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Transient simulation for large scale flow in bubble columns

T. Ziegenhein*, R. Rzehak, D. Lucas

Helmholtz-Zentrum Dresden-Rossendorf e.V., 01314 Dresden, Germany

HIGHLIGHTS

- Validated set of closure models for monodispersed and polydispersed bubbly flows.
- Improved turbulence prediction for bubble columns.
- Different bubble induced turbulence (BIT) modeling approaches are compared.
- Influence of the BIT modeling on large scales is discussed.
- Quality assurance for transient simulations for bubbly flows on large scales.

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ABSTRACT

The transient simulation of large scale bubbly flow in bubble columns using the unsteady Reynolds averaged Navier Stokes (URANS) equations is investigated in the present paper. An extensive set of bubble forces is used with different models for the bubble induced turbulence. Criteria are given to assess the independence of the simulation time and the time step length. Using these criteria it is shown that a simulation time, time step length and mesh independent solution can be obtained for complex bubbly flows using URANS equations under certain requirements. With the obtained setup the contribution of the resolved turbulence to the total turbulence and the influence of the bubble induced turbulence modeling on the resolved turbulence is investigated. Further, it is pointed out that the virtual mass force is not negligible. The simulations are compared to data from the literature at two different superficial velocities, which cover monodisperse and polydisperse bubbly flows.

1. Introduction

Problems involving multiphase flows occur in a great variety of technical and natural processes. A common flow regime is that a disperse phase exists in a continuous phase. Modeling such multiphase flows is an active area of research. In the present paper the focus is on the modeling and description of turbulent structures on the scale of an apparatus like a bubble column and the influence of the modeling of the small scales on the large scale dynamics.

A widely used approach for modeling dispersed multiphase flows on large scale is the Eulerian two-fluid approach. Here the conservation equations are formulated for each phase and are weighted with the volume fraction of the corresponding phase. The interaction between the phases appears as a sink and source terms in the conservation equations. To simulate large scale applications the small scales are averaged and the interface between gas and liquid is not resolved. Therefore, the small scale interactions between the gas and the liquid phase have to be completely treated in closure models.

Turbulence for large scale simulations is usually described with the Reynolds averaged Navier Stockes (RANS) equations. Although the model is fully time-dependent, typically only steady-state problems are considered. The reason is that the model constants have been calibrated by comparison to stationary situations (Launder and Spalding, 1974). When applied to unsteady problems the URANS frequently gives reasonable results for the time dependence at much lower computational cost then LES (Spalart, 2000). In the context of bubble columns, simulations with the Eulerian two-fluid approach and the URANS turbulence description with a two equation turbulence model have been initiated by Sokolichin and Eigenberger (1999) and are used until today for example by Masood and Delgado (2014). In the present work the SST two equation turbulence model is used with additional source terms modeling the bubble induced turbulence.

Especially 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

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* Corresponding author. Tel.: +49 3512602503; fax: +49 3512603440.
E-mail address: t.ziegenhein@hzdr.de (T. Ziegenhein).

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naturally caused by the sparger in larger bubble columns a distinct periodic plume occurs which is studied for example by Julia et al. (2007). Therefore, an influence of the transient processes can be assumed and the usual steady solution could not cover such effects.

A proper turbulence modeling in dispersed multiphase flows is essential for a correct prediction of the momentum exchange between the phases. Especially for bubbly flows the break-up and coalescence processes, which are responsible for the bubble size distribution, are dominated by turbulence (Liao and Lucas, 2010; Liao et al., 2011). Because all modeled forces depend on the bubble size, the importance of a reliable turbulence prediction is underlined. In bubble columns the large scale structures, as described for example by Joshi et al. (2002), are also very important for mixing in technical apparatuses. Mixing might be under-predicted if these large scale fluctuations are suppressed by a steady solution method.

The motivation of the present study is therefore to show that (i) a steady solution is not sufficient under certain circumstances, (ii) with the URANS solution method the transient behavior can be covered and (iii) a solution time, time step length and mesh size independent solution can be obtained for complex multiphase flows. In addition, the bubble induced turbulence modeling is investigated and a model with source terms in the turbulence equations is shown to be necessary. Further, it is shown that the virtual mass force is not negligible, in contrast to the conclusion of several recent publications (e.g. Tabib et al., 2008 or Masood and Delgado, 2014). The application is the simulation of large scale reactors with distinct transient behavior, where Large Eddy Simulation with the Euler–Lagrange treatment is too cost-intensive.

The paper is structured as follows. In Section 2 the physical modeling is presented, in Section 3 the numerical setup is presented, in Section 4 the results are shown and compared with the experiments and finally in Section 5 the results are discussed and conclusions are drawn.

2. Physical modeling

In the present work the Eulerian two-fluid model is used. This approach has been discussed in a number of books (e.g. Yeoh and Tu, 2010), while its application to bubble columns is covered in several reviews (e.g. of Joshi et al., 2001 or of Jakobsen et al., 2005). A brief summary of the equations is given in Appendix A.1. As a result of the averaged description, closure models which describe the interaction between the dispersed phase and the liquid phase are needed. In general this concerns forces acting on the liquid and dispersed phases and the induced turbulence in the liquid as a result of the motion of the dispersed phase.

Modeling and validation of forces acting on a bubble were intensively studied over the last decade, for example by Tabib et al. (2008), Krepper et al. (2009) or Lucas and Tomiyama (2011). All forces act together to produce observable phenomena like for example the distribution of void fraction. Hence, an independent validation of each single force is not possible. Therefore, a set of models which has recently been applied with good success by Rzehak and Krepper (2013b) is used in this paper, with the addition of the virtual mass force.

For the bubble induced turbulence several approaches exist. In this paper the approach used is that the bubble induced turbulence is modeled with source terms in two-equation models. Recently Rzehak and Krepper (2013a) performed a detailed study of different bubble induced turbulence models and formulated an own model which turned out to be the most reliable model for their test cases.

All simulations are carried out in a fully three-dimensional domain, which has been shown to be essential by Ekambara et al. (2005) by comparing two- and three-dimensional modeling. For computation a customized version of CFX 14.5 is used.

2.1. Two-phase turbulence

2.1.1. Using source terms

Concerning turbulence in bubbly flows it is sufficient to consider the continuous liquid phase, based on the small density and small spatial scales of the dispersed gas. Shear-induced turbulence is described by the SST model with parameters taking their usual single phase values. Bubble induced turbulence is included by additional source terms. The governing equations are given in Appendix A.2.

Concerning the source term describing bubble effects in the k-equation there is large agreement in the literature. A plausible approximation is provided by the assumption that all energy lost by the bubble due to drag is converted to turbulent kinetic energy in the wake of the bubble. Hence, the k-source becomes

$$S_L^k = F_L^{Drag} |\vec{u}_G - \vec{u}_L|. \tag{1}$$

For the ϵ-source a similar heuristic is used as for the single phase model, namely the k-source is divided by some time scale τ so that

$$S_L^\epsilon = \frac{C_{\epsilon B}(S_L^k)}{\tau}. \tag{2}$$

For use with the SST model, the ϵ-source is transformed to an equivalent ω-source which gives

$$S_L^\omega = \frac{1}{C_\mu k_L} S_L^\epsilon - \frac{\omega_L}{k_L} S_L^k. \tag{3}$$

This ω-source is used independently of the blending function in the SST model since it should be effective throughout the fluid domain.

Modeling of the time scale τ proceeds largely based on dimensional analysis. There are two velocity and two length scales for this problem, where one of each is related to the bubble and the other to the turbulent eddies, so four plausible time scales can be formed. All four time scales were compared by Rzehak and Krepper (2013b) and it was found that the best predictions were obtained for

$$\tau = \frac{d_B}{\sqrt{k_L}}. \tag{4}$$

This variant will be used also here together with a value $C_{\epsilon B} = 1.0$. The eddy viscosity is evaluated from the standard formula

$$\mu_L^{turb} = C_\mu \rho_L \frac{k_L^2}{\epsilon_L}. \tag{5}$$

2.1.2. Using additional viscosity

The addition of an extra contribution to the viscosity that describes the bubble induced turbulence is an often used alternative approach and is used for comparison in this study. The turbulent viscosity then is formulated as

$$\mu_L^{turb} = \mu_L^{turb,SinglePhase} + \mu_L^{turb,BIT}, \tag{6}$$

where the bubble induced turbulence is formulated using the model of Sato et al. (1981)

$$\mu_L^{turb,BIT} = 0.6 \rho_L \alpha_G d_B |\vec{u_G} - \vec{u_L}|. \tag{7}$$

2.2. URANS

In general URANS calculations are based on the traditional RANS approach but treated as transient. Often the relatively simple and fast URANS calculations are even treated with stationary