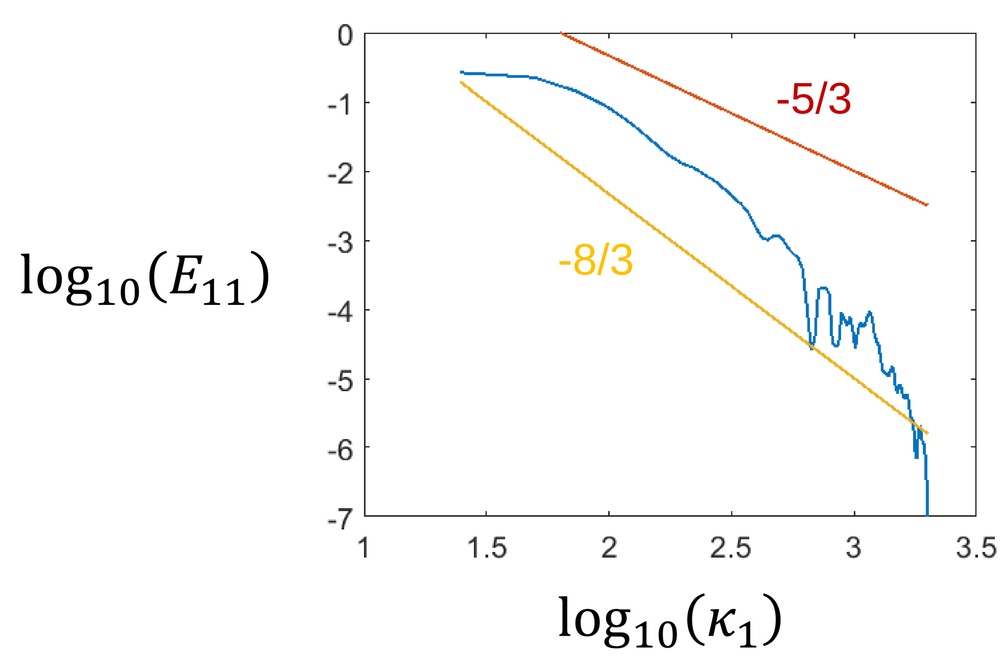


Fig. 3: Spatial energy spectrum in the bubble wake; Inertial subrange -5/3 power law for single-phase turbulence and -8/3 for two-phase turbulence according to Lance & Bataille [5]

References

[1] Haase K., Baczyzmalski D., Cierpka C., Kähler C.J.: "Charakterisierung von Blasen und deren Nachlauf in turbulenter Grundströmung", *Fachtagung Lasermethoden in der Strömungsmesstechnik*, September 2015, Dresden

[2] http://www.ida.upmc.fr/~zaleski/paris/index.html

[3] Klein M., Sadiki A., Janicka J.: "A digital filter based generation of inflow data for spatially developing direct numerical or large eddy simulations", *Journal of Computational Physics*, 186:652-665, 2003

[4] Labourasse E., Lacanette D., Toutant A., Lubin P., Vincent S., Lebaigue O., Caltagirone J.P., Sagaut P.: "Towards large eddy simulation of isothermal two-phase flows: governing equations and a priori tests", *International Journal of Multiphase Flow*, 33:1-39, 2007

[5] Lance M., Bataille J.: "Turbulence in the liquid phase of a uniform bubbly air-water flow", *Journal of Fluid Mechanics*, 222:95-118, 1991