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Eulerian modelling of turbulent bubbly flow based on a baseline closure concept

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ABSTRACT

A unified set of closures have been applied to simulating different configurations and fluids, i.e. pipe flow and bubble column, air/water and air/liquid metal. The simulated velocity, void fraction and turbulence profiles were compared with the measured ones. Starting from the baseline model for poly-disperse flows the present work is intended to prove the performance of a recently published model for bubble-induced turbulence, which was established on the basis of physical analyses and direct numerical simulation data. The model is shown to work well under various conditions without any need of tuning, and significant improvement in the prediction of turbulence parameters in comparison to other models is demonstrated. This is a great step towards developing the baseline closure concept. Finally, a brief discussion on the further development and future work regarding Eulerian closure models was given.

1. Introduction

In the nuclear power industry, needs for Computational Fluid Dynamics (CFD) high-resolution simulation tools regarding safety analysis and design optimization have been clearly identified, since the three-dimensional flow structure and geometrical effects often have a significant influence on the acceptance criterion and safety margin (Bestion, 2010). Many nuclear normal operating conditions and accident scenarios are related to turbulent bubbly flow, e.g. in the boiling water reactor core, steam generators and pressurized water reactors by LOCA (Loss of Coolant Accident) or pressure release transients. Currently, there are three approaches available for the numerical modelling and simulation of bubbly flows, i.e. Euler-Lagrange (Sommerfeld et al., 2008), Euler-Euler and direct numerical simulation (Santarelli and Frölich, 2016). Therein the Euler-Euler approach is the most widespread one and cheapest one for practical applications due to low computational costs. There are numerous references in the literature (Dhotre et al., 2007; Bannar et al., 2008; Ekambara et al., 2012; Peña-Monferrer et al., 2016; Liao and Lucas, 2016; Liao et al., 2013). Nevertheless, in spite of huge progress it is still considered as one of the greatest scientific challenges majorly due to insufficient understanding of the turbulence and interfacial forces. As a result, it is often the case that different closure models have been adopted in two simulations of the same case while both are able to achieve satisfying agreement with the data after fine tuning or as a result of combined imperfectness of theoretical models and experimental errors. For example, Pfleger et al. (1999) tried to reproduce their own experimental results for a rectangular bubble column using a combination of the Euler-Euler approach and the k-ε model. In their simulation only the drag was included while other interfacial forces were neglected, and the drag coefficient was set constant to 0.66. On the other hand, Buwa and Ranade (2002) simulated the bubble column using a multi-group approach including drag, lift and virtual mass forces. The drag coefficient was calculated according to the correlation presented in Tsuchiya et al. (Prasser, 2008) depending on the particle Reynolds number and Eötvös number, while the lift and virtual mass coefficient was set constant. General agreement on the effect of interfacial forces is not available. Among early work, some authors neglected the effect of virtual mass (Deb Roy et al., 1978; Joshi, 1980, 1983; Kumar et al., 1994); many neglected the effect of the lift force (Pfleger et al., 1999; Mudde and Simonin, 1999; Chen et al., 2005; Chen et al., 2005; Kerdouss et al., 2006), while several others have shown that the lift force has a strong influence on phase distribution (F'Dhila and Simonin, 1992; F'dhila, 1991; Lance and Lopez de Bertodano, 1994; Lathouwers, 1999). Furthermore, some models presume a constant bubble size while others incorporate various population balance equation methods. For example, different approaches for the consideration of coalescence and breakup have been tested using the data of TOPFLOW air-water pipe flow experiment (Prasser, 2006),

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which is aimed to provide high-resolution data for CFD validation. Krepper et al. (2008) simulated the poly-dispersed pipe flow using the inhomogeneous MUltiple Size Group (iMUSIG) model, where the gaseous bubbles were divided into 2 velocity groups. The drag, lift, wall lubrication and turbulent dispersion force were considered in the interphase momentum exchange. The Clift et al. (1978) drag coefficient, Tomiyama (1998) lift force coefficient and the so-called Favre-averaged-drag turbulent dispersion model (Burns et al., 2004) were used. The wall force coefficient was calculated according to the Antal et al. (1991) formulation. For the same experiment, Dorao et al. (2008) applied a least squares spectral method for solving the population balance equation and predicting the evolution of the dispersed phase. The data was also used by Dave (2016) for the validation of the interfacial area transport equation models. Cheung et al. (2013) applied the Euler-Euler approach together with three different population balance approaches, i.e. direct quadrature method of moments, average bubble number density and homogeneous MUSIG models.

Apparently there is not yet a universal interfacial closure model available for the simulation of poly-dispersed or even monodispersed bubbly flow. The situation has been discussed in Zhang et al. (2006), who pointed out the importance of turbulence modelling and a correct description of closure laws for interfacial forces. They examined the effect of various closures for bubble-induced turbulence (BIT), drag, lift and virtual mass force in bubble column simulation, but were incapable of concluding which set of closures are more universal than the others. Actually, it has been often shown that a model is able to give satisfying predictions for some parameters or in certain situations while failure in others. As a consequence, the routine use of CFD is restrained to reproduce available experimental data by trial and error instead of predicting the flow behaviour independently. Quantitative predication is actually what we expect from CFD, especially in nuclear installations where experimental tasks are often difficult or even impossible. From this practical point of view, the development of general and transferable models, which are able to predict a broad range of flow situations reliably without any tuning, is of great interest. However, generalization of Eulerian closures for bubbly flow is surely a most challenging task. Apart from the complex nature of interfacial transfer dynamics, the diversity of closures and artificial tuning make it quite difficult to assess the performance of a model and to develop it further for generality—a comparative study of closures by comparing with experimental data does not really help so much at this point.

2. A Baseline closure concept

To improve above situation, a long-term baseline closure concept for interactive model development has been proposed in the previous work by HZDR (Helmholtz-Zentrum Dresden-Rossendorf) (Liao et al., 2015; Lucas et al., 2016; Rzehak et al., 2017). It aims to provide a common basis for all research groups or researchers on Eulerian modelling of bubbly flows. In this way it is possible to collect practice experience and to promote the development process of a general closure. The basic idea is sketched in Fig. 1.

First of all, closures in the baseline model should be the most physically based ones that are available, although we are aware that we do not have ideal closures yet. Furthermore, it should include closures for all phenomena relevant to bubbly flows, e.g. total interfacial forces (drag, lift, wall lubrication, virtual mass, turbulent dispersion …), BIT, and bubble coalescence & breakup. It is reasonable that these phenomena have different contributions under different flow conditions, or even negligible in some situations. A reliable physical model should be able to reflect the variation automatically. For example, the predicted coalescence rate should be sufficiently small in cases where no obvious coalescence is observed. In other words, it makes no sense to switch off/on a model on basis of available experimental observation. In addition, all model parameters should be held constant, since a case by case tuning of constants is not helpful in achieving the goal of generally applicable closures.

As a next step, the defined baseline model is advertised internally and externally to get as much as possible test feedback. It should be used to simulate a large number of experiments with different flow configurations such as pipe flow (vertical, horizontal, inclined), bubble column (homogeneous flow, static and oscillating bubble plume), stirred-tank, with/without heat and mass transfer as well as different working media. The simulations are performed under the consideration of best practice guidelines (BPGs) with respect to grid generation, initial and boundary conditions, material and numerics selection (Scheuerer, 2005); and without any parameter tuning. It may happen that the agreement with experimental data is insufficient or even worse than other tuned models. But we should not be disappointed by the deviations since they can provide us valuable clues which physical phenomena are not well represented by the model and where we should invest our efforts for improvement.

After a systematic analysis and evaluation of the comprehensive simulation results and test feedback, the most severe shortcomings of the model are identified. Based on the expertise suitable laboratory experiments or DNS (Direct Numerical Simulation) numerical experiments are designed to provide sound insight and understanding in the investigated phenomenon. In this way, a better sub-model with more physical knowledge for the particular aspect is developed. It will be incorporated in the baseline model and all the collected simulations will be repeated. If an overall improvement can be demonstrated, the sub-model will be accepted and the baseline model will be updated even with worse agreement to some extent in some cases. We have to bear in mind that the qualification of closures for bubbly flows is extremely difficult due to the complex coupling of physical phenomena. An important point in updating is whether the new model has a better physical basis, since the premise of a general closure is the correct representation of physics.

Currently, the sub-models included in the baseline model are summarized in Table 1. The models are chosen based on the underlying physics and the experience at HZDR. Nevertheless, it doesn't mean that the selected sub-models are perfect or the best. It provides only a common basis for further development.

Wherein v_{td}, v_{tc} is the kinematic viscosity of gas and liquid, respectively, and σ is the turbulent Prandtl number.

At the selection of models we realized that the modelling of BIT and bubble coalescence and breakup remain two weakest links in the Eulerian modelling of bubbly flow. In the past few years we have put our focus on these aspects and achieved promising progress based on the baseline concept. After a comprehensive analysis and review of available models (Liao and Lucas, 2009; Liao and Lucas, 2010), a general coalescence and breakup model with consideration of all potentially relevant mechanisms have been proposed by Liao et al. (2011). It has been successfully incorporated in the baseline model and tested for vertical pipe flows (Liao et al., 2015). On the other hand, continuous efforts have been invested in studying the effect turbulence modulation induced by bubbles (Liao and Lucas, 2012; Rzehak and Krepper, 2013). Numerous investigations on BIT and models with additional k and ε source terms have been published (Politano et al., 2003; Morel, 1997; Pfleger and Becker, 2001; Troshko and Hassan, 2001), but the choice of length and time scales is still quite arbitrary or even based on dimensional analysis purely. Based on the energy spectral analysis, Ma et al. (2017) proposed a method for characterization of BIT scales more physically, and proposed a BIT model with the aid of DNS budget of turbulent kinetic energy. The source terms for k and ε/ω equations are given by

$$S_k = C_k \frac{3}{4}\rho_l \frac{C_D}{d}|\boldsymbol{u}_{rel}|^3, \tag{1}$$

$$S_\varepsilon = C_\varepsilon \frac{S_k}{\tau}, \tag{2}$$