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Three-dimensional numerical simulation of bubble dynamics by a volume-of-fluid method

by

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The rise of gas bubbles in a continuous liquid is of significant practical importance for a variety of engineering applications. However, several fundamental aspects of bubbly two-phase flow are still not fully understood. Examples are the interaction of bubbles rising in clusters and the generation of velocity fluctuations by bubbles and their wake in an otherwise laminar flow (pseudo-turbulence or bubble-induced turbulence). Although the importance of modelling the pseudo-turbulence in engineering CFD codes is well recognized, e.g. for bubble columns, reliable models are still missing. The development of such models requires detailed information about the fully three-dimensional velocity field close to the bubble and in its wake. Even advanced experimental techniques are nowadays restricted to two-dimensional cuts. In the present study a computer code is developed which allows to provide three-dimensional local field information (e.g. velocity field) by means of direct numerical simulation.

The code TURBIT-VoF, which is based on a volume-of-fluid method for volume tracking of the interface, has been developed for the direct numerical simulation of two-phase flows. In addition to the conservation equations for mass and momentum, a transport equation for the volume fraction of the liquid phase f is solved to determine the evolution of the interface. This equation is numerically solved by an improved 3D reconstruction and advection algorithm (named EPIRA, for exact plane interface reconstruction algorithm), which correctly reproduces a plane interface regardless of its orientation. Also an improved description of surface tension is obtained in TURBIT-VoF by a refined continuum surface model. The conservation equations for mass and momentum are solved using a fractional step scheme in which the convective terms are discretized with a high-resolution W-ENO scheme. A TVD Runge-Kutta scheme is used for time integration.

Calculations of several prototypical interfacial problems are performed to verify TURBIT-VoF. The accuracy of the refined continuum surface force model is demonstrated by simulating capillary waves. The surface tension acts as the sole driving force on an initially sinusoidal interface at rest. The computed temporal development of the viscously-damped oscillation is compared against the analytical solution. The verification of the implementation of the buoyancy force is performed by simulating both gravity waves and a Rayleigh-Taylor instability. For both problems, the simulation initially starts with a sinusoidal interface at rest. In the case of gravity waves the computed viscously-damped oscillation of the interface is compared against the analytical solution. In the case of the Rayleigh-Taylor instability 2D and 3D configurations are considered. The computed velocities of the rising 'bubble' and the falling 'finger' are in excellent agreement with values from literature. A very good agreement is also achieved between numerical and analytical solution for the other interfacial problems.

Computations of single bubbles rising in stagnant liquid are performed. In order to classify and characterize these bubbles the dimensionless parameters bubble Reynolds ($Re_B = \rho_l U_T d_B / \mu_l$), bubble Eötvös ($Eo_B = g d_B^2 (\rho_l - \rho_g) / \sigma$) and bubble Morton ($M_B = g \mu_l^4 (\rho_l - \rho_g) / \rho_l^2 \sigma$) number are used, where ρ represents the density (l for liquid and g for gaseous phase), U_T denotes the terminal rise velocity of the bubble, d_B denotes the equivalent spherical diameter of the bubble, μ_l denotes the viscosity of the liquid phase, σ denotes the surface tension and g denotes the value of the gravitational acceleration.

Figure 1 shows an example of a bubble rising in a stagnant fluid. The bubble Morton number corresponds to the system air bubbles in water. Due to periodic boundary conditions in the x_1-direction (as well as in the x_2-direction) the simulation yields to a periodic street of bubbles. In the x_3-direction, the computational domain is bounded by rigid walls. Simulations with different dimensionless parameters (Eo_B and M_B) lead to different shapes of the rising bubbles (ellipsoidal, cap, and ellipsoidal wobbling) and to different terminal rise velocities, i.e. bubble Reynolds numbers. The numerical results concerning shape, terminal rise velocity, and wake structure are in very good agreement with experimental data. Simulations have also been performed with the new method for wobbling bubbles with a strong dynamics of the interface. The pathline of the center of mass of the bubble is almost helical and the wake is turbulent.

Five rising bubbles have been simulated to demonstrate the applicability of TURBIT-VoF for bubble clusters. Initially, the five bubbles have spherical shapes and are at rest. As the bubbles rise, they soon assume an ellipsoidal shape. The rising bubbles induce an upward directed mean flow in the continuous phase due to the displacement of the liquid and due to viscosity. The corresponding mean velocity profile between the rigid walls is parabolic. The bubbles therefore rise in a shear flow and experience a lateral force, the lift force, which lets the bubbles approach the walls. This, as well as other important phenomena observed in experiments of bubbly flows, is well captured by our direct numerical simulations (DNS). The DNS results can thereforce be used to test and improve models for interfacial forces within conventional two-fluid models, e.g. models for the lift force. This, and the analysis of bubble-induced turbulence will be the subject of future work.

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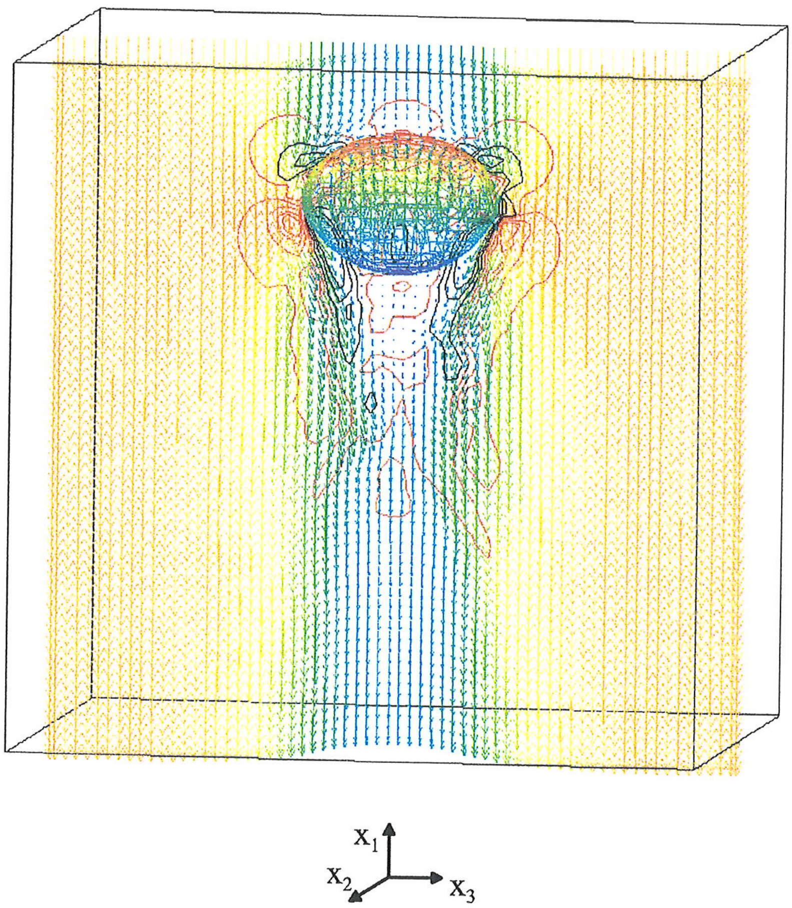

Figure 1: Single bubble ($Eo_B = 0.20$ and $\log M_B = -10.60$) rising in stagnant liquid; visualization of bubble interface, velocity vectors and vorticity contours in plane $x_2 = 0.5$; $\vec{g} \parallel \vec{x}_1$; grid: $64 \times 64 \times 64$.