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On the dynamics of instabilities in two-fluid models for bubbly flows

Klas Jareteg [a,*], Henrik Ström [b], Srdjan Sasic [b], Christophe Demazière [a]

[a] Division of Subatomic and Plasma Physics, Department of Physics, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
[b] Division of Fluid Dynamics, Department of Applied Mechanics, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

HIGHLIGHTS

- Instabilities in bubbly gas-liquid flows are investigated.
- A shared-pressure two-fluid model is applied to low bubble loadings.
- Inclusion of virtual mass force leads to change in the nature of the system.
- Physical phase heterogeneities follow the numerically-triggered instabilities.
- Implications for using two-fluid models for predicting bubbly flows are discussed.

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ABSTRACT

In this paper we look at instabilities in bubbly gas-liquid flows and investigate the emergence and characteristics of phase heterogeneities. We apply a shared-pressure two-fluid model to low bubble loadings and demonstrate the existence of persistent gas fraction instabilities of a characteristic size larger than the applied computational grid. In particular, we investigate the influence of a virtual mass effect on the stability of the two-fluid model and we demonstrate a change in the emergence and the dynamics of the phase heterogeneities. The change is accounted to a difference in the degree of hyperbolicity due to the inclusion of the virtual mass force. Furthermore, the results indicate that an initial instability, concluded as numerical in its character, evolves into a state with a physical character of the heterogeneities. We discuss implications of the existence and dynamics of the heterogeneities and the importance of the numerical behavior for interpretation of the results. In particular, we argue that underlying characteristics of the model cannot and should not be concealed with additional sub-models (such as momentum exchange terms) but must be acknowledged in the analysis of results from the two-fluid model for bubbly flows.

1. Introduction

Bubbly gas-liquid flows are important for many industrial processes due to their advantageous characteristics of heat and mass transfer. However, the complexity of the flow and the extensive range of flow regimes in combination with large industrial devices make computational modeling of such systems a major challenge. For full scale simulations, the computational burden makes it unfeasible to use Direct Numerical Simulation (DNS)-like methods where the interface between the two-phases is directly tracked or reconstructed. Examples of the latter include the volume of fluid method (VOF) (Noh and Woodward, 1976; Hirt and Nichols, 1981), the level set method (LS) (Osher and Sethian, 1988; Sussman et al., 1994) or front tracking (Unverdi and Tryggvason, 1992). As a consequence of the system sizes, typically much larger than the length scales relevant for a single bubble or gas entity, it is necessary to rely on a simplified representation, such as the two-fluid model (Lahey and Drew, 1989; Ishii, 1990; Prosperetti and Tryggvason, 2007).

In the two-fluid method, both phases are described in an Eulerian frame of reference. The fluids, in the present case gas and liquid, are treated as interpenetrating continua that coexist in every computational volume. The proportions of the respective phases are described as a volume fraction and the flow properties are assumed homogeneous for each phase in each discrete cell. Due to such a local homogenization of the flow, information about the interface between the phases is discarded. For a bubbly flow, this means that the local characteristics such as the size of bubbles is not predicted and that the dynamic behavior of the two phases is also only recovered in an average sense.

* Corresponding author.
E-mail address: klas.jareteg@chalmers.se (K. Jareteg).

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Additionally, the governing equations of the two-fluid model are typically derived under the assumption of a slow variation in space of the phasic properties, for example the volume fractions of the phases (Lahey and Drew, 1989). Such a requirement is an attempt to reach the separation of scales, where the void fraction fluctuations should not rapidly change on the scale of the computational mesh. The assumption of a slow variation is a major drawback when it comes to the applicability of the two-fluid model. An assumption of small gradients, often neglected in practice, limits the validity of the model to bubbly flows of low bubble loadings. For flow regimes with higher gas fractions, such as slug or churn flow, the computational cells would have to be enlarged to the extent that no relevant fully dimensional resolution could be achieved. For some applications, a coarse mesh and one dimensional (1D) conservation equations are of relevance to compute macroscopic system properties (Prosperetti and Tryggvason, 2007). In this paper we shall consider low ranges of the void fraction (i.e. the gas fraction) in an attempt to fulfill the discussed criteria.

Although the phases are represented in a spatially averaged sense, the dynamic behavior of the phase fractions and velocities is potentially important both for mass and heat transfer applications. It is thus of interest to accurately capture possible variations and also the phenomena that contribute to the appearance of non-uniform distributions of the void fraction. We will refer to such a non-uniform state in the void distributions as heterogenities, i.e. heterogeneous in terms of the spatially averaged phase fraction fields. In contrast to fully resolved interfaces in VOF or LS, the two-fluid formulation can only capture meso-scale fluctuations, here used to denote heterogenities larger than the computational cell but smaller than the system size. The meso-scales are throughout the paper significantly larger than the actual bubble size, and thus in accordance with the requirement of slow variations over the averaging volume.

From experiments, it is well established that initially homogeneous bubbly flows can become heterogeneous at high enough bubble loadings (Mudde et al., 2008). The physical mechanisms responsible for this transition are however not yet fully understood. There have been several attempts to identify those mechanisms based on mathematical or numerical analyses of two-fluid models, resulting in a range of possible, and sometimes even conflicting, suggestions for routes leading to an unstable behavior in the sense of fluctuating values of the phase fractions or velocities (Sankaranarayanan and Sundaresan, 2002; Lucas et al., 2005, 2006; Monahan and Fox, 2007b; Yang et al., 2007; Chen et al., 2009; Yang et al., 2010). We will refer to the term instability for the cause and transition of the homogeneous to the heterogeneous void fraction distribution.

Complementary to the theoretical studies of flow regime transitions, many authors have attempted to capture the experimentally demonstrated change from uniform to heterogeneous flow based on simulations. Notably, Monahan et al. (2005) simulated the experiments by Harteveld (2005) with a variety of momentum exchange terms and proposed the need for a large number of terms to be accounted for to accurately capture the transition. As noted in another paper from the same group (Monahan and Fox, 2007a), the simulations can lack stability (in the sense of reaching a physical and convergent solution) in the limit of small bubbles, which is particularly interesting as the two-fluid model is derived under the assumption of sufficiently small bubbles and slow variations relative to the averaging scales. As made evident from the referenced simulations, not all properties of the two-fluid model are well understood. This is especially pertinent for the dynamic behavior of heterogeneities in fully-dimensional (3D) flow simulations, where an excessive use of additional model terms is likely to significantly contribute with a diffusivity, in effect an excessive viscosity, and thus overshadow potential fluctuations of phase fractions.

In relation to the discussed numerical issues, it is known that the degree of hyperbolicity affects the numerical stability of a two-fluid model (Drew et al., 1979; Lahey et al., 1980; Dinh et al., 2003) and it is therefore of interest for the current investigation of the dynamics of the two-fluid model. In formulations based on 1D conservation equations, issues with instabilities have been seen for models with no viscosity (Lhuillier et al., 2010). As a remedy, a mathematical or numerical regularization may be applied to achieve hyperbolicity (Dinh et al., 2003). A numerical regularization is, in its simplest form, induced from a coarse spatial discretization which results in much numerical diffusion as discussed by Pokharna et al. (1997). The need for viscosity (physical or numerical) is confirmed by linear stability analysis based on simplified models, where it can be shown that such terms enhance the stability of the short wave lengths (Arai, 1980).

Another way to deal with the model instabilities is to include specific momentum exchange terms directly aimed to stabilize the solution in the numerical sense. An example of this is to include the virtual mass force in the formulation of the governing equations. The virtual mass force corresponds to the force exerted on a moving object immersed in a fluid when it accelerates relative to its surrounding, and hence must also accelerate some of the surrounding fluid. Although the effect of that force may be of little significance to the final results, the virtual mass force can have a profound effect on the numerical behavior of the problem (Lahey et al., 1980; Toumi and Kumbaro, 1996). Theoretical studies on 1D models for various formulations of the virtual mass force confirm that hyperbolicity is obtained, but typically only for a sufficiently low void fraction (Prosperetti and Satrape, 1990). Such a finding is again of interest and importance for the two-fluid model applied to low bubble loadings and small bubbles as it potentially affects the dynamics of the heterogeneities. As relates to the dynamics of bubbly flow, studies have shown that the virtual mass force is crucial for accurate predictions of transient phenomena such as a bubble plume oscillation (Mudde and Simonin, 1999; León-Becerril et al., 2002). As such, an inclusion of the virtual mass force has multiple advantages, both improving numerical characteristics and the predictability of transient behavior.

In effect, the two-fluid model is typically accompanied with a turbulence model. The turbulence model enhances stability of the two-fluid model due to existence of a significant turbulent viscosity. However, to rely on this approach is not straightforward if the two-fluid model is applied to a successively refined mesh, as - in contrast to single-phase turbulence - meso-scale instabilities in disperse two-phase flows typically originate from the very small scales, which are increasingly well resolved as the cells become smaller (Agrawal et al., 2001; Ström et al., 2015). Furthermore, turbulence models, such as Reynolds-averaged Navier-Stokes (RANS) models, are often applied to the continuous phase, not necessarily taking the effect of the dispersed flow into account. There is still no consensus on how to adapt well-established single-phase two-equation turbulence models to properly account for complex two-phase phenomena, such as bubble-induced turbulence (Rzehak and Krepper, 2013). In relation to the virtual mass force, Lhuillier et al. (2013) argue that it needs to be combined with a model for the turbulent velocity fluctuations in order to guarantee hyperbolicity. In a similar manner, Stewart (1979) demonstrate that the two-fluid equations are well-behaved given a large enough momentum exchange between the phases and a coarse enough mesh. However, it should be emphasized that such a finding does not guarantee that the underlying equations are stable, but rather that the model is well-behaved on a coarse mesh without addressing the underlying ill-posedness.