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Large eddy simulations of the gas–liquid flow in a rectangular bubble column

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ABSTRACT

The paper presents Euler–Euler Large Eddy Simulations of dispersed bubbly flow in a rectangular bubble column at a low Reynolds number. The physical models describing the momentum exchange between the phases including drag, lift and wall force were chosen according to previous experiences of the authors. The emphasis of the study is the analysis of bubbly flows concerning the investigation of the influence of the bubble-induced turbulence model. It is found that the presented modeling combination provides fairly good agreement with experimental data for the mean flow. The impact of the modeling on the liquid velocity fluctuations is investigated and the energy spectrum obtained from the resolved velocity is discussed.

1. Introduction

Many technical flows situations feature a continuous liquid phase and a dispersed gaseous phase. The turbulence of the liquid phase is an important phenomenon in such multiphase flows, as it has a strong influence on the local distribution of the dispersed phase, including bubble coalescence and breakup. The distribution of the dispersed phase on the other hand impact on the large-scale velocity field and the small-scale turbulence, so that a very complex interaction mechanism arises (Balachander and Eaton, 2010).

A bubble column provides a good experimental system for the study of turbulent phenomena in bubbly flows and a suitable setup for the development of computational models. In bubble columns a wide range of length and time scales exists on which turbulent mixing takes place. The largest turbulent scales are comparable in size to the characteristic length of the mean flow and depend on the column geometry and boundary conditions. The smaller scales depend on the bubble dynamics and are proportional to the bubble diameter. In bubbly flows, the small scales are responsible for the dissipation of the turbulent kinetic energy as in single-phase flow, but the bubbles can also generate back-scatter, i.e. energy transfer from smaller to larger scales (Dhotre et al., 2013). The combination of both effects can yield an overall enhancement or attenuation of the turbulence intensity.

In gravity-driven bubbly flows, a distinct transient behavior can be identified through large-scale circulation as reviewed by Mudde (2005). Also, through the uneven aeration, naturally caused by the sparger in larger bubble columns, a distinct periodic bubble plume occurs, which is studied for example by Pfleger et al. (1999) and Julia et al. (2007). Therefore, an influence of the transient processes can be assumed which a usual steady-state Reynolds-Averaged Navier–Stokes (RANS) model is not able to capture.

The computation of such flows in and around bubble plumes in a bubble column poses severe challenges to turbulence modeling due to the presence of massive oscillations of the bubble plume with dominating anisotropic large-scale vortex systems. Under these circumstances, Large Eddy Simulation (LES) is an approach potentially capable of yielding improved results compared to RANS methods due to the reduced amount of modeling which is traded against computational resolution and hence CPU time (Fröhlich et al., 2002). On the other hand, this kind of flow is usually characterized by a low Reynolds number and with the Euler–Euler approach the mesh requirement in such a LES is comparable to unsteady RANS simulations (Deen et al., 2001; Dhotre et al., 2008; Ma et al., 2015a,b).

Simulations related to the present study have been performed by different authors combining the Euler–Euler approach with LES. Deen et al. (2001) used LES with the Smagorinsky model to simulate a bubble plume in a bubble column with a square cross-section and the gas inlet placed in the center of the bottom. These authors compared the results of LES with the prediction of a transient k–ε model and concluded that better results can be obtained with LES.

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Zhang et al. (2006) reported LES using the Smagorinsky model for the same experiment of Deen et al. (2001). They investigated the influence of using different values of the Smagorinsky constant C_s and found that too high values lead to an unphysically high effective viscosity which in turn damps the bubble plume dynamics. Ma et al. (2015a) studied a bubble column with homogeneously distributed gas inlet at the bottom for two gas inlet velocities and employing LES with the Smagorinsky model. The averaged liquid vertical velocity and gas void fraction fitted well with the experimental data in the both cases. However, the turbulence parameters could only be reproduced with this approach in the case with a higher gas inlet velocity, since large-scale turbulence is not present for the case with lower homogeneous distributed gas inlet. Furthermore, an extensive discussion of the merits of LES can be found in the work of Dhotre et al. (2013), providing a systematic evaluation of prior work on the modeling of turbulent bubbly flows.

The present study follows the work of Pfleger et al. (1999) using a 3D URANS simulation, which successfully predicted the time-averaged liquid vertical velocity of different heights of the column. However, difficulties arise with this approach to reproduce the amplitude and the large-scale period of the horizontal fluid velocity in the experiment. Here, Euler–Euler LES is performed for the same rectangular air/water bubble column (Fig. 1) at ambient pressure (Pfleger et al., 1999). The bubble column has a cross-section of 0.2 m × 0.05 m and is filled with distilled water up to a height of 0.45 m. One distributor plate containing 8 needles was placed in the center of the bottom with a cross-section of $A_{in} \approx 0.02\,\mathrm{m} \times 0.0125\,\mathrm{m}$. Measurements were performed for a gas superficial velocity of 1.7 mm/s and took place 0.13 m, 0.25 m and 0.37 m above the distributor plate in the center plane ($z = 0.075$ m). A laser Doppler velocimetry (LDA) system was used to simultaneously measure the liquid velocity.

2. Physical and numerical models

2.1. Euler–Euler approach

In this work the Euler–Euler two-fluid model is used. The conservation equations are discussed in detail in a number of books, such as Ishii and Hibiki (2011), and a broad consensus on this model has been reached. For the special case of adiabatic flows the governing equations in this approach are the continuity and momentum equations including sources for the interfacial momentum transfer

$$\frac{\partial}{\partial t}(\alpha_i\rho_i) + \nabla\cdot(\alpha_i\rho_i\bar{\boldsymbol{u}}_i) = 0, \tag{1}$$

$$\frac{\partial(\alpha_i\rho_i\bar{\boldsymbol{u}}_i)}{\partial t} + \nabla\cdot(\alpha_i\rho_i\bar{\boldsymbol{u}}_i\bar{\boldsymbol{u}}_i) = -\nabla\left(\alpha_i\mu_i\bar{\boldsymbol{S}}_i\right) - \alpha_i\nabla p + \alpha_i\rho_i\boldsymbol{g} + \boldsymbol{M}_i - \nabla(\alpha_i\tau_i). \tag{2}$$

Here, the lower index i denotes the different phases and can assume the letter L for liquid and G for gas. Furthermore, α, ρ, μ and $\bar{\boldsymbol{u}}$ denote volume fraction, density, molecular viscosity and resolved velocity, respectively, while $\bar{\boldsymbol{S}}$ is the strain rate tensor. The vector $\boldsymbol{M}$ represents the sum of all interfacial forces acting between the phases such as drag force, lift force, wall lubrication and turbulent dispersion force. The unresolved stress tensor $\boldsymbol{\tau}$, and all interfacial forces have to be modeled. The applied modeling is discussed below.

2.2. Turbulence

In this study, turbulence is treated differently for the two phases. The turbulence in the dispersed gas phase is of little relevance and is modeled with a simple zero equation model $\mu_G^t = (\rho_g/\rho_l)\mu_L^t$, where μ_G^t and μ_L^t are the eddy viscosity of the gas and the liquid phase, respectively. It was found that this model has nearly no influence on the result, because of the low density of the gas and the low volume fraction in this case. For the liquid phase, LES was used. The SGS model is the dynamic Smagorinsky model of Germano et al. (1991), with the modification of Lilly (1992). The model coefficient C_d in the Smagorinsky expression

$$\nu_{sgs} = C_d\Delta^2\left|\bar{S}\right|, \quad \left|\bar{S}\right| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}}, \tag{3}$$

where the index L is dropped for readability.

Table 1
Models for the interfacial forces employed in the present work.

Drag force	Ishii and Zuber (1979)
Lift force	Tomiyama et al. (2002)
Wall force	Hosokawa et al. (2002)
Virtual mass	$C_{VM} = 0.5$
Turbulent dispersion	None

The grid scale is $\Delta = \sqrt[3]{\Delta x\Delta y\Delta z}$ which is convenient with the cartesian grid employed for the simulation as described below. The test filter used in the dynamic procedure is determined using an explicit box filter of width twice the mesh size. To avoid numerical instability, a relaxation of C_d in time is applied and an upper and lower limit of the coefficient is imposed with $C_d^{\max} = 0.04$ and $C_d^{\min} = 0$.

In the Euler–Euler approach bubbles are treated statistically, i.e. single bubbles are not resolved. The resolved part of the velocity field in LES produces only the shear-induced turbulence. The influence of bubbles traveling through the liquid on the liquid turbulence has to be modeled. Here, the model for bubble-induced turbulence (BIT) of Sato et al. (1981) is used. In this model the influence of bubbles on in liquid turbulence is represented by an additional contribution to the SGS turbulent viscosity, so that

$$\mu_L^{\mathrm{eff}} = \mu_L^{\mathrm{mol}} + \mu_L^{\mathrm{sgs}} + \mu_L^{\mathrm{bub}}, \text{ with } \mu_L^{\mathrm{bub}} = C_B\rho_L\alpha_G d_B\left|\boldsymbol{u}_G - \boldsymbol{u}_L\right| \tag{4}$$

here C_B is a model constant equal to 0.6, and d_B represents the bubble diameter.

2.3. Interfacial forces

In the Eulerian two-fluid model the interaction between the bubbles and the liquid phase is modeled through exchange terms in the momentum equation of the liquid and the gas phase. There is still no agreement in the community on the closures to be used at best. The corresponding interfacial transfer models employed here are listed in Table 1. A complete description of all these models can be found in the original papers as well as the description of the so-called baseline model of Helmholtz–Zentrum Dresden–Rossendorf (Ziegenhein et al., 2015)

The turbulent dispersion force represents the bubble dispersion caused by the turbulent fluctuations of the liquid velocity. In RANS simulations, it has to be modeled because these turbulent fluctuations are not resolved. In LES, however, the resolved part of the turbulent dispersion is explicitly calculated, and the unresolved part has little influence on bubble dispersion if the bubble size is on the scale of the filter size (Niceno et al., 2008).

3. Results

3.1. Simulation setup

The rectangular bubble column was discretized with uniform cubic cells of $\Delta x = \Delta y = 5$mm and $\Delta z = 3.125$ mm, resulting in 57,600 cells, overall. The mesh was selected here according to a mesh study as discussed in Section 3.3.1. The bubbles are treated as mono-disperse with bubble diameter $d_B = 2$ mm. The gas inlet is